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**NAME:** Mr. Dan Tong-in

**THIS THESIS HAS BEEN ACCEPTED BY**

______________________________ **THESIS ADVISOR**
( Mr. Pornthep Anussornnitisarn, Ph.D. )

______________________________ **COMMITTEE MEMBER**
( Associate Professor Kongkiti Phusavat, Ph.D. )

______________________________ **COMMITTEE MEMBER**
( Mr. Peerapong Triyacharoen, Ph.D. )

______________________________ **COMMITTEE MEMBER**
( Associate Professor Anan Mungwattana, Ph.D. )

______________________________ **COMMITTEE MEMBER**
( Associate Professor Prapaisri Sudasna-na Ayudthya, Ph.D. )

______________________________ **DEPARTMENT HEAD**
( Associate Professor Anan Mungwattana, Ph.D. )

**APPROVED BY THE GRADUATE SCHOOL ON** ______________________________

______________________________ **DEAN**
( Associate Professor Gunjana Theeragool, D.Agr. )

THESIS

# THE EFFECT OF STRESS RELIEVING TREATMENT CONDITIONS ON THE QUALITY OF HIGH TENSILE STEEL WIRE IN PROGRESSIVELY DRAWN PEARLITIC STEEL

DAN TONG-IN

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This study was aimed to determine the effects of processing condition of stress relieving processes on the quality of high tensile steel wire in progressively drawn pearlitic steel. The hot rolled high carbon steel wire rods, grade SWRH 82B for producing pre-stressed concrete wire and the final commercial product (Pre-stressed concrete wire: heavily cold drawn) were received from wire products company. Stress relieving treatments were also carried out in order to relieve the residual stresses accumulated after the cold work. The heat treatment temperature, tension ratio and time exposure to heat, which are the parameters of stress relieving treatments, were changed. Stress relieving treatment experiments were performed under two differing analysis methods, namely the Classical and Taguchi methods. The stress relieving treatments were determined by changing the heat treatment temperature, tension ratio and time duration and by observing the effect of these changes on tensile strength, yield strength, elongation, and relaxation behavior of the quality of pre-stressed concrete wires. The heat treatment temperature had a very strong effect on elongation. The value of elongation is about 5.73% when the temperature and other parameters are at the lower limits, and it is about 6.78% when the temperature and other parameters are at the higher levels. The tension ratio had a profound effect on relaxation. The value of relaxation is about 6.67% when the tension ratio and other parameters are at lower levels, and it is about 3.75% when the tension ratio and other parameters are at higher levels. The process parameters, heat treatment temperature, had a negative effect on elongation at 375C°

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| Acc | = | Accuracy |
| RA | = | Reduction area |
| S/N | = | Signal to noise |
| SEM | = | Scanning electron microscopy |
| UTS | = | Ultimate strength |

# THE EFFECT OF STRESS RELIEVING TREATMENT CONDITIONS ON THE QUALITY OF HIGH TENSILE STEEL WIRE IN PROGRESSIVELY DRAWN PEARLITIC STEEL

## INTRODUCTION

### General Background

One of the most innovative materials invented is pre-stressed concrete. The pre-stressing and pre-casting of concrete is one of the defining features of the modern building industry. Through the application of imaginative design and quality control, it has had, since the 1930's, an increasing impact on architectural design and construction procedures. Pre-stressing of concrete is the application of a compressive force to a concrete member and may be achieved by either pre-tensioning high tensile steel strands before the concrete has set, or by post-tensioning the strands after the concrete has set. Although these techniques are commonplace, misunderstandings of the principles and the way they are applied, still exist. High strength wire has had an essential role in producing pre-stressed concrete.

The construction possibilities of pre-stressed concrete are as broad as those of ordinary reinforced concrete. Typical applications of pre-stressing in building and construction are as follows:-

1. Structural components for integration with ordinary reinforced concrete construction, e.g. floor slabs, columns, beams.

2. Structural components for bridges.

3. Water tanks and reservoirs where water tightness, (i.e. the absence of cracks), is of paramount importance.

4. Construction components e.g. piles, wall panels, frames, window mullions, power poles, fence posts etc.

5. The construction of relatively slender structural frames.

In pre-stressed concrete composites, steel wires with a higher elastic limit and tensile strength are required. Concrete has lower tensile strength compared to its higher compression strength. Steel wires are used to improve the tensile strength of concrete and higher strength steel wires naturally serve to increase the strength of whole concrete composites as a whole. In pre-stressed concrete composites, tensioned steel wires are embedded in concrete and there should be no loss of tension. In industrial applications, steel wires are cold drawn to achieve high strength. Interior stresses developed during the cold drawing produce some important changes in tensile strength, such as Hook slope or elongation of the material. In order to minimize the negative effects of residual stresses, stress relieving processes should be induced. 5.5-13 mm diameter carbon steel wires are used in the production of pre-stressed concrete composites, which are then cooled in a controlled atmosphere after the hot rolling process, this results in a relatively homogeneous pearlite type structure. Re-heating the wires up to temperatures of $400^{O}$C and stretching them by up to 50% of ultimate strength produce drawn wires, which have high hardness and strength. This stress relieving process is done to improve the steel’s mechanical properties. The mechanical requirements of pre-stressed concrete wire are specified in a number of various standards, such as BS 5895, ASTM 421 and ASTM 416. Robert (2001) acknowledged that during pre-stressing the wire or strand is stressed with a high load and it is necessary that the single wire or strand wire keeps this high level of stress throughout the end product’s life. Thus, it is very important that the wire or strand also has good relaxation properties. These are achieved by using a stress-relieving treatment. The previous type of reinforcement wire was known as stress-relieved wire or normal relaxation wire. However, the modern stress relieving or low-relaxation wire has superseded globally.

It would be pertinent to examine how the stresses initially arise. We are familiar with the fact that a drawn wire generally has residual tensile stresses at the surface and residual compressive stresses in the center but how and why these occur are not always so well known. When a wire is deformed by the drawing work done on it, the mechanical energy that does this work is dissipated primarily as heat within the metal. An additional source of heat comes from the frictional effect between wire and die and at high drawing speeds the heat is evolved within milliseconds. High temperatures and steep temperature gradients are therefore to be expected, together with differences in the temperature between the wire's surface and core resulting in residual stresses. During wiredrawing, the deformation is not uniform throughout the cross-section of the wire and this also results in internal stress (Allan, 1989).

The residual stresses in cold drawn steel wire will cause themselves to distort either during the manufacturing process and/or later during the useful life of the wire. The thermal stress relief process is widely used to reduce or modify the internal or residual stresses in cold drawn steel wire. It is difficult to obtain analytical solutions to predict the mechanical properties of wire. With the increasingly competitive environment, steel wire product companies, which historically have had thin profit margins are looking for ways to reduce costs so as to increase their competitiveness and maximize shareholder value. Until now, there has been a lot of work and research done to lower costs.  However, little research has been done on the quality of high tensile steel wire. Higher quality enables companies to reduce error rates, reduce waste, field failures, warranty charges and customer dissatisfaction: It also shortens the time required to put new products on the market, increases yield capacity, improves delivery performance, increases customer satisfaction; makes products salable, increases market share, provides sales income, secures premium prices and meets competition.

## Problem Statement

Many business enterprises in the real world have the objective of maximizing profits and efficiency while minimizing cost or risks. Furthermore, given the limited resources that are available to the industry as well as the rapidly changing technical requirements, it is clear that personnel at all levels need an in-depth understanding of production processes. It is also evident that such an understanding is a prerequisite for controlling and optimizing existing processes and the sustainable development of new technology. The problems of producing high strength wire for pre-stressed concrete can be summarized as the following:

1. Mechanical properties of high tensile steel wire sometimes do not conform to standard.

2. Non-uniformity in mechanical properties is passed on to the end user.

3. Lack of knowledge of the interrelationship between the main factors of high tensile steel wire mean that is very difficult to adjust or correct the production process in order to get the stable qualities necessary in high tensile steel wire.

4. Losses from production processes.

## Benefits of the Research

1. To identify influential factors which affect mechanical properties of high tensile steel wire.

2. To determine the factors which control the production process of high tensile steel wire.

3. The quality of products will be constant and conform with industrial standards, leading to reduced risk and higher safety.

# OBJECTIVES

There are four primary objectives for this research. They are as follows:

1. To design and construct an experimental stress relief unit for high tensile steel wire.

2. To study the effects of processing condition of stress relieving processes on the quality of high tensile steel wire in progressively drawn pearlitic steel.

3. To develop a mathematical model, which relates the quality of steel wire in terms of tensile strength, yield strength, elongation, and relaxation to the input variables.

4. To make a comparison between the Classical and Taguchi methodologies.

# LITERATURE REVIEW

In this chapter, we will first review several types of theories related to this research. Then, we will also survey the extensive research which has been done in design and analysis of these theories.

## 1. The theory of deformation in cold drawing and its effect.

Plastic deformation is the one property that makes wiredrawing possible. It has been responsible for the increased technological and commercial importance to mankind. The capacity of steel wire to undergo a high level of reduction in a cross-sectional area without fracturing, as well as the ability to control strength and other properties over a wide range are primary attributes that have enabled drawn wire products to become ubiquitous in society, even as numerous other materials have become available.

Plasticity theory is the foundation for the numerical treatment of metal-forming processes. Metallurgy can explain the origins of the plastic state of metallic bodies and its dependence on various parameters, such as process speed, prior history, temperature, and so on. Plasticity is the capacity of a material to change its shape permanently under the action of forces when the corresponding stress state reaches a material-dependent critical magnitude called yield strength or initial flow stress. As seen from the results of the standard tension test, when the stress is below the yield strength, the deformation disappears upon unloading: the material unloading the work piece has a form that is different from its initial one. It is then said to have been plastically or permanently deformed, or, if a definite final shape was sought, it has been formed. Materials which behave in an elastic-plastic manner can, after having been permanently deformed, again be loaded until the flow stress is reached without additional permanent deformation setting in. This increase in the flow stress as a result of prior deformation is called strain hardening. (Lange, 1985)

The theory of continuum plasticity involves the definition of yield criteria when a material yield plastically or flows. In bulk deformation, yielding of the work piece is intended, and yield criteria are used in the modeling of flow under combined stresses. The first yield criteria for metals were proposed by Henri Tresca in the 1860's. The Tresca criteria are based on the premise that yielding is dependent on just shear stresses, whereby plastic flow begins when the shear stresses exceed the shear yield strength of the metallic material. Although the Tresca yield criteria are adequate, they neglect the intermediate principal stress.

Richard (1883, 1953) was an American professor of applied mathematics, who also derived conditions for plastic deformation. Tresca postulated that the yield surface is the surface of a hexagonal prism of infinite length in the stress. Yielding will not occur as long as the stress acting upon the body remains within the confines of this prism. The centerline of the prism makes equal angles of 54.73° with the principal stress axes. Von Mises' yield surface is the surface of a circular cylinder in which Tresca's hexagonal prism is inscribed. Strain hardening during cold working enlarges the cross-section of the prism or cylinder.

It is not easy to express the hexagon in a mathematical form. For simplification, therefore, von Mises introduced in 1913 a circle that circumscribes the hexagon. His original motivation was in fact just the simplification, but the new yield surface was later given a physical interpretation called the distortion energy theory. According to this theory, yielding occurs when the elastic energy, causing distortion in the body, reaches a critical value. Tresca's criterion in mathematical form state that yielding occurs when some function of the maximum shear stress reaches a critical value. This implies for pure shear that $\sigma_{max} - \sigma_{min} = c$. For uniaxial tension this means that yielding will occur when $\sigma_1$reaches the yield strength in tension. $\sigma_1 = \sigma_y$. and $\tau_{max} = ½ * \sigma_y$. For pure shear the yielding will occur when $\tau_y$ or k = ½ * $\sigma_y$. (the symbol k is used for the yield strength in pure shear and is used interchangeably with $\tau_y$). for the Tresca criterion $\sigma_{eff} = \sigma_1 - \sigma_3$ when $\sigma_1 > \sigma_2 > \sigma_3$. The von Mises criterion postulates that yielding occurs when the elastic energy, causing distortion, reaches a critical value. This implies that the tensile and shear yield stresses are related in the following way:

$$\tau_y = \frac{\sigma_y}{\sqrt{3}} \; ; \; \sigma_{eff} = \frac{1}{\sqrt{2}} .[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2} \qquad (1)$$

A comparison:

$$(2k)_{Tresca} = \sigma_y. \qquad (2k)_{Mises} = 1.15.\sigma_y.$$

Taylor in 1934 postulated a theory known as the dislocation theory which occurs along atomic planes of crystal lattices, and slipping which occurs along atomic planes of crystal lattices. However, contrary to the slip illustrated by the playing card, analogy, the atomic planes do not slip over each other as rigid entities. Instead, slip takes place at one or more places in the slip plane and progresses gradually over the remainder of the plane. The theories of Cottrell and Parker describe edge and screw dislocation in slip planes. In addition to edge dislocations which move perpendicularly to their length, there are also screw dislocations which have been described by Parker. Screw dislocation is similar to an edge dislocation except that the direction of slip is parallel to the dislocation line rather than being perpendicular to it. It should be noted that dislocations are found in annealed as well as in cold worked materials.

In an important paper from 1958, Wistreich gave a careful analysis of the situation at that time for metal forming processes. The modern theory of plasticity can be used to describe the metal forming process and to calculate the forces, pressures and material behavior within the die. The solution to the associated equations is usually very difficult to calculate. However, in elementary theories of plasticity, these mathematical difficulties are avoided by making certain assumptions with regard to the mode of deformation and the stress states in the component during the process.

One simplification involves assuming that the deformation is entirely homogenous i.e. plane sections remain plane throughout the passage of the wire through the die. However, metal forming processes are by nature inhomogeneous and some of the elementary or equilibrium equations can be completed by including corrections for inhomogenity and friction. These equations (Sachs, Whitton and Siebel) can still serve as models for the process and can be tested against experimental determinations of the drawing force. The value of some parameters, including the coefficient of friction, can be calculated by interaction.

The slip-line field theory, first described by Hill and Tupper, was developed to describe the flow pattern in the region being deformed. Most of the assumptions made in the common approach to the slip-line field method are similar to those in the upper-bound method described below. Computer programs for the construction of slip-line fields have been developed. One example is a matrix-operational method presented by Dewhurst and Collins.

It is not always possible to calculate the precise load that initiates the plastic deformation. One approach is to use the upper bound solution, which gives a value higher than or equal to the actual stress. Methods suitable for use with this calculation are given by Avitzur. There is also a lower bound solution, which gives values equal to or less than the actual stresses. Both methods are described by Mielnek and Hosford and Caddell. The upper bound method is also exemplified and explained in three papers by Wikander and Stalberg. (Enghag**,** 2002)

Howard J. Godfrey summarizing plastic deformation in his Mordica Memorial lecture given before the Wire Association in Baltimore in 1962, showed that metals can be plastically deformed if sufficiently large forces are applied. He first reviewed the older theories of plastic flow which describe plastic deformation as a slip process that takes place by the displacement of one part of the metal relative to another. This general mechanism is illustrated by a deck of playing cards.

Finite Element Analysis Process modeling for the determination of deformation mechanics has been a major concern in modern metalworking technology. Proper design and control of metal forming processes requires global as well as local knowledge of the mechanics during deformation. In this regard, the finite-element method has a central role in metal-forming process modeling. To simulate metal flow during deformation processes, the most promising technique is the finite-element method. The concept of the finite-element method is one of discretization. The finite-element model is constructed in the following manner: a number of finite points are identified in the domain of the function, and the values of the function and its derivatives, when appropriate, at these points are specified. These points are called nodal points. The domain of the function is represented approximately by a finite collection of subdomains called finite elements. The domain then is an assemblage of elements connected together appropriately on their boundaries. The function is approximated locally within each element by continuous functions which are uniquely described in terms of the nodal point values associated with the particular element. (Kobayashi, 1989)

While dislocations prevent the achievement of the theoretical strength of a metal, paradoxically, they are the reason that strength increases during deformation at room temperature. Their behavior at elevated temperatures also controls the mechanical properties obtained after annealing. Most methods of developing strength in metals essentially involve inhibiting the slip process so that a higher proportion of the inherent crystal strength is used. This is achieved by reducing dislocation mobility in one or more ways. (Robert, 2008)

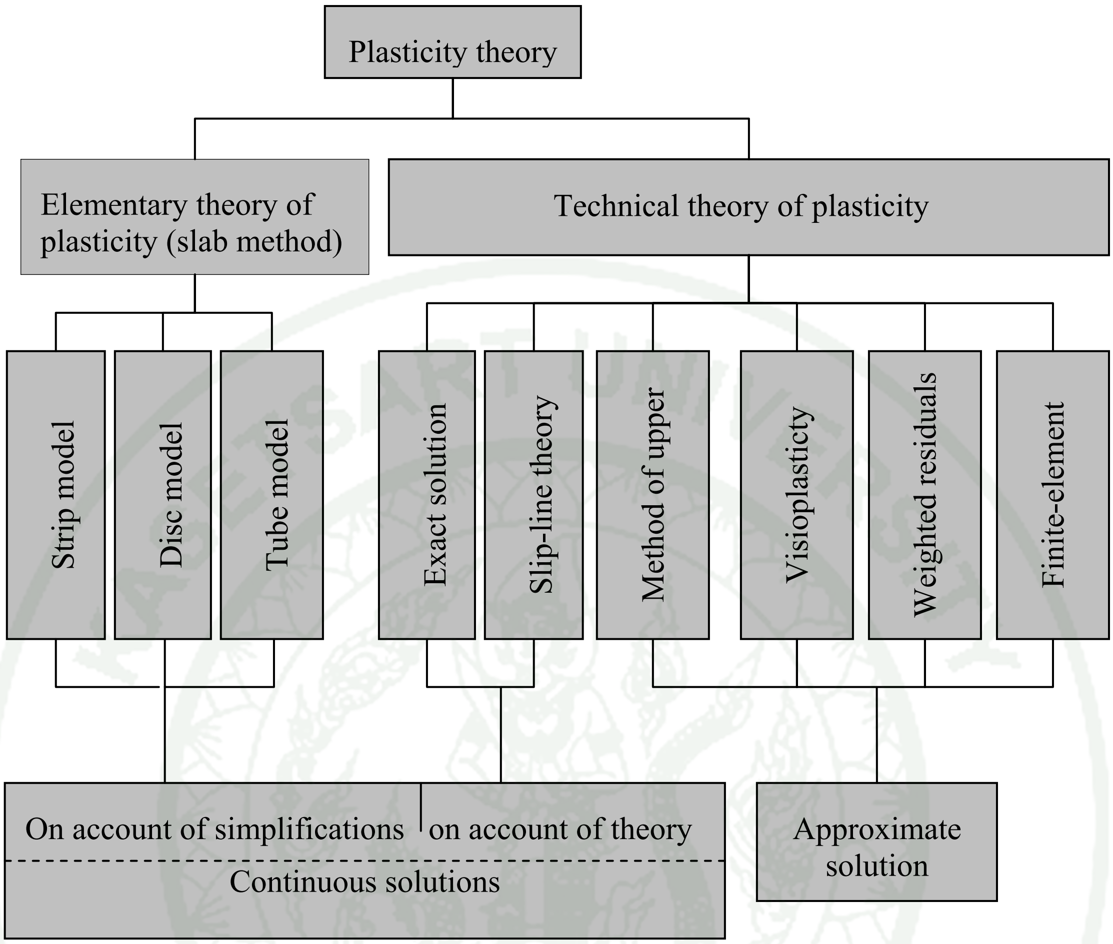



**Figure 1** Theoretical solution techniques for metal-forming problems

**Source:** Lange (1985)

1.1 The theory of wire drawing

Deformation in wiredrawing is influenced by number of factors: wire chemistry, approach angle, lubrication, drawing speed, and reduction are the most significant. The primary emphasis in wiredrawing mechanics is on understanding and defining the relationships that exist between these process conditions and the resulting thermo-mechanical response of the wire. Many of the technological developments that have taken place in wiredrawing over the past 20years have been the result of an increased understanding of these relationships.

Although the fact that volume is not lost during deformation may seem obvious, it is, in fact a highly useful concept that forms the most common applications involved in the determination of wire speed at different stands and the necessary capstan speeds that should be used. Simply stated, constancy of volume states that the volumetric rate of wire entering a die must be the same as that exiting. Because the cross-sectional area is reduced during drawing, it is necessary that a wire must increase in speed for the same volumetric rate of material to enter and exit the die. Volumetric rate is defined as the cross-sectional area of the wire multiplied by the wire velocity. This can be expressed mathematically as;

$$V_i = \frac{3.14159 \times d_i^2}{4} = V_f \frac{3.14159 \times d_f^2}{4} \qquad (2)$$

Where $V_i$ and $V_f$ represent the wire velocities (feet or meters per minute) and $d_i$ and $d_f$ are the wire diameters (inch or millimeters) entering and exiting the die, respectively. For circular wire, Equation I can be simplified and reduced to:

$$V_i d_i^2 = V_f d_f^2 \qquad (3)$$

In multi-pass drawing, wire speed exiting each die must increase so that the volumetric rate of metal flow is equal at all dies. (Robert, 2008)

Drawing is an operation in which the cross-sectional area of wire is reduced by pulling it through a converging die. The die opening may be any shape. Wire drawing involves materials of smaller diameter to those used for rod drawing, with sizes as small as 0.025 mm. The drawing process, which was an established art by the $11^{th}$ century AD, is some what similar to extrusion, except that in drawing, the bar is under tension, whereas in extrusion it is under compression. (Serope, 2003)

The work of drawing consists of two parts; that used in effecting deformation, and the portion consumed in overcoming friction between the surfaces of wire or rod and die. Ideally, all portions of the cross section should be deformed equally, but in actuality some distortion or redundant deformation occurs which requires additional energy over that necessary to provide final dimensional change. The energy consumed by friction is a minor part of the total energy required for deformation.

It will be appreciated that in the wiredrawing block of former times; where wire speeds seldom exceeded 400 ft. per minute and where the material was allowed to cool to a considerable degree before being placed on a reel and fed into a second or further drawing operation, the temperature of the wire (expressed as a difference between the temperature of the wire entering the die and leaving it); was not subject to great change. Cooling devices were unnecessary, except that it had been found that if dies were water-cooled, particularly in the drawing of high carbon wire, there was less risk of their overheating during the drawing operation. We know that die cooling cannot be expected to remove more than 5% of the heat generated in the wire. Nevertheless, this amount of heat concentrated in the die would cause excessive temperatures to develop which would interfere with proper lubrication, and for this reason, cooling of the die case was important.

With the advent of multiple die machinery however, an entirely new set of conditions was created. In machines which had low build-up capacity between passes, it was possible to have a cumulative effect on wire temperature because the wire entered the successive dies at ever-increasing speeds as it progressed along the machine, with disastrous effects, evidenced by overheating of the lubricant, and from increasing surface friction with loss of wire properties, such as torsion, as side effects of the rising temperature. A very careful study of this particular point was carried out by Norman A. Wilson in his paper, "Cooling of steel wire during continuous drawing". Wilson (1954).In it he pointed out that in continuous drafting, particularly with finishing speeds exceeding 300 fpm, the heating of the wire would be cumulative, "frequently resulting in a temperature rise which is detrimental to the quality of the wire." These remarks were particularly applicable to high carbon wire.

1.2 Temperature increases in practical drawing

Heat is generated primarily by work of deformation and friction at the die surface. Adiabatic heating is proportional to the amount of deformation; therefore, heating and temperature are higher at the wire surface than at the centerline. Although an exact calculation would require complex mathematics, a reasonable estimate of the temperature rise ($\Delta T$) in degrees Fahrenheit in the wire can be obtained by using an empirical equation proposed by Wilson,

$$\Delta T = \frac{1.069\times10^{4} \times F}{C\times A_f \times\rho} \quad (4)$$

Where:

F is the die pull (lbs, -force)

C is the specific heat capacity of steel (cal per gm per C = 0.1153 at 100 C)

$A_f$ is final wire cross-sectional area (in.$^2$)

$\rho$ is density of steel (lbs./in.$^3$)

Eichinger and Lueg (1941) investigated the problem of the work of deformation and heat development at low drawing speeds of only 25 fpm and the effect of speed was later investigated by Wilson. Theoretically the die pull required for a given reduction, die shape and wire composition is independent of speed, and this naturally leads to the assumption that the temperature rise of wire during drawing should remain almost constant, regardless of speed, for any given set of drawing conditions, always assuming that the coefficient of friction is constant over the range of drawing speeds involved.

The theoretical temperature rise which might be expected can be calculated from the equation:

$$T = P/A_2\, hd \times1.069\times10^{-4} \quad (5)$$

Where:

T is the theoretical temperature rise in degrees Fahrenheit

$A_2$ is the area leaving the die in square inches

P is the die pull in pounds

h is the specific heat of steel 0.115 and

d is the density of steel in pound per cubic inch

This equation provides values which are stated to be with in 12% of the actual temperature rise and agree with the results reported by the German investigators. The means used to lower wire temperatures during continuous drawing resolve themselves into internal and external cooling of the wire and the drawing block. As the speed increases, more feet of wire surface pass through the die, causing frictional heat, part of which is transmitted to the die.

1.3 Drawing force calculation

The mechanics of wiredrawing deal with the stresses and strains within the confines of the die and with associated external forces. The work of drawing is consumed in effecting the deformation of the wire and in overcoming the friction between the wire and the die. The deformation process is in itself complicated, being split into two parts; namely, the work in changing the dimensions of the wire and that of redundant deformation by which is meant the internal distortion of the metal not contributing to the dimensional change of the wire. The main forces operating in a drawing die can easily be derived from the drawing force neglecting redundant deformation. For practical purposes, Wistreich (1958), has suggested the use the following empirical formula for calculating the drawing force:

$$P = A_2.U. \frac{(1+\mu\cot\alpha)\, 2r}{2-r} \qquad (6)$$

Where:

| | | |
|---|---|---|
| $A_2$ | = | Cross-sectional area of wire |
| P | = | Drawing force |
| U | = | Average of ultimate tensile strength before and after drawing |
| r | = | fractional reduction of area |
| α | = | Semi-angle of die bore expressed in degree |
| μ | = | Mean coefficient of friction. |

In order to use these formulae to calculate the drawing force, the coefficient of friction μ must be known. It is suggested that for dry soap drawing a value of $\mu = 0.01$ and for wet drawing a value of $\mu=0.10$ should be used. It must be noted, however, that these equations should not be used to try to estimate the coefficient of friction or the average tensile strength of the wire.

**2. Pearlitic steel**

In 1854, James Horsfall received a patent for a heat-treating process that would produce wire with high tensile strength and good ductility from high-carbon eutectoid steel. This high-quality steel wire was called patented wire and the heat-teatment for making it was called patenting. The key to the patenting process was the eutectoid transformation of the high temperature, face-centered cubic phase of steel (Austenite) into a fine, lamellar structure of body-centered cubic iron (ferrite) and iron carbide (cementite) called pearlite**.** The equilibrium eutectoid structure contains 0.76 percent carbon; compositions less than 0.76 percent are called hypoeutectoid (ferrite-rich), and compositions greater than 0.76 percent are called hypereutectoid (carbide-rich). (Golis *et al*., 1999)

The difference in pearlite formation occurs during the cooling process. According to steel wire technology, in wire rod and drawn wire carbon is present as cementite. During heating of the wire in a furnace during patenting and hardening, the iron is transformed to austenite and the carbon from the $Fe_3C$ is dissolved into the steel base material. If the wire is cooled slowly after leaving the furnace, cementite lamellae are reformed. However, in patenting and hardening, the wire is not cooled slowly. When very fast cooling and quenching in oil is used, there is not enough time for cementite to be formed. Instead it remains dissolved in the iron although it cannot remain in solution at room temperature. This forced condition results in stresses and hardness, and gives a structure, with carbon in a supersaturated solid solution, that is known as martensite. This structure is hard and brittle.

When austenite is cooled slowly and the cooling curve passes through 1% pearlite and 99% pearlite at temperatures above 550C, a complete transformation to pearlite occurs resulting in coarse cementite lamellae and poor drawability. If the steel is cooled in molten lead at 550C, austenite cannot exist but stays super-cooled for a very short time. Therefore, when it starts its transformation into pearlite, at this low temperature, fine cementite lamellae are formed, which give the wire good drawability. (Enghag, 2002)

**3. Stress relieving treatments in the Wire Industry**

Stress relief is defined as heating to a suitable temperature that is held long enough to reduce residual stresses and then cooling slowly enough to minimize the development of new residual stresses. This definition requires some further explanation.

First, residual stresses arise in wire (or any other metallic component) that has been subjected to deformation beyond its elastic limit, i.e., when plastic deformation has occurred. Hence, stress relief heat treatment is relevant to as-drawn wire and to wire that has been formed into a product. Wire that has been annealed or hardened and tempered as its final process can be assumed to have, as near as is possible, zero residual stress.

Second, a suitable temperature needs definition. Stress relief heat treatment should not involve any major structural transformation, re-crystallization, or softening in the wire, but, as will be shown, minor structural changes will occur. Hence, there is a maximum temperature that applies to this type of heat treatment, which, if exceeded will lead to annealing.

Thirdly, holding long enough is rather a vague term and isn't really correct because even the shortest time at room temperature may cause some reduction in residual stresses, but their relief will increase with holding temperature and time. It is important to recognize that both time and temperature are important to this type of heat treatment, as is usually the case with most heat-treatment process, and these two parameters have to be considered together. It is also necessary to point out that stress relieving is an accurate name for this process. Residual stresses are relieved or reduced but not eliminated. To eliminate residual stresses it is necessary to heat to a temperature high enough, or for a time period long enough, to cause appreciable softening or annealing of the wire. Hence, stress relieving heat treatment processes relive 1-99% of the residual stress.

Stress reliving heat treatments are all designed to enhance ductility, or to modify physical properties for specific purposes. Heat treatment can begin at temperatures as low as 190C. In a process known as warm forming, low temperatures in this range are applied in heading operations to assist forming. (Robert, 2008)

The aging of high carbon wire after deformation has a pronounced effect on its strength. The yield strength is increased by a larger factor than the tensile strength and the limits of proportionality are influenced more than the yield point. At the same time the ductility is decreased. Heat treatment at temperatures from 200 C to 400 C after drawing improves the relaxation and creep of the wire. (William, 1990)

It is important to reiterate that in pre-stressed concrete composites, steel wires with a higher elastic limit and tensile strength are required. Concrete has a lower tensile strength compared to its higher compression strength. Steel tendons are used to improve the tensile strength of concrete. Higher strength steel wires naturally serve to increase the strength of whole concrete composites. In pre-stressed concrete composites, steel wires are embedded in concrete under tension and during its use there should not be a loss of tension. Therefore, steel wires should have a low relaxation property. In industrial applications, steel wires are cold drawn to achieve high strength. Interior stresses developed during the cold drawn process produce some important changes in tensile strength, Hook slope, elongation, etc. of the material. In order to minimize the effects of residual stresses, Stress relieving treatments should be induced.

**4. Design of experiments:**

The first statistician to consider a methodology for the design of experiments was Sir Ronald A. Fisher. He described how to test the hypothesis that a certain lady could distinguish by flavor alone whether the milk or the tea was first placed in the cup. While this sounds like a frivolous application, it allowed him to illustrate the most important ideas of the experimental design. The design of experiments was built on the foundation of the analysis of variance, a collection of models in which the observed variance is partitioned in to components due to different factors which are estimated and/or tested. The developments of the theory of linear models have encompassed and surpassed the cases that concerned early writers. Today, the theory rests on advanced topics in abstract algebra and combinatorics. (Ronald, 1991)

Michael (1992) mentioned that there is not a tool more powerful for the improvement process than the design of experiments, (DOE). DOE is a series of statistically based techniques to organize experimentation in order to obtain the maximum amount of information with the minimum time expenditure. This enables the experimenter to select variables thought to affect the process output, to methodically change those variables, and then to observe if the changes actually did affect the process output. The theories were advanced in the United States and the United Kingdom in the 1940's and 1950's; then the Japanese applied them to other industries in the 1960's. They are part of the "off-line" quality techniques touted by the Japanese. (They are "off-line" because the process is not making production parts as it is shut down for experimentation). The success of the DOE technique not only contributed to improvement in agricultural yields but has also contributed greatly to the rise to manufacturing excellence that the world has seen from the Japanese in the last 30 years.

Montgomery (2005) stated that experiment design is a critically important tool in the engineering world for improving the performance of the manufacturing process. In particular, the formal introduction of "Experiment Design" methodology at the earliest stage of the development cycle, where new products are designed, existing product designs improved, and manufacturing process optimized, is often the key to overall product success.

4.1 Factorial design of experiments:

Montgomery (1997) mentioned that Factorial designs are the most efficient for the study of the effects of two or more factors. By this approach, in each complete trial or replication of the experiment, all possible combinations of the levels of the factors are investigated. Factorial design is necessary when interactions may be present to avoid misleading conclusions. It also allows the effects of a particular factor to be estimated at several levels, yielding conclusions that are valid over a range of experimental conditions. The effect of factor is defined to be the change in response produced by a change in level of the factor, frequently called a "main effect". An interaction between the factors is the difference in response between the levels of one factor and another. It is not the same at all levels of the other factors. Thus, interaction is a form of curvature in the underlying response surface model for the experiment.

4.2 The design of experiments has three widely accepted approaches.

- Classical method
- Taguchi method
- Shainin method

4.3 Classical method

This approach is based on the pioneering work of Sir Ronald Fisher, who applied design of experiments (DOE) to the field of agriculture as early as the 1920’s. It is difficult to conceive of an application that has as many variables as agriculture: soil, rain, water, sun, climate, seed, fertilizer, terrain, etc. Yet Fisher, using only the full factorial method improved the productivity of the British farm and was knighted for his great contribution. In fact, Fisher, used DOE to reduce variation. The classical approach is the oldest of the three. This approach uses full Factorial. Classical DOE methods have been used successfully for several decades. The DOE term covers the system of methods that are used to build a relationship between several input design parameters and one or several responses. The DOE is most commonly used to analyze the data obtained through experiments which enables independent error estimate by randomly repeating one or several runs. This design is called replicated design. Some types of experiments however, do not enable repeatability, for example, too costly experiments or deterministic computer simulations. The design is then called unreplicated design.

4.4 The Taguchi method

Taguchi methods are statistical methods developed to improve the quality of manufactured goods. Genichi Taguchi of Japan adapted the Classical approach, simplifying it with his orthogonal arrays**.** He proposed that engineering optimization of a process or product should be carried out in a three-step approach:

- system design,
- parameter design, and
- tolerance design.

In system design, the engineer applies scientific and engineering knowledge to produce a basic, functional, prototype design. This design, includes the product design stage and the process design stage. In the product design stage, the selection of materials, components, tentative product parameter values, etc., are involved. At the process design stage, the analysis of processing sequences, the selections of production equipment, tentative process parameter values, etc., are involved. Since system design is an initial functional design, it may be far from optimum in terms of quality and cost.

Following on from system design is parameter design. The objective of parameter design is to optimize the settings of the process parameter values for improving quality characteristics and to identify the product parameter values under the optimal process parameter values. In addition, it is expected that the optimal process parameter values obtained from parameter design are insensitive to variations in the environmental conditions and other noise factors.

Finally, tolerance design is used to determine and analyze tolerances around the optimal settings recommend by the parameter design. Tolerance design is required if the reduced variation obtained by the parameter design does not meet the required performance, and involves tightening tolerances on the product parameters or process parameters in which variations result in large negative influences on the required product’s performance. Typically, tightening tolerances means purchasing better-grade materials, components, or machinery, which increase costs.

However, based on the above discussion, parameter design is the key step in the Taguchi method to achieving higher quality without increasing cost. Basically, experimental design methods were developed originally by Fisher. However, Classical experimental design methods are too complex and not easy to use. Furthermore, a large number of experiments have to be carried out when the number of the process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. The experimental results are then transformed into a signal-to-noise (S/N) ratio. Taguchi methods of experimental design provide a simple, efficient and systematic approach for the optimization of experimental designs for performance quality and cost. It has been proved successful in many manufacturing situations.

4.5 Shainin method

The third approach is a collection of simple but powerful techniques invented or perfected by Dorian Shainin of the United States. This method is often called Shainin. In the 1950s Shainin recognized that the Pareto principle could be applied effectively to the solving of variation problems. Shainin concluded that, amongst the thousands of variables that could cause a change in the value of an output, one cause-effect relationship had to be stronger than the others. Shainin called this primary cause the “Big Red X” and demonstrated that the cause can exist as an interaction among independent variables. The effect of the Red X is then magnified by the square-root-of-the-sum-of-the-squares law, thereby isolating the root cause. Shainin asserted that his application of statistical methods was more cost-effective and simpler than Taguchi methods. In order to determine the "Red X," Shainin would swap pairs of parts between functional and faulty equipment until the one part responsible for the failure is discovered. Shainin would claim that he could often find the primary defective part within a dozen paired swaps. Shainin's policy of "talking to the parts" was the primary distinguishing factor that set his methods apart from Taguchi's. In Classical or Taguchi DOE (Design of Experiments),engineers would brainstorm to form hypotheses regarding possible causes of a problem. Shainin's methods circumvent this theoretical step, requiring first the diagnosis of causes via one or more of four clue generation techniques designed to determine, through the empirical testing of the actual parts in question, the root cause, or "Red X". In the 1940s Leonard Seder, an MIT classmate and friend, developed the Multi-vari chart, a graphical method for analysis of variance. Shainin was an early adopter of this method, discovering that with Multi-vari charts, he could quickly converge on the root cause of a problem. Multi-vari charts also played an influential role in Shainin's development of the Red X concept.

4.6 The difference between Taguchi and Classical DOE

Taguchi experimental designs are based on orthogonal arrays. They are usually identified with a name such as $L_8$, to indicate an array with 8 runs. Classical experimental designs are also based on orthogonal arrays, but are identified with a superscript to indicate the number of variables thus, a $2^3$ classical experimental design also has 8 runs. Thus, designs generated by the two methods appear to be similar - and they often are Some industries and organizations swear by Taguchi methods, while others prefer Classical methods.

Taguchi methodology emphasizes:

- Robust design-searching for the set of conditions to achieve optimum behavior

- Minimization of the Loss function - minimizing economic loss due to running at non-optimum conditions

- Maximization of signal-to-noise ratio - achieving best process targets under all uncontrolled conditions (noise)

- Selection of experimental design from examination of Linear Graphs, which allows investigation of desired interaction effects, based on process knowledge.

4.7 Classical methodology emphasizes:

- Sequential experimentation to model process behavior (i.e. develop empirical process models, including modeling the effect of "noise" factors)

- Prediction of future process behavior, including optimal settings from empirical models

- Investigation and isolation of factors affecting mean and variation independently

- Selection of experimental design from consideration of the trade-offs in running a fraction of a full factorial design-e.g. a $2^{8-4}$ design investigates the effects of 8 factors in 16 runs, and the tradeoffs are known before running the experiment. Additional experimentation may be required to clearly identify the effects of interactions.

4.8 The difference between Taguchi and Shainin method

The Taguchi method has more to do with robust design and early product development then does Shainin, although the Taguchi method can be used for product improvement as well. It is significant to note that the Shainin method concerns variation reduction. You must have a good part and a bad part to use the Shainin method. If all the parts being considered are bad, “Red X” is probably not the tool that you would want to use. The Taguchi method is a design of experiment whereby all parameters are varied simultaneously. The Taguchi method can be used to fix or design products. Several prominent problem-solving models along with a collection of supporting strategies have been introduced during the past century. Although many of these models and supporting strategies have been widely accepted as breakthrough developments, they have yet to realize their full potential for problem solving.

In the table below, a summary is provided in which the three processes, or methods, are compared with regard to philosophy, sources of variation optimization, control and tolerance

**Table 1** Summary comparison

| TOPICS | SHAININ | TAGUCHI | CLASSICAL |
|---|---|---|---|
| 1. Philosopy | - Focus on sources of Variation<br>- Appropriate tolerances<br>- Search methods<br>- Rely on engineering knowledge | - Process/product robustness(noise)<br>- Reduction of variation<br>- around target<br>- Efficient response Variable (loss function, S/N)<br>- Saturated designs | - Randomization<br>- Sequential testing<br>- Best models<br>- Data transformation, interactions, response surface |
| 2. Sources of variation | - Multi-vari<br>- Comp./variable search | - N/A (done in conjunction with optimization) | - Fractional factorials<br>- Steepest ascent<br>- Nested designs |
| 3. Optimization | - Full factorial | - Saturated factorial designs<br>- Inner/outer arrays<br>- Robust response variables | - Full factorial.<br>- Response surface<br>- Multi-level<br>- Central composite |
| 4. Control | - Pre-control | - On-line techniques | - Control chart |
| 5.Tolerancing | - Tolerance parallelograms<br>- ISO plots | - Tolerance designs (factorial) | - Stack-up<br>- RMS analysis |

**5. Articles relating to aspects of the study:**

In this section, eight articles are referred to. The first three deal with the procedural effects due to, respectively: high-speed drawing, cold drawing, and progressively drawn wire. While the fourth deals with angular distortions and the fifth article focuses on improving billet surface quality. I will examine each in turn.

Firstly in this work, the effect of high speed drawing (about 20m/s) on the mechanical and technological properties of high-carbon steel wires has been investigated. Wire rod (5.5 mm) from steel grades C52D2(0.52%c) and C72DP (0.72%C) were drawn down to 1.35mm in 13 draws and two drawing speeds (0.5m/s and 20 m/s). After each draw, the following properties were determined: tensile strength, yield strength, contraction, elongation, number of twists and number of bends.

Additionally a draw force has been estimated after each draw. The wire's sure temperature and an average temperature have been calculated by several equations. Also the thickness of a heated layer has been determined. It has been found that an increased drawing speed has a significant effect on the mechanical properties of drawn wire, especially on the number of twists. A large drop in the number of twists has been observed for final wires because of the increased draw speed. However, there is also an advantage as the wire surface is much smoother after drawing at high speed than at low speed. Research results were statistically estimated with reference to the research of Ivo Nemec, Bogdan Golis, Jan W. Pilarczyk, Ryszard Budzik and Wieslaw Waszkielewicz, 2007.

Secondly, the mechanical properties of cold-drawn pearlitic wires are controlled largely by the microstructure developed during processing and, to some extent, by the residual stresses during drawing. The advent of powerful computers and the availability of equipment to perform diffraction experiments have made possible numerical predictions and accurate measurements of residual stresses. This paper, a review of work done by the author and collaborators, shows how stress-relaxation losses, and how environmentally assisted cracking and the fatigue-life of cold-drawn pearlitic wire are influenced by residual stresses. The role of pre-stretching loads, or stress relieving treatments, on stress- relaxation can be understood when the profile of residual stresses is known. Nevertheless, some awkward results occur during hydrogen embrittllement. Tests can be explained if accurate values of residual stresses near the surface are known, and the same is true of fatigue life. In this context, numerical simulations and measurements performed on cold-drawn pearitic wires, with different profiles of residual stresses, have shown a very good quantitative agreement with reference of the research of M. Elices, 2004

Thirdly let us examine the fracture behavior of progressively drawn pearlitic steels. To this end, samples from different stages of an industrial manufacturing process were analyzed to elucidate the consequences of steelmaking by cold drawing on the fracture toughness and the microscopic fracture modes. The real manufacturing chain was stopped in the course of the process, and samples of five intermediate stages were extracted, together with the original material or base product which was a hot rolled bar; not cold drawn at all. The final commercial product was a pre-stressed steel wire; heavily cold drawn. The results demonstrated that progressive cold drawing clearly affects the fracture performance of the materials, so that the most heavily drawn steels exhibit anisotropic fracture behavior with crack deflection, i.e., a change in crack propagation direction which deviates from the original model I propagation and approaches the wire axis or cold drawing direction, thereby producing a mixed mode stress state. At the microscopical level, clear changes are observed in the micrographs with appearances from cleavage-like in the slightly drawn steels, to predominant micro-void coalescence in the heavily drawn steels. From the macroscopic fracture mechanics viewpoint, the manufacturing process by cold drawing is beneficial, since the fracture toughness is progressively increased by steel making. These important results demonstrate that both the traditional mechanical properties, (e.g. the yield strength) and the fracture mechanics properties (e.g. the fracture toughness) are improved by cold drawing. (Toribio, 2002)

Fourthly the research of Murugan and Gunaraj (2000), inform us of the effects of process variables on the angular distortion of multipass GMA welded structural steel plates. Angular distortion is a major problem and the most pronounced among different types of distortion in the but welded plates. This angular distortion is mainly due to non-uniform transverse shrinkage along the depth of the plates welded. Restriction of this distortion by restraint may lead to higher residual stresses. These can be reduced by providing initial angular distortion in the negative direction if the magnitude of angular distortion is predictable. However it is difficult to obtain a complete analytical solution to predict angular distortion that may be reliable over a wide range of processes, materials, and process control parameters. In this study, the statistical method of three-factor, five-level factorial central composite rotatable design has been used to develop mathematical models to correlate angular distortion with multipass GMAW process parameters. Furthermore these mathematical models help to optimize the GMAW process and to make it a cost-effective one by eliminating the weld defects due to angular distortion with reference to the research. of Murugan and Gunaraj (2000)

The factorial designed matrix experiment the Taguchi method was set up to study conditions affecting the formation of pinholes. This experiment succeeded in identifying important factors needed to decrease billet surface pinholes on silicon killed at high carbon heat, ($C \geq 0.46$ percent). An interaction between mold oil flow rate and bellows shroud nitrogen line pressure was determined to be critical in producing zero pinhole billet etch tests. Currently, over 90 percent of all high carbon billet etch tests show zero pinholes. Just prior to the experiment, the number was 72 percent. A surprising subsequent decrease in billet surface bleeds was also realized. Greatly improved billet surface quality has been produced by implementing the new practices on a full-time basis. Experimental design defines and studies operating practices necessary to ensure consistent production of high quality products. Suspected factors at various levels can be simultaneously examined with regard towards their individual and combined effects on quality. This experimental design is not passive, it actively pursues, defines and finds solutions to quality problems in an efficient manner. By using this method, one finds out what factors and settings are needed to eliminate a problem. The Taguchi experimental design method provides an economical method of studying the parameters associated with billet surface pinholes. A normal full factorial experiment involving seven factors at two levels would require 128 trials to cover all possible combinations. The Taguchi method reduces the number of required trials to 8. In general, a matrix experiment consists of a set of experiments where the settings of various products or process parameters are changed in an organized fashion from one trial to the next. Conducting matrix experiments using special matrices called orthogonal arrays allows the effects of several parameters to be determined efficiently. With reference to the research of Gregory of Georgetown Steel who used experimental design to solve a billet surface pinhole problem. Billet surface quality has shown a consistent improvement since implementing the practices defined by the designed experiment. The improvement was accomplished by optimizing operational settings on existing equipment. (Gregory, 1992)

The research of Panteghini *et al*. (2006) used a finite element model (FEM) to study the multi-pass drawing of a wire of high strength steel and the effect of thermo-mechanical treatments on the residual stresses in the wire. They were able to demonstrate that the post-drawing treatment is very successful in reducing the residual stresses produced by the drawing.

The research of Atienza *et al*. (2004), used 3D finite element mode to understand the effects of the cold-drawing process. This showed that the drawing process generates a residual stress state with significant tensile stresses at the surface of the rods.

The research of Stone (1991), showed that residual stresses are created and minimized through a variety of processes in spring manufacture. He demonstrated that benefits of residual stress type depend on the product type and it’s application.

# MATERIALS AND EQUIPMENT

## 1. Materials

Samples from an industrial manufacturing process were supplied by Thai Wire Products Public Company Limited. The chemical composition common to the steels is given in Table 2. The name of each steel indicates the number of cold drawing steps which each has undergone, as given in Table 3, together with the diameter of each wire and the mechanical properties of the different steels. The samples were prepared as follows.

### 1.1 Sample Preparation:

A typical chemistry for pre-stressed concrete wires quality steel used today is:

- Carbon (0.79% to 0.84%)
- Manganese (0.75% to 0.85%)
- Silicon (0.15% to 0.32%)
- Sulfur (0.025% max)
- Copper (0.10% max)
- Aluminum (.015% to 0.045%)
- Chromium (0.15% to 0.25%)

After draw size Diameter. 4 mm. RA 80% Length 1,600 mm/sample Charge No. 841227 Coil No.037

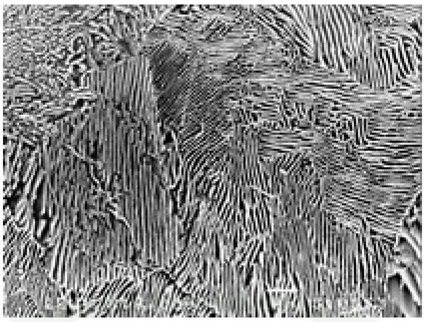


**Figure 2** SEM micrograph at × 10,000 magnification of wire rod 82 B diameter 9 mm showing pearlite structure

**Table 2** Chemical composition test of the steel wire compared for this investigation listed in weight percent

| C | Mn | Si | P | S | Cr | V | Al |
|---|---|---|---|---|---|---|---|
| 0.80 | 0.69 | 0.23 | 0.012 | 0.009 | 0.250 | 0.060 | 0.004 |

1.2 Wire drawing

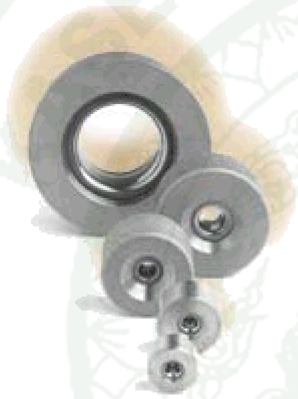
In drawing wire, the required deformation is accomplished by drawing the wire through the conical bore section of the die, thereby reducing the diameter through plastic deformation. During deformation, a thin film of lubricant between wire surface and die surface is essential to minimize friction, reduce die wear and to keep the die cool. For good wire deformation, it is necessary to select a drawing die tool with the appropriate profile, designed for either ferrous or non-ferrous materials.

- Entry Lubrication is introduced, and the material is guided to the deformation zone (reduction/bearing) of the die.

- Reduction Generally speaking harder, (ferrous) materials require smaller reduction angles; softer, (non-ferrous) materials require larger reduction angles. Included angles (2-alpha) may vary within the range 8°-30°, zone length (0.5...1) d.

- Bearing In this cylindrical part the deformed wire is calibrated to the desired size. The bearing length depends on the materials drawn and is specified as a percent of the bore hole diameter (0.3...0.6) d. As a general rule, harder materials demand longer bearings than softer ones. Wear on the bearing only occurs when heavy wear in the reduction zone is not remedied in a timely fashion.

- Exit This zone, from which the deformed wire leaves the die tool, must provide sufficient support for the axial mechanical wire drawing stress which occurs.



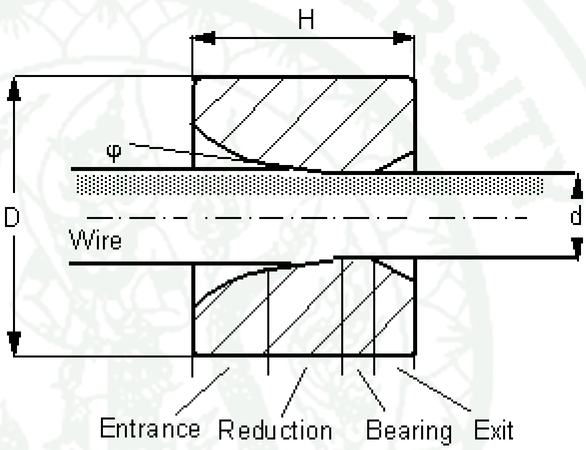



**Figure 3** Illustration wire drawing

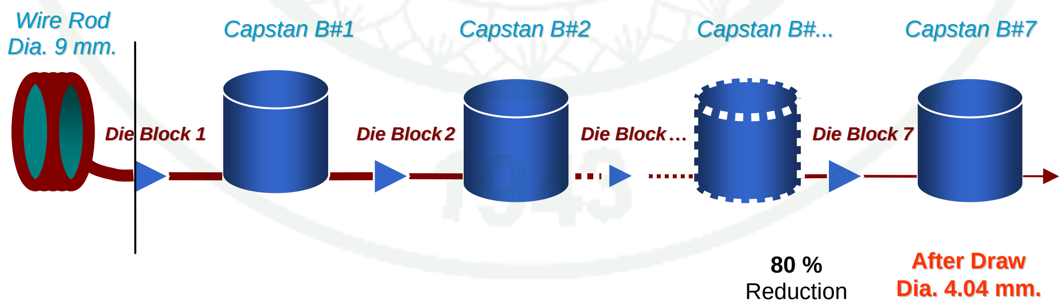



**Figure 4** Diagram to show a sample wire (diameter at inlet = 9 mm) to a diameter of 4 mm. 80% reduction by drawing machine

**Table 3** To show the % reduction of the drawing process

| Capstan Block | Block No.1 | Block No.2 | Block No.3 | Block No.4 | Block No.5 | Block No.6 | Block No.7 |
|---|---|---|---|---|---|---|---|
| % Reduction Area | 19 | 37 | 51 | 61 | 69 | 75 | 80 |

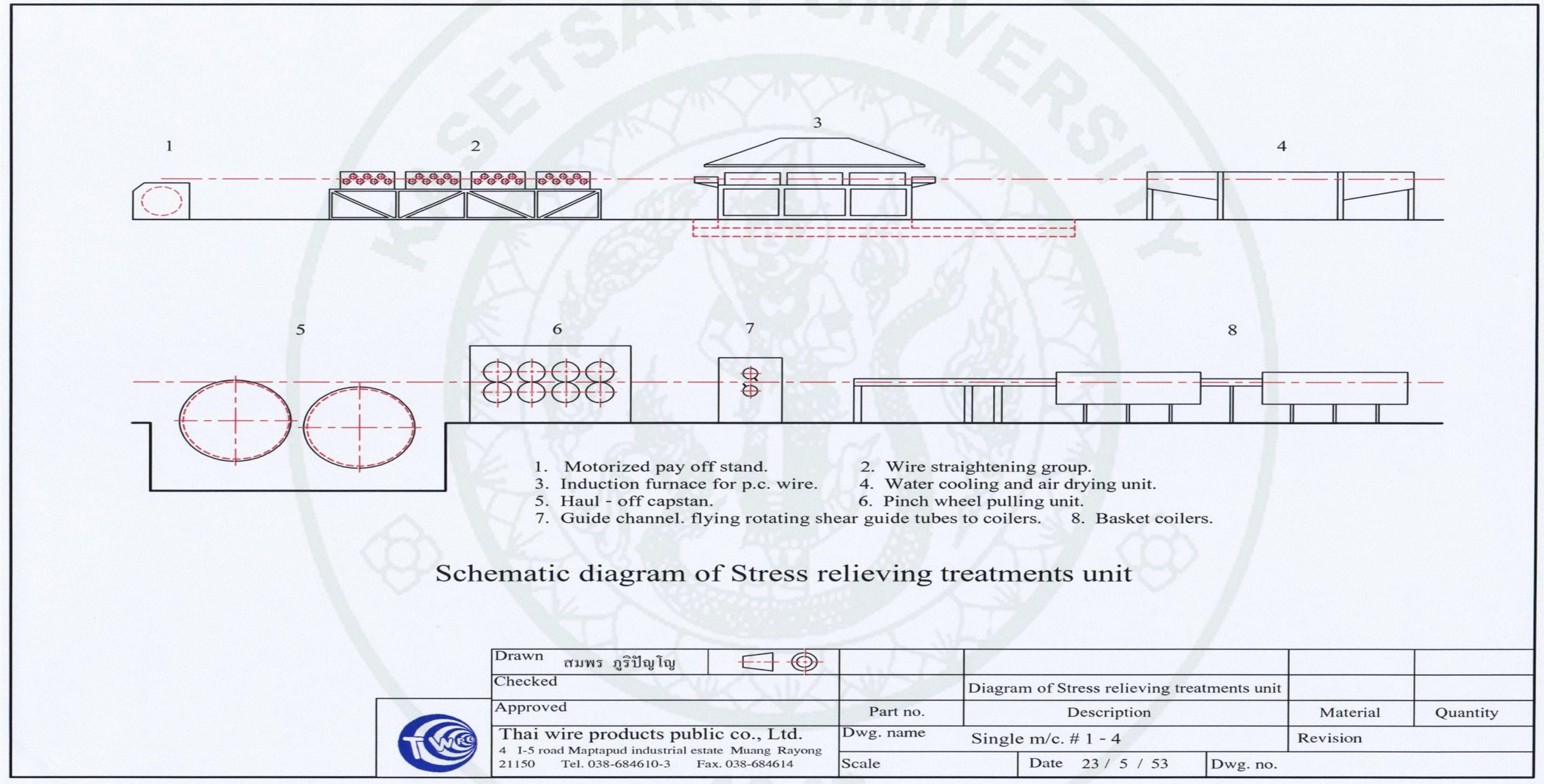



**Figure 5** Schematic diagram of stress relieving treatments unit

1. Motorized pay off stand.
2. Wire straightening group.
3. Induction Furnace for p.c. wire.
4. Water cooling and air drying unit.
5. Haul-off capstan.
6. Pinch wheel pulling unit.
7. Guide channel, flying rotating shear guide tubes to coilers.
8. Basket coiler

**Table 4** Nomenclature, diameter reduction and mechanical properties of the steels

| | A1 | A2 | A3 | A4 | A5 | A6 | A7 |
|---|---|---|---|---|---|---|---|
| Elongation % | 6.5 | 6 | 5.5 | 5 | 4.8 | 4.5 | 4 |
| Yield strength kg/mm$^2$ | 124 | 133 | 135 | 146 | 154 | 163 | 165 |
| Tensile strength kg/mm$^2$ | 143 | 149 | 153 | 164 | 173 | 184 | 186 |

**2. The Instruments and equipments used in this experiment are listed below:**

- Drawing Machine
- Stress-Relieved Simulation Machine
- Micrometer 0 ~ 25 mm. Acc. ± 0.002 mm.
- Tensile Test machine
- Extensometer
- Relaxation Test Machine

**3. Research Plan and Experimental Design.**

In the conduct of the study the methodology used in the research process can be outlined in the following four stages:

Firstly, the design and fabrication of the stress relieving process and calibration equipment were initiated. This was the first part of the trial.

The second part of the trial consisted of preliminary experiments on the stress-relieving process to study the effects of process parameters. This was conducted in both the Classical and Taguchi methods. Thereafter, the experiment was run and the results recorded. Data was analyzed to study the Main effects and interaction effect between the process parameters.

The third part of the study consisted of additional experiments for extending graphs and mathematical models.

Lastly, results from the experiments were analyzed and conclusions were drawn. Refer to the schematic diagram of research plan. (Figure 6)

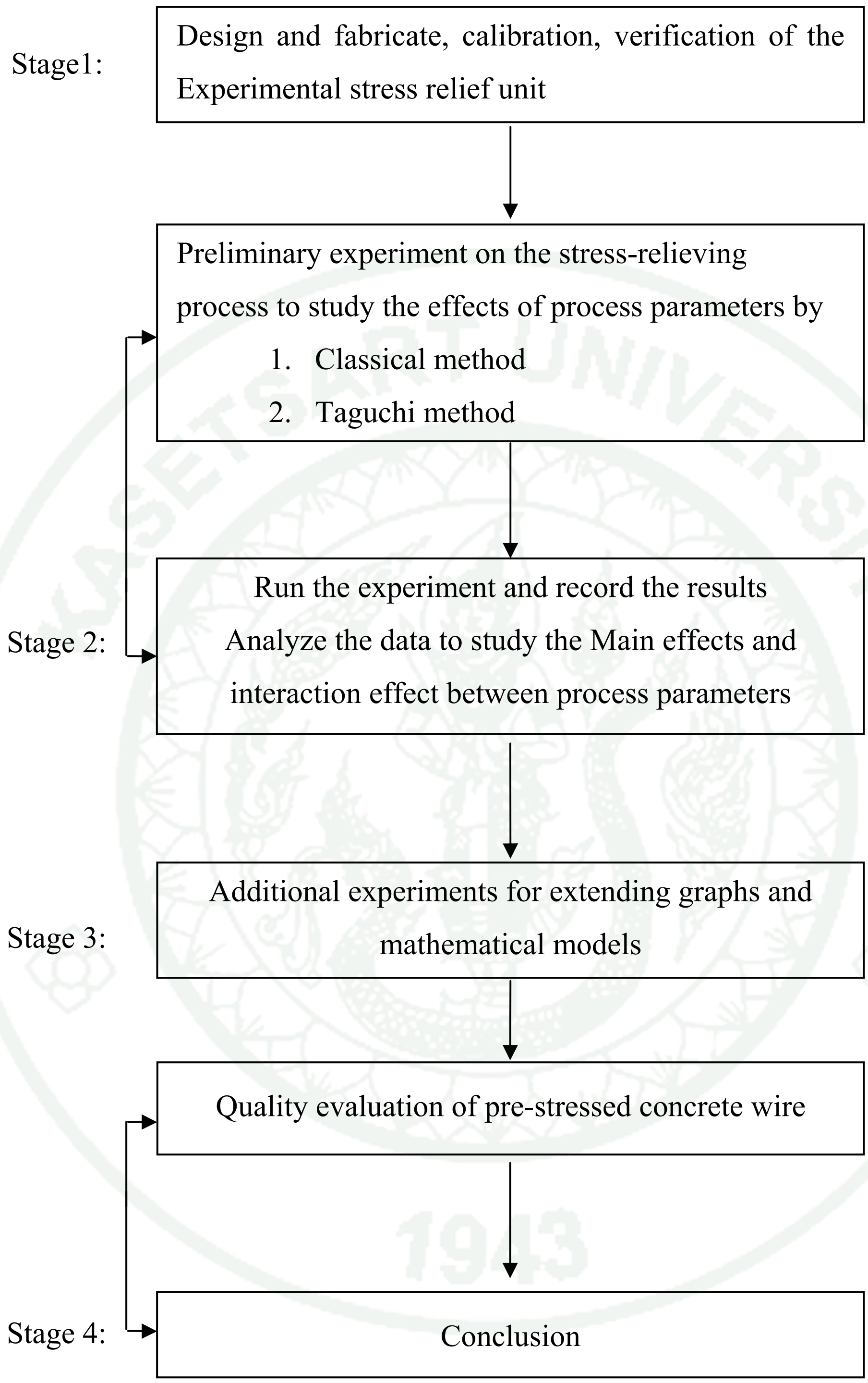



**Figure 6** Schematic diagram of research plan

**4. Investigate the problem with existing processes to find basic factors that affect the quality of steel wire:**

One way of investigating the problem with existing processes is to use the historical data of the quality record of steel wire from the production report. The important basic factors that affect the quality of steel wire are Tensile Strength, Yield Strength, Elongation and Relaxation. These properties are very important in order to achieve the final finished steel wire properties.

**5. Identify potential factors:**

The plan was to carry out the research in the following steps.

- Identify the important process parameters.
- Find the upper and lower limits of the process parameters.

Identification of the process parameters:

The following independently controllable process parameters were identified to carry out the experiments:

- Duration of exposure to heat.
- Temperature during process
- Tension on wire during process

Finding the limits of the process parameters:

The working range was decided upon by inspecting the process for smooth appearance and the absence of any visible defects. The selected process parameters with their limits, units, and notations are given in Table 5.

**Table 5** Process parameters, levels and their limits

| Factor | Units | Level Treatment | level 1 | level 2 | level 3 |
|---|---|---|---|---|---|
| Temperature | °C | Level Treatment = 3 | 350°C | 375°C | 400°C |
| Tension | kgf | Level Treatment = 3 | 30% UTS | 40% UTS | 50% UTS |
| Time exposure to heat | sec | Level Treatment = 2 | 15 sec | 25 sec | |

**6. Developing the design matrix:**

Employing the identified process parameters at 3 levels of the full factorial design produced 54 sets of code conditions (shown in table 5) of the response factors; yield strength, Elongation and Tensile Strength 36 sets of code conditions of the relaxation% were also identified.

Response (Dependent Variable) = 4 Factors

- Relaxation, Yield Strength, Elongation, Tensile strength,

Factor (Independent Variable) = 3 Factors

- Temperature, Tension, Time exposure to heat.

**Table 6** Sample code and condition testing

| % Tension | Time of heating 15 sec | | | Time of heating 25 sec | | | Response (Independent Variable) Factors |
|---|---|---|---|---|---|---|---|
| | Temperature °C | | | Temperature °C | | | |
| | 350 | 375 | 400 | 350 | 375 | 400 | |
| | 801533501 | 801533701 | 801534001 | 802533501 | 802533701 | 802534001 | Yield strength, Elongation |
| | 801533502 | 801533702 | 801534002 | 802533502 | 802533702 | 802534002 | Tensile strength |
| **30** | 801533503 | 801533703 | 801534003 | 802533503 | 802533703 | 802534003 | |
| | 801533504 | 801533704 | 801534004 | 802533504 | 802533704 | 802534004 | % Relaxation |
| | 801533505 | 801533705 | 801534005 | 802533505 | 802533705 | 802534005 | for Test (1000 hr/sample) |
| | 801543501 | 801543701 | 801544001 | 802543501 | 802543701 | 802544001 | Yield strength, Elongation |
| | 801543502 | 801543702 | 801544002 | 802543502 | 802543702 | 802544002 | Tensile strength |
| | 801543503 | 801543703 | 801544003 | 802543503 | 802543703 | 802544003 | |
| **40** | 801543504 | 801543704 | 801544004 | 802543504 | 802543704 | 802544004 | % Relaxation |
| | 801543505 | 801543705 | 801544005 | 802543505 | 802543705 | 802544005 | for Test(1000 hr/sample) |
| | 801553501 | 801553701 | 801554001 | 802553501 | 802553701 | 802554001 | Yield strength, Elongation |
| | 801553502 | 801553702 | 801554002 | 802553502 | 802553702 | 802554002 | Tensile strength |
| **50** | 801553503 | 801553703 | 801554003 | 802553503 | 802553703 | 802554003 | |
| | 801553504 | 801553704 | 801554004 | 802553504 | 802553704 | 802554004 | % Relaxation |
| | 801553505 | 801553705 | 801554005 | 802553505 | 802553705 | 802554005 | for Test(1000 hr/sample) |
| Total Sample | 15 | 15 | 15 | 15 | 15 | 15 | |

**7. Quality Evaluation Tests.**

7.1 Tensile strength:

The test involves straining a test piece by tensile force generally to fracture, for the purpose of determining one or more of mechanical properties. The test is carried out at ambient temperature between 10°C and 35°C, unless otherwise specified.

7.2 Yield strength:

Yield strength is measured at 1% extension under load. The minimum yield strength shall be 90% of tensile strength for low-relaxation pre-stressed concrete wire and 85% of tensile strength for normal-relaxation

The extension under load shall be measured by an extensometer calibrated with the smallest division not larger than 0.001 mm of gauge length.

7.3 Elongation:

The total elongation under load shall not be less than 3.5% using a gauge length of not less than 600 mm. In practice the total elongation value may be determined by adding to the 1.0% yield extension the percentage of extension or movement between the jaws gripping the strand after yield determination. The percentage is calculated on the new base length of jaw-to-jaw distance.

7.4 Relaxation:

The relaxation test is one such special requirement although evidence is usually acceptable from records of tests made in past production. A common test temperature of 20 c, initial stress 70% or 80%of specified strength and test duration of 1000 hours, are normally used.

**8. Perform the experiments**

The experiments are classified by two different methods.

- Classical method
- Taguchi method

8.1 Classical experimental design:

In Classical experimental design the effect of each factor is tested, independently. In order to investigate the full interaction between 3 different factors, each of which is set at 3 and 2 predetermined levels, requires 54 experimental combinations to be performed. The structure of the 54 experiments is shown in Table 8 and is designed to include all the different possible combinations of all 3 experimental factors.

**Table 7** Design matrix for classical method

| Control Factor | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Time (sec) | 15 | 25 | |
| Temperature ($^{o}$C) | 350 | 375 | 400 |
| Tension (kgf) | 30 | 40 | 50 |

The whole set of the 54 experiments carried out. All experimental runs were repeated three times.

**Table 8** The orthogonal array for 3 factors Level 2, 3, 3

| Run | Time | Tension | Temp | Results |
|---|---|---|---|---|
| 1 | 1 | 1 | 2 | Y1 |
| 2 | 2 | 1 | 3 | Y2 |
| 3 | 2 | 2 | 3 | Y3 |
| 4 | 2 | 2 | 2 | Y4 |
| 5 | 1 | 1 | 3 | Y5 |
| 6 | 2 | 2 | 1 | Y6 |
| 7 | 2 | 3 | 1 | Y7 |
| 8 | 1 | 3 | 2 | Y8 |
| 9 | 2 | 2 | 2 | Y9 |
| 10 | 2 | 3 | 2 | Y10 |
| 11 | 2 | 2 | 3 | Y11 |
| 12 | 2 | 1 | 1 | Y12 |
| 13 | 2 | 3 | 2 | Y13 |
| 14 | 2 | 1 | 3 | Y14 |
| 15 | 1 | 2 | 1 | Y15 |
| 16 | 1 | 3 | 1 | Y16 |
| 17 | 2 | 1 | 1 | Y17 |
| 18 | 2 | 2 | 1 | Y18 |
| 19 | 2 | 3 | 3 | Y19 |
| 20 | 2 | 1 | 2 | Y20 |
| 21 | 1 | 3 | 1 | Y21 |
| 22 | 2 | 3 | 1 | Y22 |
| 23 | 1 | 2 | 2 | Y23 |
| 24 | 1 | 3 | 3 | Y24 |
| 25 | 1 | 2 | 3 | Y25 |
| 26 | 1 | 3 | 2 | Y26 |
| 27 | 2 | 2 | 1 | Y27 |
| 28 | 1 | 3 | 3 | Y28 |

**Table 8** (Continued)

| Run | Time | Tension | Temp | Results |
|---|---|---|---|---|
| 29 | 1 | 2 | 3 | Y29 |
| 30 | 2 | 1 | 2 | Y30 |
| 31 | 1 | 1 | 2 | Y31 |
| 32 | 2 | 1 | 2 | Y32 |
| 33 | 1 | 1 | 1 | Y33 |
| 34 | 1 | 2 | 3 | Y34 |
| 35 | 2 | 3 | 3 | Y35 |
| 36 | 2 | 3 | 2 | Y36 |
| 37 | 2 | 3 | 3 | Y37 |
| 38 | 2 | 1 | 1 | Y38 |
| 39 | 2 | 3 | 1 | Y39 |
| 40 | 1 | 3 | 2 | Y40 |
| 41 | 2 | 2 | 3 | Y41 |
| 42 | 1 | 2 | 1 | Y42 |
| 43 | 1 | 3 | 1 | Y43 |
| 44 | 1 | 1 | 3 | Y44 |
| 45 | 1 | 3 | 3 | Y45 |
| 46 | 1 | 2 | 1 | Y46 |
| 47 | 2 | 2 | 2 | Y47 |
| 48 | 2 | 1 | 3 | Y48 |
| 49 | 1 | 1 | 2 | Y49 |
| 50 | 1 | 2 | 2 | Y50 |
| 51 | 1 | 2 | 2 | Y51 |
| 52 | 1 | 1 | 3 | Y52 |
| 53 | 1 | 1 | 1 | Y53 |
| 54 | 1 | 1 | 1 | Y54 |

The order in which the all observations were taken was selected at random so that this design is a completely randomized design.

8.2 Taguchi experimental design:

In Taguchi designs, responses are measured at selected combinations of the control factor Levels. Each combination of control factor Levels is called a run and each measure an observation. The Taguchi design provides the specifications for each experimental test run.

A Taguchi design, also known as an orthogonal array, is a fractional factorial matrix that ensures a balanced comparison of levels of any factor. In a Taguchi design analysis, each factor can be evaluated independently of all other factors.

8.3 The steps of Taguchi method with noise factors can be summarized as the followings:

- Identify the design parameters and the noise factors,
- Construct the design matrix and noise matrix.
- Determine the signal-to noise ratio for each run.
- Compute the average signal-to noise ratio for each factor level and generate a response table.
- Construct the signal-to-noise ratio response graph base on the value from step 4.
- Analyze the signal-to-noise ratio response table and graph.
- Perform some basic mean of the data for each column of the signal factors and calculate the average response.
- Compute an estimate of the predicted signal-to-noise ratio based on the selected level of signal-to noise factors on the response mean.

8.4 Analysis techniques:

We can identify the strong effects and ascertain the best level or settings for each of control factors under consideration.

The smaller the better $$S/N_S = -10*\text{Log}\left(\sum_{i=1}^{n} y_i^2 / n\right) \tag{7}$$

The larger the better $$S/N_L = -10*\text{Log}\left(\sum_{i=1}^{n} 1/y_i^2\right)/n \tag{8}$$

Target value is the better $$S/N_t = 10*\text{Log}\left(\bar{y}^2 / s^2\right) \tag{9}$$

Taguchi design $L_{18}$ $(2^1\ 3^7)$

In order to evaluate the performance of the Taguchi methods, based on 11 degrees of freedom determined from the number of the control factor and their corresponding number of levels, a Taguchi design $L_{18}$ $(2^1\ 3^7)$ was selected for the inner array.18 experiments were carried out employing the orthogonal array $L_{18}$ $(2^1\ 3^7)$ to investigate the effect of 3 factors Time (sec)**,** Temperature (°C), Tension (%of ultimate tensile strength)**.** Interaction between Time (sec) and the other factors was inserted into the array and was used to examine the interaction between Time (sec) and Tension, Time and Temperature, Tension and Temperature which was set at Table 9.

**Table 9** Taguchi experimental design plan

| Control Factors | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Time (sec) | 15 | 25 | |
| Temperature ($^{o}$C) | 350 | 375 | 400 |
| Tension (kgf) | 30%UTS | 40%UTS | 50% UTS |

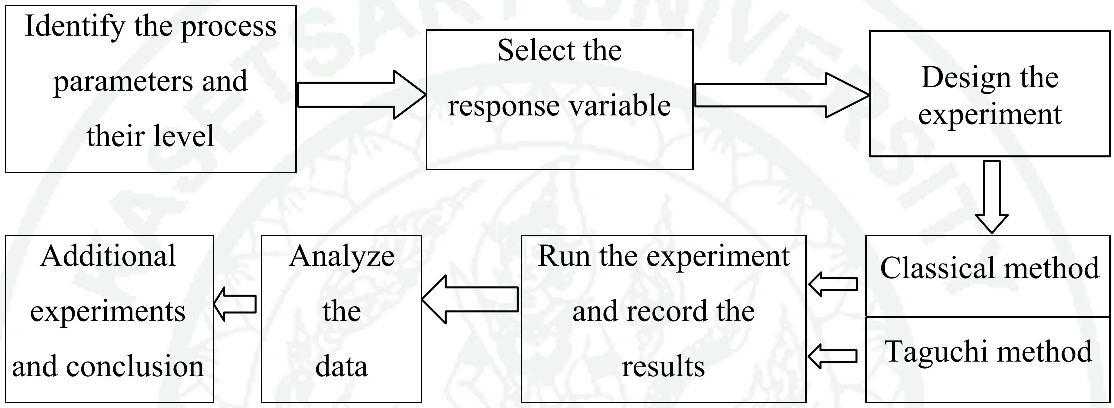



**Figure 7** Designed experiment sequence

**9. The Design of the Experimental Stress Relief Unit**

The process of designing the unit followed the standard design process steps:

- Requirement
- Preliminary design
- Review
- Detailed design
- Fabrication
- Verification
- Implementation

The requirement was for a machine that mimics the stress- relieving properties of the production line. These properties are as follows:

- Setting temperature at 300-400ºC

- Setting tension at 1-101970 kgf
- Line speed 80-420 m/min

The preliminary design necessitates independent units for setting temperature and tension and a control unit for both of them. Settings should be constant, irrespective of changes to the other.

The design of the tension unit is shown in figure 8 below.

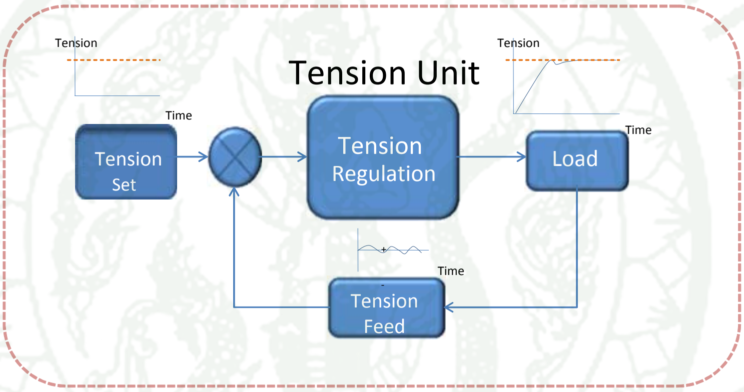



**Figure 8** Schematic design of the tension unit

The equipment required for the tension unit is as follows:

- Tension Regulation and Power
  - Motor
  - Gear
  - Drive AC Inverter
- Tension Feedback
  - Load cell
  - Load signal amplifier and indicator

Please note that the feedback equipment concerns measurement and the calibration has to be checked for accuracy by a recognized third party.

The design of the temperature unit is shown in figure 9 below.

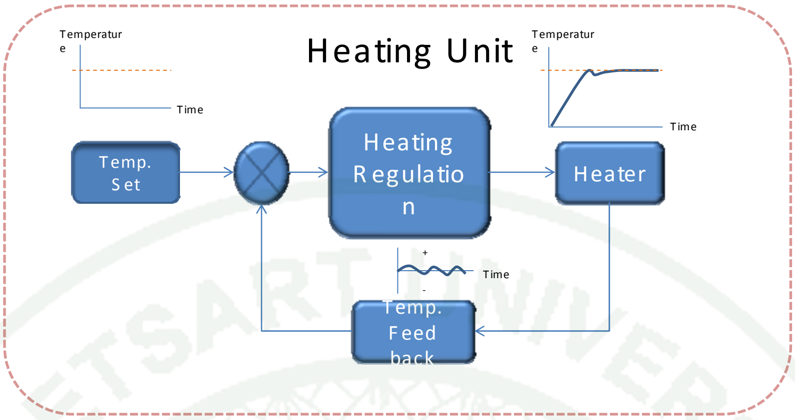



**Figure 9** Schematic design of the Temperature Unit

The equipment required for the temperature unit is as follows:

- Heating
  - Coil heater
  - Power regulator
- Heating signal feedback
  - Thermocouple
  - Temperature signal amplifier and indicator

Please note that the feedback equipment concerns measurement and the calibration has to be checked for accuracy by a recognized third party.

In addition, a timer is required that is automatically activated when both temperature and tension conditions have been reached. This equipment also has to be checked for accuracy by a third party.

The detailed flowchart of the experimental stress relief unit is shown in figure 10, and a schematic diagram of the process in figure 11.

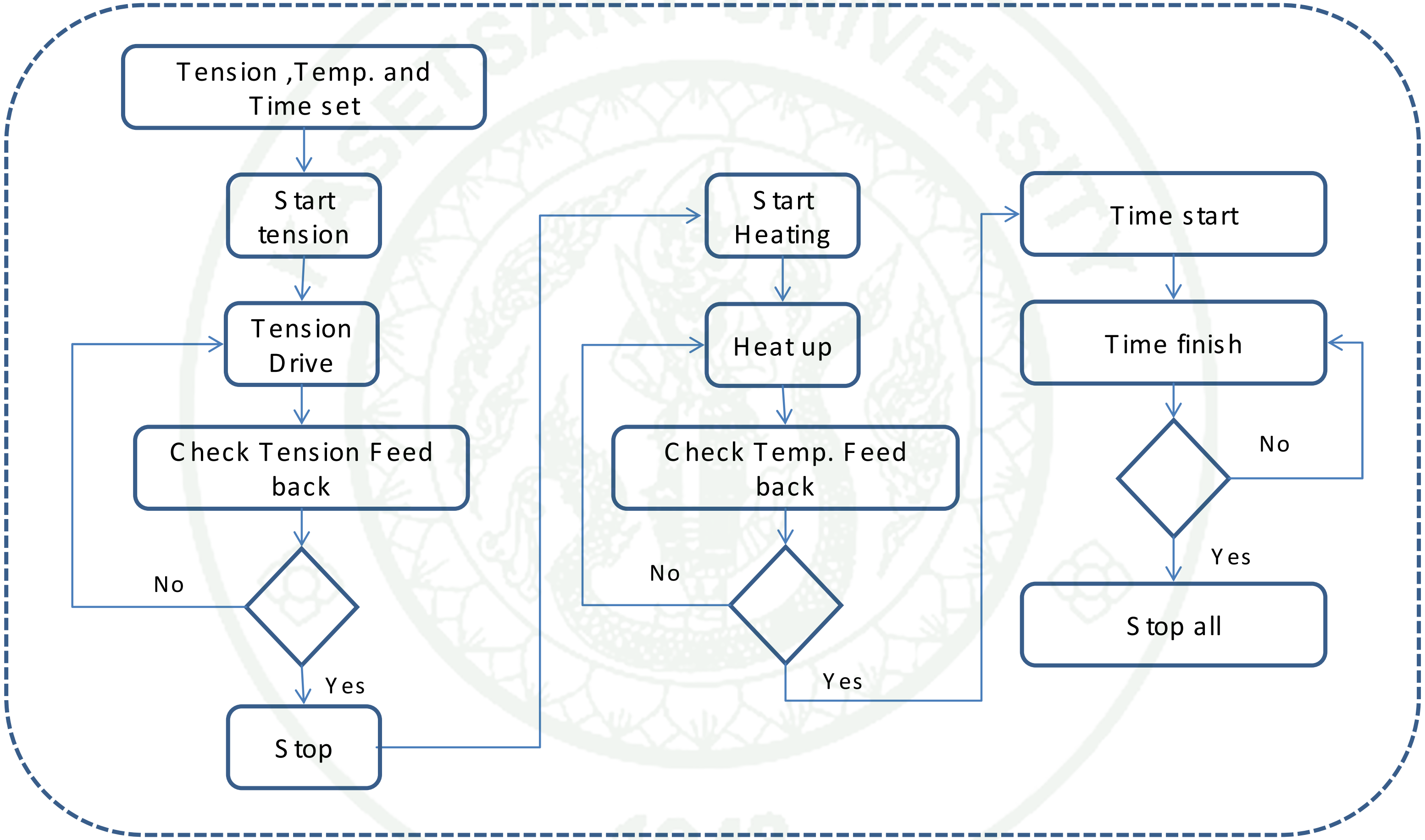



**Figure 10** Flow chart of the operation of the experimental stress relief unit

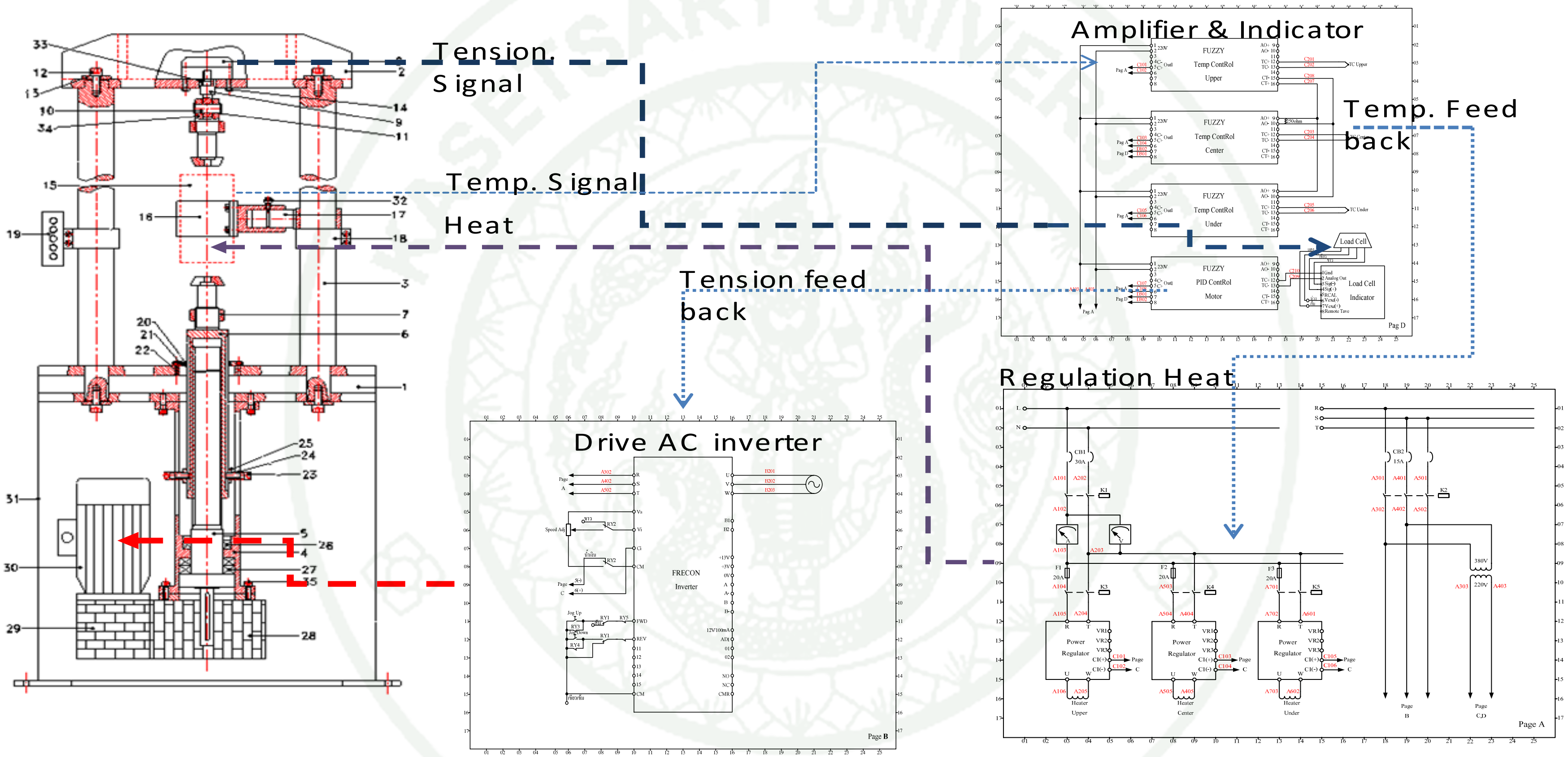



**Figure 11** Schematic diagram of the experimental stress relief unit

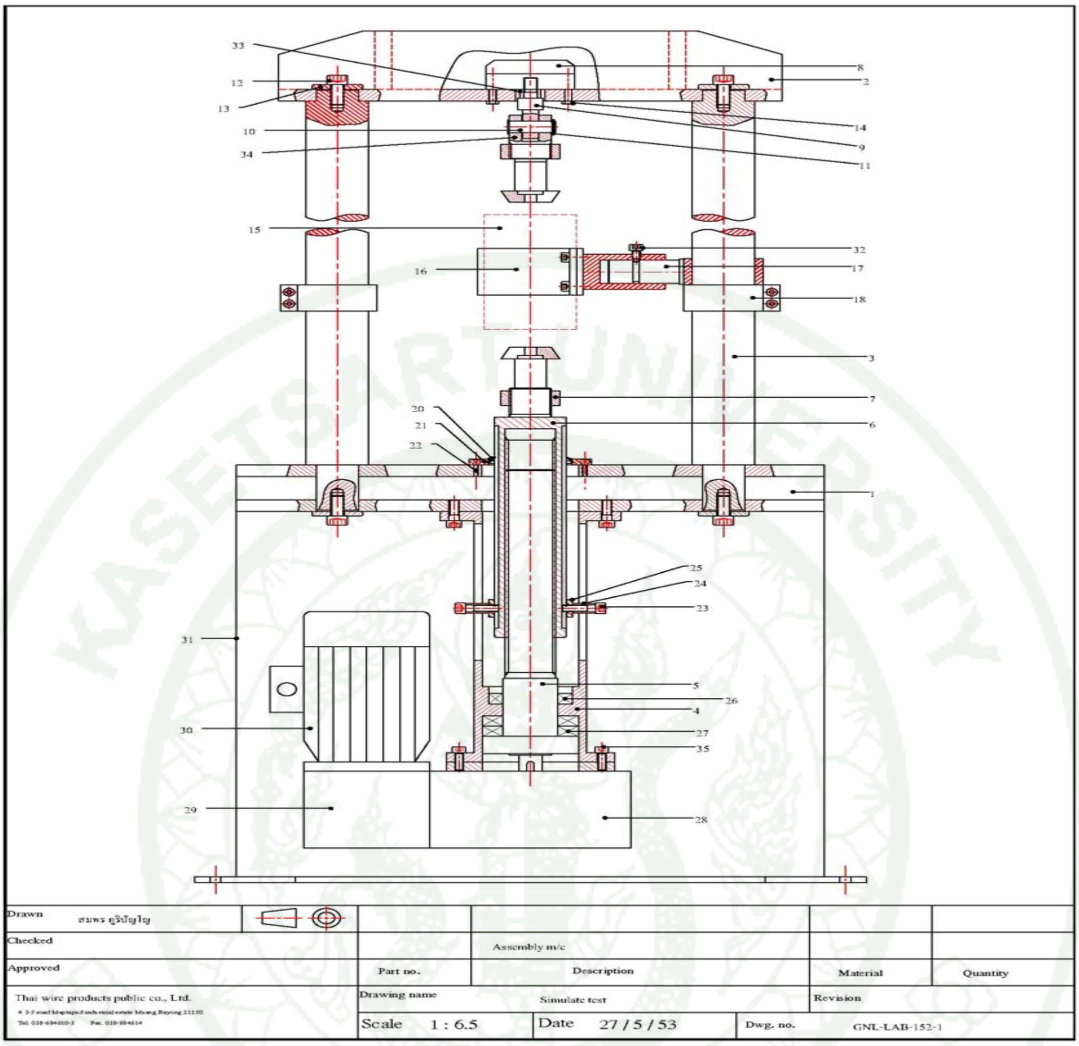



**Figure 12** Drawing of the machine designed specifically for this study

| Part no. | Description | Material | Quantity |
|---|---|---|---|
| 35 | Socket head cap screw M12*30 | Standard | 6 |
| 34 | Joint | 6582 | 1 |
| 33 | Bush load cell | Mild steel | 1 |
| 32 | Adjust screw M10*20 | Standard | 1 |
| 31 | Base | Mild steel | 1 |
| 30 | AC motor 3.7 Kw 380 V | Standard | 1 |
| 29 | Reduce gear 1:10 | Standard | 1 |
| 28 | Reduce gear 1:60 | Standard | 1 |
| 27 | Bearing 51313 | FAG | 2 |
| 26 | Bearing 6013 2RS | SKF | 1 |
| 25 | Screw lock | Mild steel | 1 |
| 24 | Bush pull nut | Brass | 4 |
| 23 | Socket head cap screw M12*40 | Standard | 4 |
| 22 | Socket head cap screw M6*20 | Standard | 4 |
| 21 | Seal cover | Mild steel | 1 |
| 20 | Seal 100*85*7 | - | 1 |
| 18 | Column clamp | Mild steel | 1 |
| 17 | Adjust pin | Mild steel | 1 |
| 16 | Heater clamp | Mild steel | 1 |
| 15 | Heater 4 Kw. 220 V. | - | 1 |
| 14 | Hexagon bolt BSW. 5/16"*2.5" | Standard | 8 |
| 13 | Spacer Ø60*8 | Mild steel | 4 |
| 12 | Socket head cap screw M16*35 | Standard | 4 |
| 11 | Snap ring Ø20 MM. | Standard | 1 |
| 10 | Pin | scm4 | 1 |
| 9 | Load cell connector | 6582 | 1 |
| 8 | Load cell Interface 50 Kn. | Standard | 1 |
| 7 | Grip hoder | 6582 | 2 |
| 6 | Pull nut S 60*4 | 6582 | 1 |
| 5 | Shaft screw S 60*4 | 6582 | 1 |
| 4 | Housing bearing | scm4 | 1 |
| 3 | Column | Mild steel | 2 |
| 2 | Upper plate | Mild steel | 1 |
| 1 | Lower plate | Mild steel | 1 |

| | | | |
|---|---|---|---|
| Drawn Somporn Phuripunyo | | | |
| Checked | | | |
| Approved | | | |
| Thai wire products public co., Ltd.<br>4 I-5 road Maptapud industrial estate Muang Rayong 21150<br>Tel. 038-684610-3 Fax. 038-684614 | Drawing name Simulate test | | Revision |
| | Scale | Date 27 / 5 / 53 | Dwg. no. GNL-LAB-152 |

**Figure 13** List of parts required for assembly of machine depicted in Figure 8

**Figure 14** Picture showing the machine designed and built especially for this study


**Figure 15** Machinery used in the procedure to test the relaxation of wire after the stress-relieving procedure


**Figure 16** Machinery used in the procedure to test the tensile strength and yield strength of wire after the stress-relieving procedure

**Locations and Time Duration**

The detailed locations and duration of conducting this research are as follows:

| | | |
|---|---|---|
| May 2004 – September 2004 | : | Literature survey at Kasetsart University, Bangkok , Thailand. |
| January 2005 – December 2006 | : | Literature survey, write and submit thesis proposal, at Kasetsart University, Bangkok, Thailand and Conduct research, at Thai Wire Products Public Company Limited, Bangkok, Thailand. |
| January 2007 – December 2009 | : | Conduct research, at Thai Wire Products Public Company Limited and write The Thesis, final defense at Kasetsart University, Bangkok, Thailand. |

# EXPERIMENTAL RESULTS AND MATHEMATICAL MODELLING

## Preliminary experiments

Two different analysis methods were used, namely the Classical and Taguchi methods, to ascertain the effects of process parameters on the stress-relieving process. First, the effect of stress relieving treatment conditions on the quality of high tensile steel wire is analyzed by using the Classical Method. The results of the 54 experimental conditions are shown in Table 12.

### 1. Using the classical method

**Table 11** Legend result of the experiment factors

| Runs: 54 | Replicates: 3 | | |
|---|---|---|---|
| Factor | Type | Levels | Values |
| Time | fixed | 2 | 15 25 sec |
| Tension | fixed | 3 | 30 40 50 % UTS |
| Temperature | fixed | 3 | 350 375 400$^{o}$C |

**Table 12** The properties of steel wire after stress relieving treatments

| Number of treatments | Factors control and level | | | Results | | |
|---|---|---|---|---|---|---|
| Run | Time | Tension | Temperature | Tensile strength | Yield strength | Elongation |
| 1 | 15 | 30 | 350 | 192.68 | 179.42 | 6.7 |
| 2 | 15 | 30 | 375 | 191.12 | 171.62 | 4.3 |
| 3 | 15 | 30 | 400 | 187.22 | 163.81 | 7.2 |
| 4 | 15 | 40 | 350 | 191.12 | 175.52 | 4.9 |
| 5 | 15 | 40 | 375 | 191.66 | 173.18 | 4.7 |

**Table 12** (Continued)

| Number of treatments | Factors control and level | | | Results | | |
|---|---|---|---|---|---|---|
| Run | Time | Tension | Temperature | Tensile strength | Yield strength | Elongation |
| 6 | 15 | 40 | 400 | 187.37 | 165.37 | 7.2 |
| 7 | 15 | 50 | 350 | 190.88 | 175.52 | 8.6 |
| 8 | 15 | 50 | 375 | 188.54 | 171.62 | 4.7 |
| 9 | 15 | 50 | 400 | 188.15 | 169.67 | 6.6 |
| 10 | 25 | 30 | 350 | 193.22 | 177.47 | 6.7 |
| 11 | 25 | 30 | 375 | 190.10 | 171.62 | 3.9 |
| 12 | 25 | 30 | 400 | 189.71 | 171.62 | 6.3 |
| 13 | 25 | 40 | 350 | 190.88 | 173.18 | 7.0 |
| 14 | 25 | 40 | 375 | 191.90 | 173.57 | 4.6 |
| 15 | 25 | 40 | 400 | 182.93 | 160.69 | 5.9 |
| 16 | 25 | 50 | 350 | 191.12 | 173.57 | 6.7 |
| 17 | 25 | 50 | 375 | 191.12 | 173.57 | 4.5 |
| 18 | 25 | 50 | 400 | 191.66 | 175.52 | 6.5 |
| 19 | 15 | 30 | 350 | 191.51 | 177.47 | 6.8 |
| 20 | 15 | 30 | 375 | 192.68 | 175.52 | 4.5 |
| 21 | 15 | 30 | 400 | 189.56 | 167.71 | 7.2 |
| 22 | 15 | 40 | 350 | 193.22 | 183.32 | 4.8 |
| 23 | 15 | 40 | 375 | 192.68 | 175.52 | 4.8 |
| 24 | 15 | 40 | 400 | 186.98 | 165.37 | 7.1 |
| 25 | 15 | 50 | 350 | 192.29 | 173.57 | 8.6 |
| 26 | 15 | 50 | 375 | 191.12 | 175.52 | 5.4 |
| 27 | 15 | 50 | 400 | 185.03 | 167.71 | 6.4 |
| 28 | 25 | 30 | 350 | 192.68 | 179.42 | 6.8 |
| 29 | 25 | 30 | 375 | 189.95 | 171.62 | 3.9 |
| 30 | 25 | 30 | 400 | 191.90 | 175.52 | 7.0 |
| 31 | 25 | 40 | 350 | 191.66 | 177.86 | 6.9 |
| 32 | 25 | 40 | 375 | 190.73 | 171.62 | 5.1 |

**Table 12** (Continued)

| Number of treatments | Factors control and level | | | Results | | |
|---|---|---|---|---|---|---|
| Run | Time | Tension | Temperature | Tensile strength | Yield strength | Elongation |
| 33 | 25 | 40 | 400 | 184.88 | 163.81 | 7.0 |
| 34 | 25 | 50 | 350 | 192.68 | 179.42 | 6.8 |
| 35 | 25 | 50 | 375 | 188.78 | 171.62 | 4.5 |
| 36 | 25 | 50 | 400 | 181.91 | 165.76 | 6.1 |
| 37 | 15 | 30 | 350 | 192.29 | 175.52 | 7.1 |
| 38 | 15 | 30 | 375 | 193.07 | 175.52 | 4.5 |
| 39 | 15 | 30 | 400 | 188.15 | 167.71 | 7.2 |
| 40 | 15 | 40 | 350 | 192.68 | 175.52 | 4.9 |
| 41 | 15 | 40 | 375 | 191.51 | 175.52 | 4.8 |
| 42 | 15 | 40 | 400 | 186.98 | 162.25 | 7.1 |
| 43 | 15 | 50 | 350 | 187.61 | 171.62 | 8.2 |
| 44 | 15 | 50 | 375 | 192.44 | 177.47 | 4.7 |
| 45 | 15 | 50 | 400 | 182.15 | 165.76 | 5.5 |
| 46 | 25 | 30 | 350 | 191.51 | 177.47 | 6.7 |
| 47 | 25 | 30 | 375 | 191.90 | 173.57 | 4.2 |
| 48 | 25 | 30 | 400 | 188.54 | 165.76 | 7.7 |
| 49 | 25 | 40 | 350 | 193.07 | 179.42 | 6.7 |
| 50 | 25 | 40 | 375 | 189.71 | 171.62 | 5.0 |
| 51 | 25 | 40 | 400 | 185.66 | 163.81 | 7.2 |
| 52 | 25 | 50 | 350 | 192.05 | 173.57 | 7.2 |
| 53 | 25 | 50 | 375 | 188.54 | 171.62 | 4 |
| 54 | 25 | 50 | 400 | 189.95 | 173.57 | 6.7 |

1.1 Effect of stress relieving treatments on tensile strength

The Tensile strength is the maximum load under which the test piece can withstand the tension test. Tensile strength is important because it can be used to estimate the incremental tensile strength of a wire resulting from heat treatment, deformation and strain hardening during drawing.

**Table 13** Analysis of Variance for Tensile strength

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Time | 1 | 0.070 | 0.070 | 0.070 | 0.02 | 0.887 |
| Tension | 2 | 29.462 | 29.462 | 14.731 | 4.27 | 0.022 |
| Temperature | 2 | 224.107 | 224.107 | 112.054 | 32.45 | 0.000 |
| Time*Tension | 2 | 14.224 | 14.224 | 7.112 | 2.06 | 0.142 |
| Time*Temperature | 2 | 10.933 | 10.933 | 5.467 | 1.58 | 0.219 |
| Tension*Temperature | 4 | 21.015 | 21.015 | 5.254 | 1.52 | 0.217 |
| Time*Tension*Temperature | 4 | 13.933 | 13.933 | 3.483 | 1.01 | 0.416 |
| Error | 36 | 124.330 | 124.330 | 3.454 | | |
| Total | 53 | 438.075 | | | | |

Table 13 shows that in the experiments for tensile strength the influential factors are tension and temperature which have p-values equal to 0.022 and 0.000. Tension was influential with 95% confidence and temperature was influential with 99% confidence.

The main effects plot (Figure 17) shows that tensile strength decreased when both temperature and tension are increased. It also shows that the maximum increase in strength occurs with temperature at 350$^{o}$C and tension at 30%. Tensile strength begins to fall with temperatures over 350$^{o}$C and tensions over 30%.

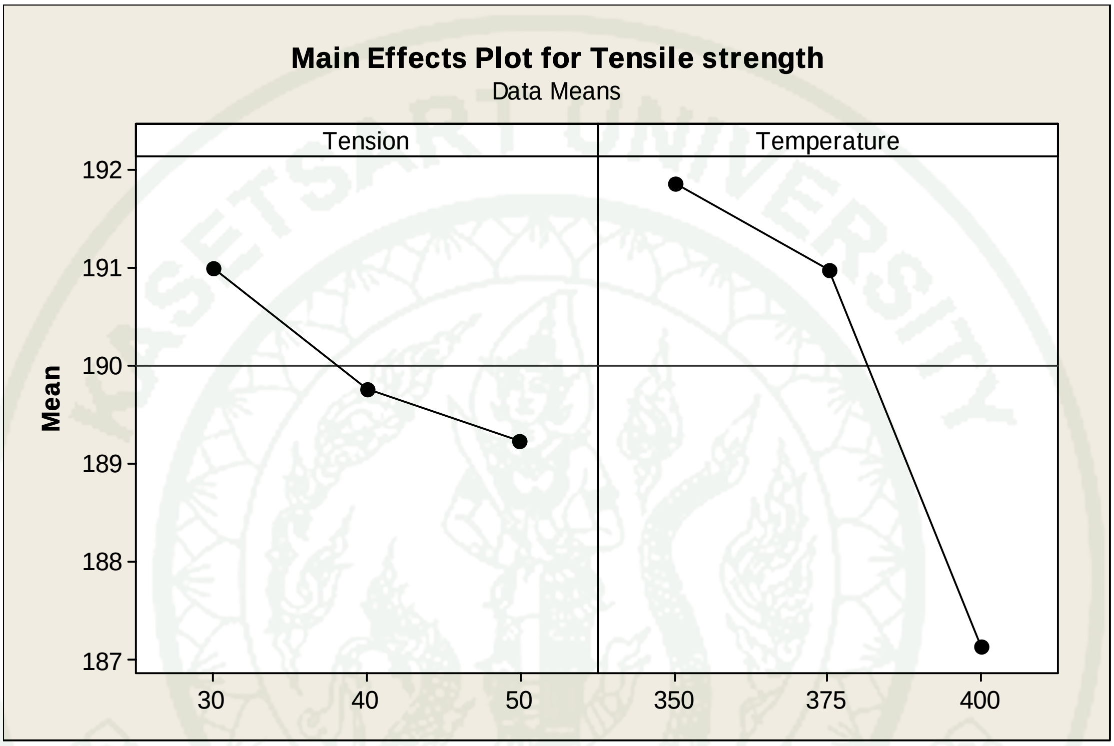



**Figure 17** Main Effects of tension and temperature on tensile strength

The pronounced effect of temperature is clearly shown by the contour surface in figure 18. The effect of tension is shown to be much less pronounced.

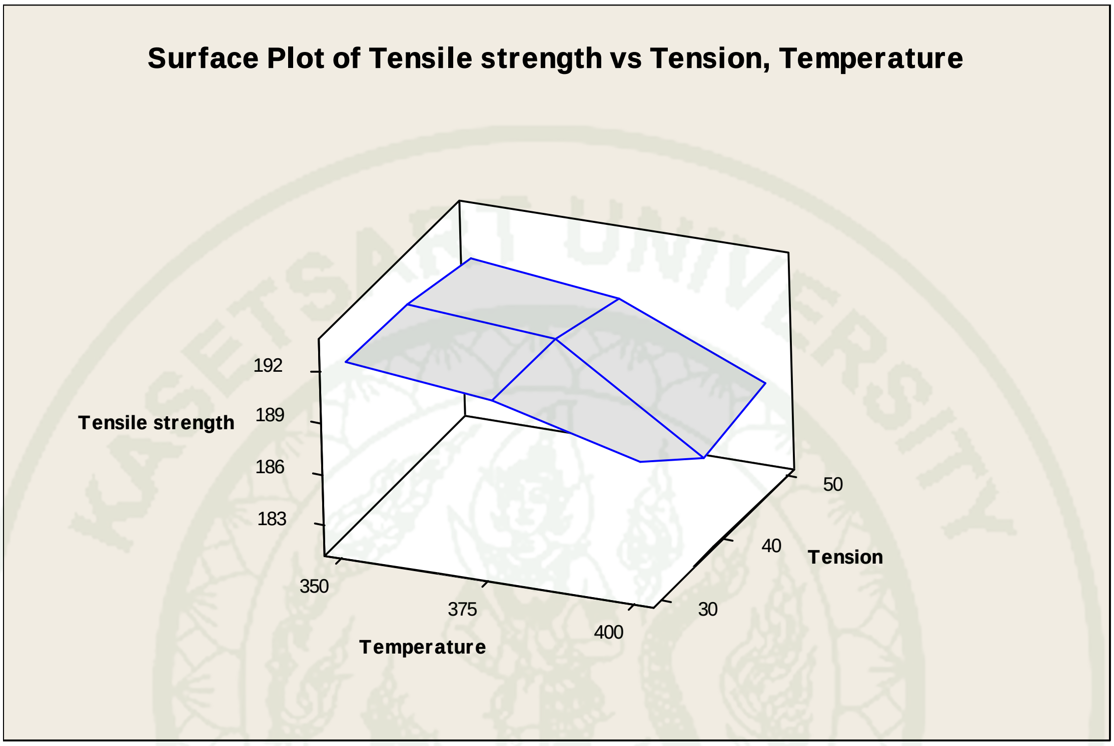



**Figure 18** Response surface for interaction effect of tension and temperature on tensile strength

Overall, we can conclude that with temperature at 350°C, the most beneficial results for tensile strength can be observed.

1.2 Effect of Stress Relieving Treatment on Yield strength

Yield strength testing involves taking a sample with a fixed cross sectional area, and then pulling it with a controlled, gradually increasing force until the sample changes shape. Longitudinal and/or transverse strain is recorded using mechanical or optical extensometers.

**Table 14** Analysis of Variance for Yield strength

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Time | 1 | 0.228 | 0.228 | 0.228 | 0.03 | 0.863 |
| Tension | 2 | 27.610 | 27.610 | 13.805 | 1.82 | 0.177 |
| Temperature | 2 | 804.196 | 804.196 | 402.098 | 52.92 | 0.000 |
| Time*Tension | 2 | 24.545 | 24.545 | 12.272 | 1.62 | 0.213 |
| Time*Temperature | 2 | 49.005 | 49.005 | 24.502 | 3.22 | 0.051 |
| Tension*Temperature | 4 | 140.534 | 140.534 | 35.134 | 4.62 | 0.004 |
| Time*Tension*Temperature | 4 | 17.631 | 17.631 | 4.408 | 0.58 | 0.679 |
| Error | 36 | 273.540 | 273.540 | 7.598 | | |
| Total | 53 | 1337.289 | | | | |

Table 14 shows that in the experiments for yield strength the influential factors are temperature and the interaction between tension and temperature which have p-values equal to 0.000 and 0.004 and confidence levels of 99% and 95% respectively

The Main effects plot for temperature (figure 19) clearly shows that yield strength decreases as temperature is increases.

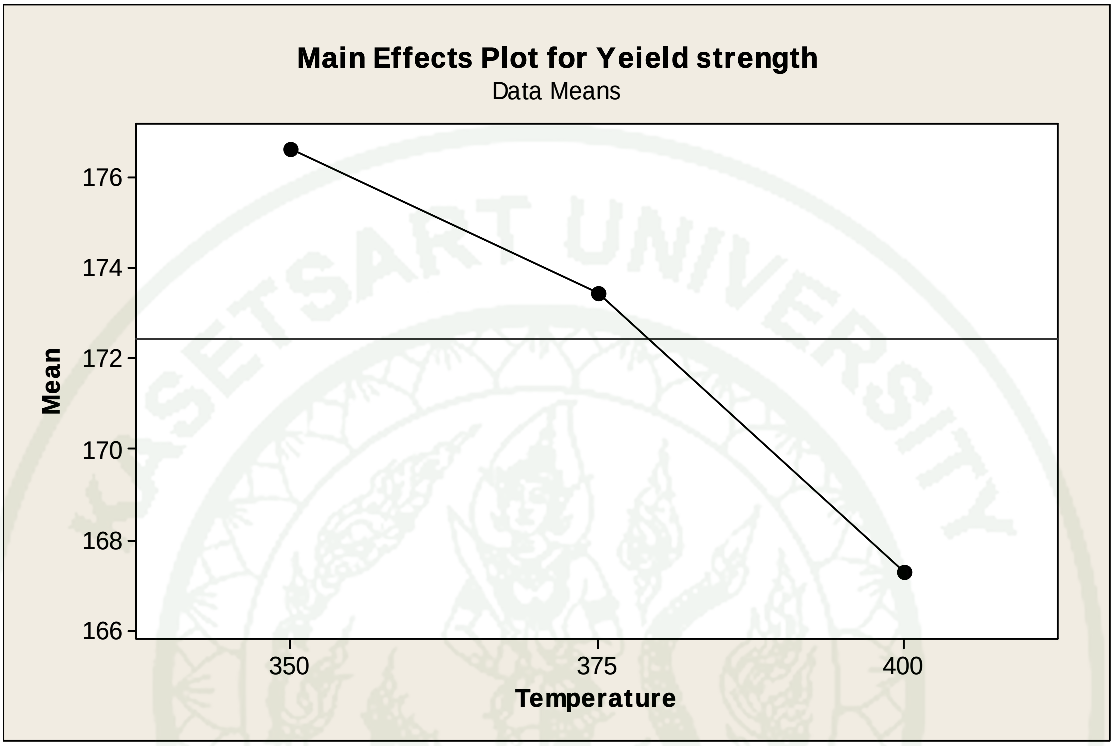



**Figure 19** Main effects of temperature on yield strength

The interaction effects plot (figure 20) confirms that yield strength decreases when the temperature is increased. Yield stresses tend to be effected positively by stress relieving and will increase by 3 to 5% at a temperature of 350°C and tension set at 40%. When temperature is over 350°C, the yield stresses drop gradually until 375°C and then drop sharply thereafter. With tension set between 30% and 40% and temperature at 350°C, the yield stresses increased 5%.

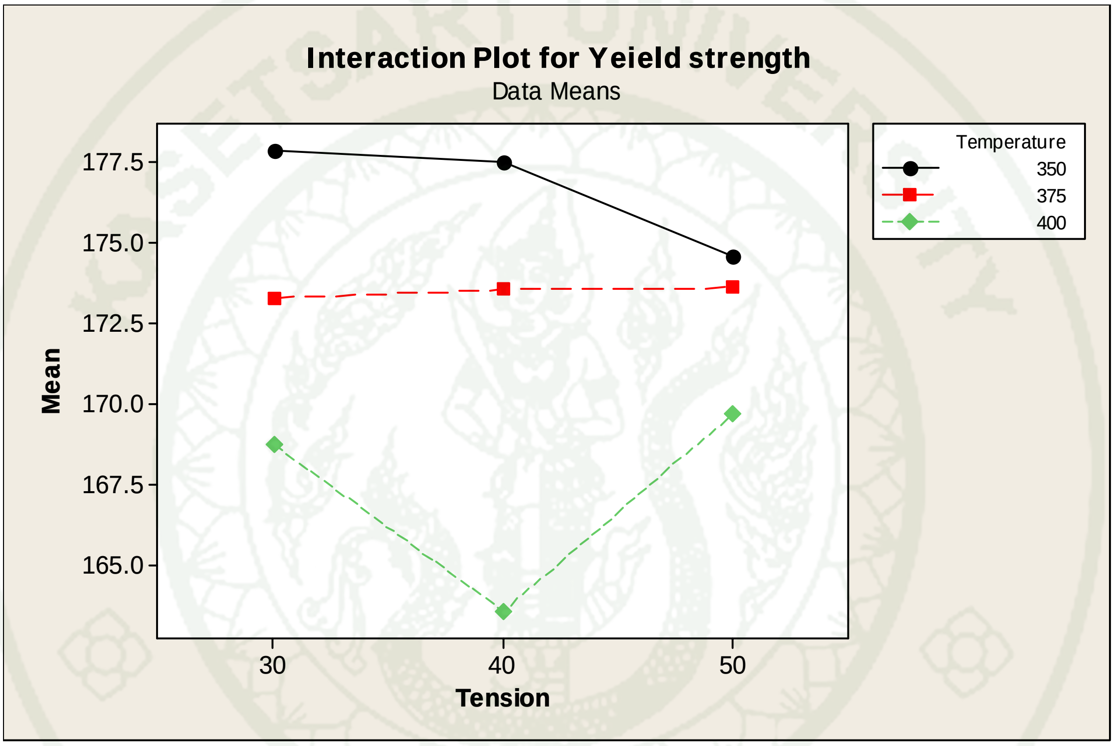



**Figure 20** Interaction effects of tension and temperature on yield strength

The contour surface shown in figure 21 confirms that yield strength is maximized with tension and temperature set at the lower limits of 30% and 350°C respectively. At higher temperatures, yield strength decreases irrespective of the effect of tension.

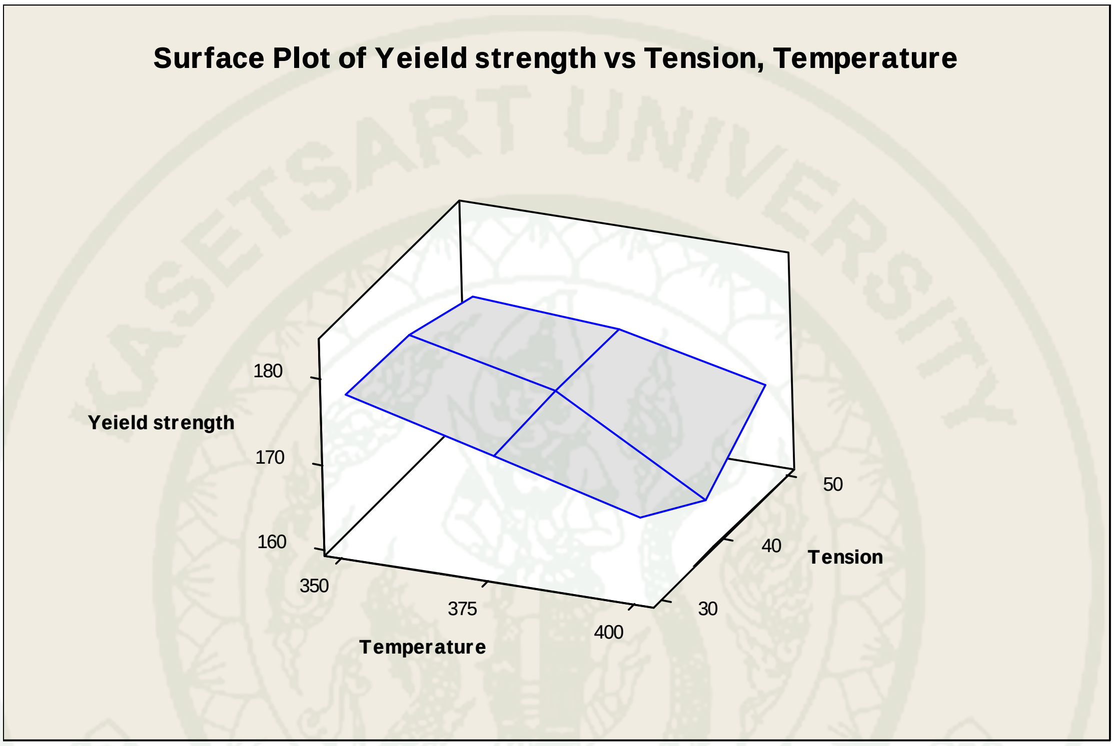



**Figure 21** Response surface for interaction effect of tension and temperature on yield strength

Overall, we can conclude that temperature is the most significant factor effecting yield strength. Yield strength is maximized with set at 350°C. Tension should be held at 30% or 40%.

1.3 Effect of Stress Relieving Treatments on Elongation

Elongation is the difference between the gauge length and the gauge length with load applied, expressed as a percentage of the original gauge length.

**Table 15** Analysis of Variance for Elongation

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Time | 1 | 0.5807 | 0.5807 | 0.5807 | 3.23 | 0.081 |
| Tension | 2 | 0.3700 | 0.3700 | 0.1850 | 1.03 | 0.368 |
| Temperature | 2 | 63.2544 | 63.2544 | 31.6272 | 175.71 | 0.000 |
| Time*Tension | 2 | 1.8381 | 1.8381 | 0.9191 | 5.11 | 0.011 |
| Time*Temperature | 2 | 0.0715 | 0.0715 | 0.0357 | 0.20 | 0.821 |
| Tension*Temperature | 4 | 8.6889 | 8.6889 | 2.1722 | 12.07 | 0.000 |
| Time*Tension*Temperature | 4 | 4.3296 | 4.3296 | 1.0824 | 6.01 | 0.001 |
| Error | 36 | 6.4800 | 6.4800 | 0.1800 | | |
| Total | 53 | 85.6133 | | | | |

Table 15 shows that in the experiments for elongation the influential factors are temperature, the interaction effect of tension and temperature, and interaction effect of time and tension which have p-values equal to 0.000, 0.000, and 0.011 and confidence levels of 99%, 99%, and 95% respectively.

It is accepted widely that three factor interaction effects may be ignored (Montgomery, 2001).

Figure 22 depicts the main effects of temperature on elongation. It can be seen that the amount of elongation is at its highest point at a temperature of 350°C. When the temperature is increased to 375°C, elongation falls sharply and then increases sharply when the temperature is 400°C. However, this latter increase still results in a lower figure for elongation than that at 350°C.

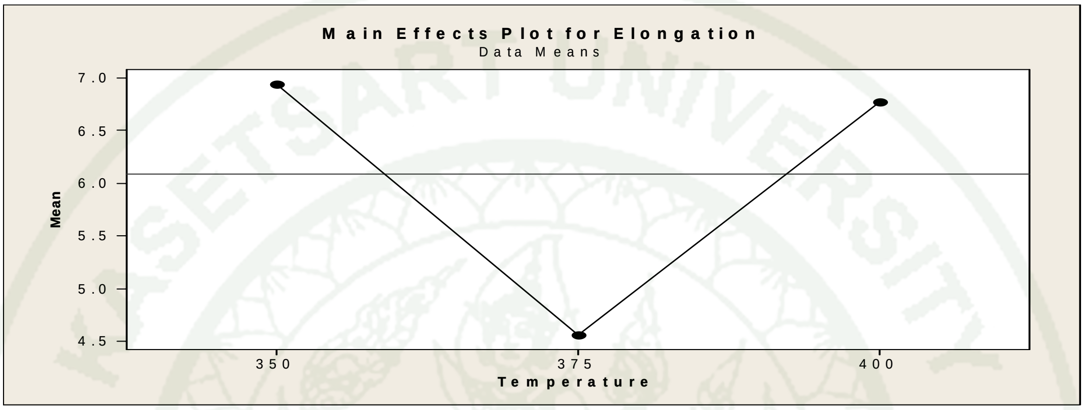



**Figure 22** Main effects of temperature on elongation

The interaction effects of temperature and tension are shown in figure 23. It can be seen the effects closely resemble the effect of just temperature (figure 24), but that elongation is maximized when tension is set at the highest level.

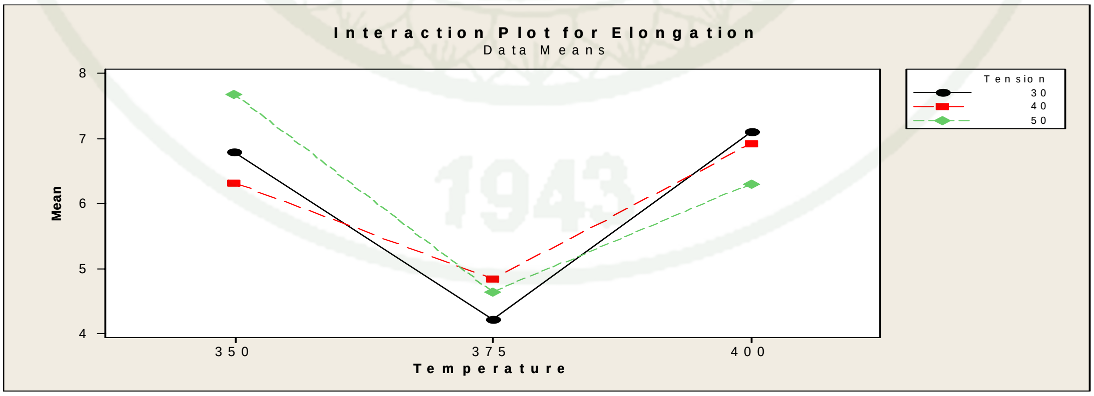



**Figure 23** Interaction effects of tension and temperature on elongation

The interaction effects of time and tension are shown in figure 24. It can be seen that elongation improves significantly when tension is set at the high point of 50 and time is restricted to 15 seconds. Strangely, when time is increased to 25 seconds the effects are inverted, but elongation remains low throughout.

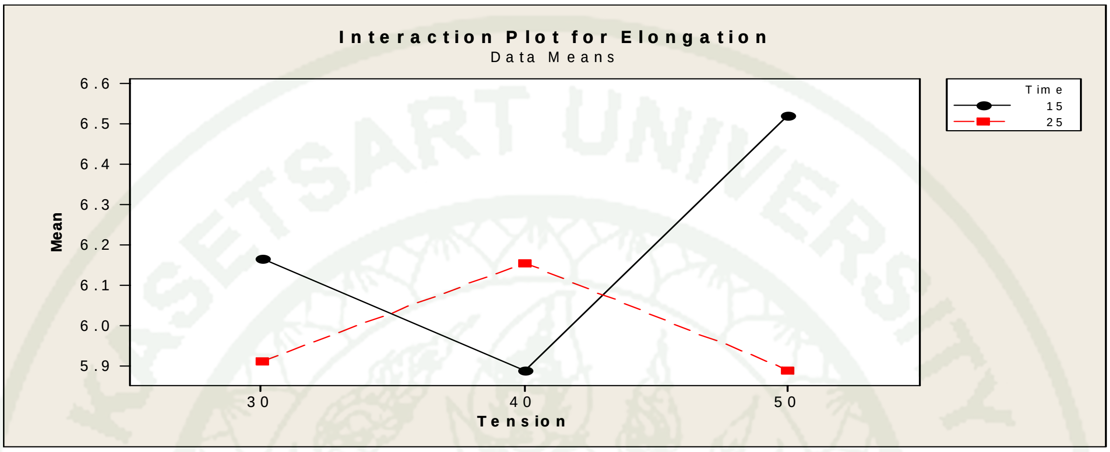



**Figure 24** Interaction effects plot of time and tension on elongation

The experiments reveal that elongation is maximized when temperature is set at the lower limit of 350°C and tension is set at the higher limit of 50 and time restricted to 15 seconds.

1.4 Effect of Stress Relieving Treatments on Relaxation

Specimens with a length of 1.2 m from each group have been placed in to a 30 tons capacity machine chamber with 20°C temperature control precision. Experiments are conducted with Shimusu relaxation test equipment for 1000 hr. The load to be applied during the test is set at 80% of the tensile strength of each specimen. Three variables, time, tension, and temperature, are used in the experiments to measure relaxation. The results of these experiments are shown in table 16.

**Table 16** Results of the experiment % Relaxation

| Number of treatments | Factors control and levels | | | Results |
|---|---|---|---|---|
| Run | Time | Tension | Temp | % Relax |
| 1 | 15 | 30 | 350 | 5.72 |
| 2 | 15 | 30 | 375 | 6.98 |
| 3 | 15 | 30 | 400 | 7.78 |
| 4 | 15 | 40 | 350 | 4.55 |
| 5 | 15 | 40 | 375 | 4.83 |
| 6 | 15 | 40 | 400 | 6.32 |
| 7 | 15 | 50 | 350 | 3.17 |
| 8 | 15 | 50 | 375 | 3.99 |
| 9 | 15 | 50 | 400 | 4.22 |
| 10 | 25 | 30 | 350 | 6.5 |
| 11 | 25 | 30 | 375 | 7.08 |
| 12 | 25 | 30 | 400 | 7.23 |
| 13 | 25 | 40 | 350 | 5.31 |
| 14 | 25 | 40 | 375 | 4.73 |
| 15 | 25 | 40 | 400 | 5.05 |
| 16 | 25 | 50 | 350 | 4.27 |
| 17 | 25 | 50 | 375 | 3.78 |
| 18 | 25 | 50 | 400 | 4.7 |
| 19 | 15 | 30 | 350 | 5.79 |
| 20 | 15 | 30 | 375 | 6.11 |
| 21 | 15 | 30 | 400 | 6.18 |
| 22 | 15 | 40 | 350 | 4.4 |
| 23 | 15 | 40 | 375 | 5.22 |
| 24 | 15 | 40 | 400 | 6.19 |
| 25 | 15 | 50 | 350 | 3.05 |
| 26 | 15 | 50 | 375 | 3.78 |
| 27 | 15 | 50 | 400 | 3.32 |

**Table 16** (Continued)

| Number of treatments | Factors control and levels | | | Results |
|---|---|---|---|---|
| Run | Time | Tension | Temp | % Relax |
| 28 | 25 | 30 | 350 | 6.2 |
| 29 | 25 | 30 | 375 | 7.42 |
| 30 | 25 | 30 | 400 | 7.47 |
| 31 | 25 | 40 | 350 | 5.77 |
| 32 | 25 | 40 | 375 | 4.88 |
| 33 | 25 | 40 | 400 | 5.65 |
| 34 | 25 | 50 | 350 | 3.62 |
| 35 | 25 | 50 | 375 | 3.49 |
| 36 | 25 | 50 | 400 | 3 |

ANOVA analysis is used to study the results (table 17).

**Table 17** Analysis of Variance for % Relaxation

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Time | 1 | 0.3501 | 0.3501 | 0.3501 | 1.35 | 0.260 |
| Tension | 2 | 54.3311 | 54.3311 | 27.1655 | 104.75 | 0.000 |
| Temperature | 2 | 2.5582 | 2.5582 | 1.2791 | 4.93 | 0.020 |
| Time*Tension | 2 | 0.8315 | 0.8315 | 0.4158 | 1.60 | 0.229 |
| Time*Temperature | 2 | 1.0640 | 1.0640 | 0.5320 | 2.05 | 0.158 |
| Tension*Temperature | 4 | 1.9240 | 1.9240 | 0.4810 | 1.85 | 0.162 |
| Time*Tension*Temperature | 4 | 0.6951 | 0.6951 | 0.1738 | 0.67 | 0.621 |
| Error | 18 | 4.6679 | 4.6679 | 0.2593 | | |
| Total | 35 | 66.4218 | | | | |

ANOVA reveals that, in the experiments for relaxation, the influential factors are tension and temperature, which have p-values equal to 0.000 and 0.020 and hence confidence levels of 99% and 95% respectively.

The main effects of tension on relaxation are shown in figure 25. It can be seen that there is a steady decrease in relaxation as tension increases.

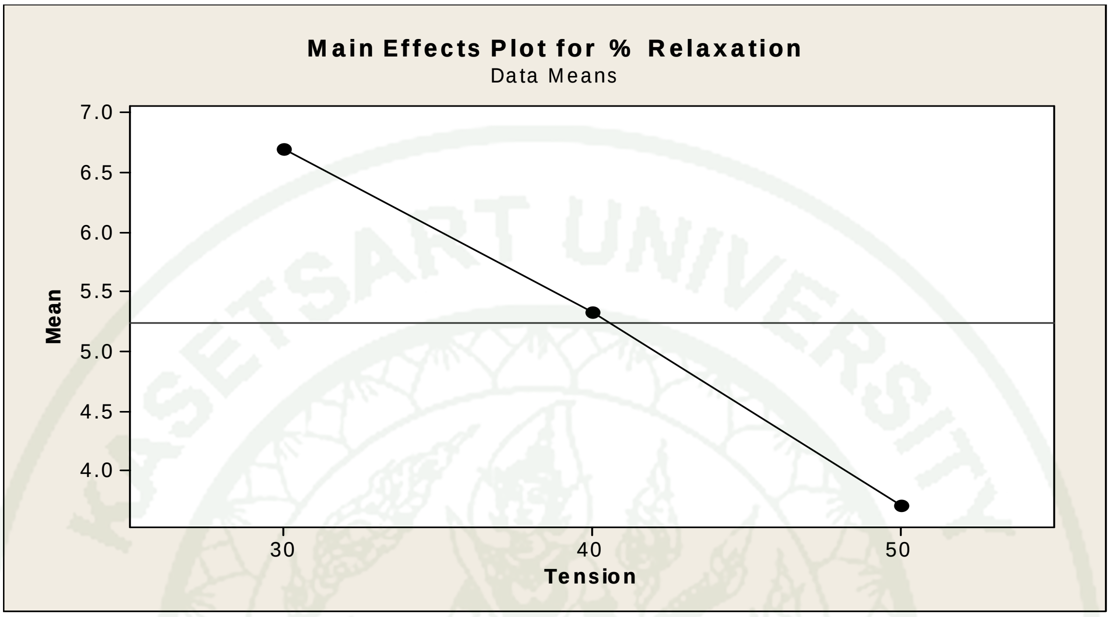



**Figure 25** Main effects of tension on relaxation

Figure 26 shows the main effects of temperature on relaxation. From this, it is clear that relaxation increases with the increases in temperature.

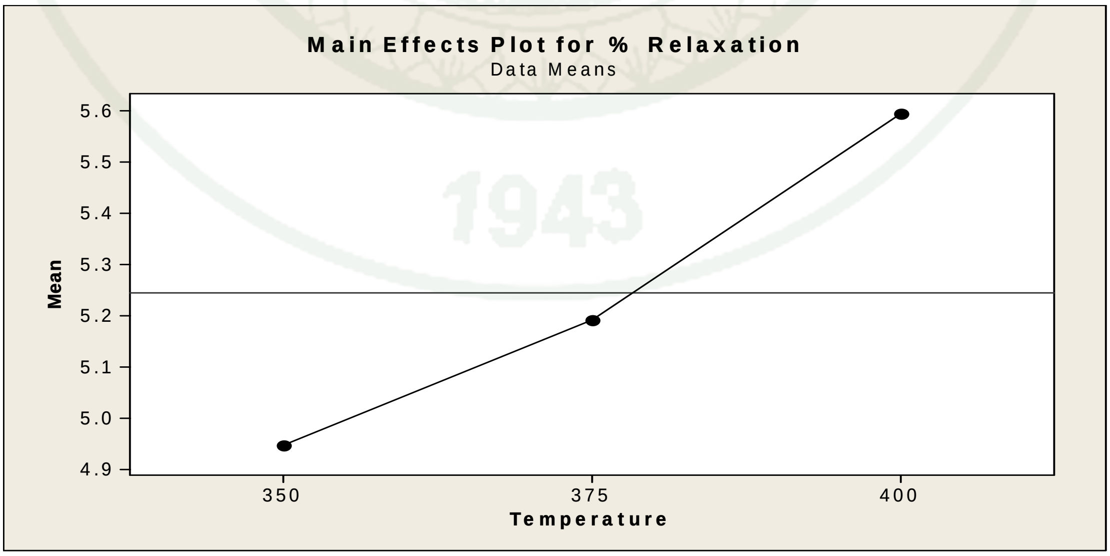



**Figure 26** Main effects of temperature on relaxation

When we plot the results for both tension and temperature three dimensionally in figure 27, the positive effects of these stress relieving treatments can be clearly seen. It is evident from the contour surface that relaxation is at a maximum of about 7.5%, when tension is at the lower limit of 30% and temperature is at the higher limit of 400°C.  Conversely, it is at a minimum when tension is at its higher limit and temperature is at its lower limit. Furthermore, it can be seen that the tension parameter has the greatest effect on relaxation. Decreases of between 2% and 3% can be achieved with tension set at tension 50%.

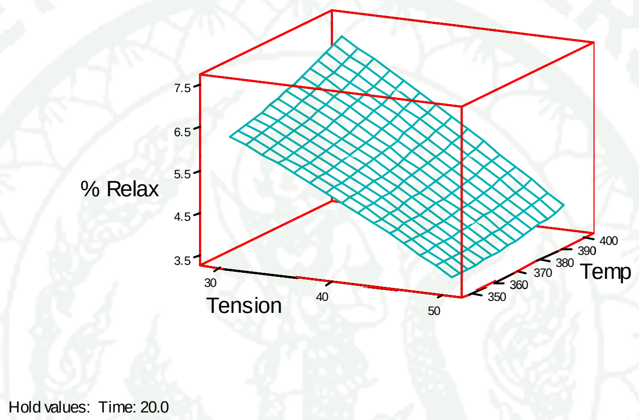



**Figure 27** Response surface for the effects of both tension and temperature on relaxation

**2. Analysis of Results by using the Taguchi method**

To ascertain the effects of process parameters on the stress-relieving process, this study employed two different analysis methods, namely the Classical and Taguchi methods. In section 1, the Classical method was discussed. In section 2, the Taguchi Method is used to analyse the effects of stress relieving treatments on the quality of high tensile steel wire.

**Table 18** Legend for the experiment factors

Runs: 18 Replicates: 3

| Factor | Type | Levels | Values |
|---|---|---|---|
| Time (A) (sec) | fixed | 2 | 15 25 |
| Tension (B)%UTS | fixed | 3 | 30 40 50 |
| Temperature (°C.) | fixed | 3 | 350 375 400 |

Factor Levels:

| | | | |
|---|---|---|---|
| Time (A) | A1 = 15, | A2 = 25 | |
| Tension (B) | B1= 30, | B2 = 40, | B3 = 50 |
| Temperature (°C.) | C1=350, | C2 = 375, | C3 = 400 |

Tensile strength (Kg). Larger is better

The formula for signal to noise is: $S/N_L = -10*\text{Log} (\sum_{I=1}^{n} 1/y^2_i)/n$

2.1 Effect of stress relieving treatments on tensile strength.

The results of the experiments and the subsequent ANOVA are shown in table 20.

**Table 19** The averages S/N tensile strength larger is better

| Run | Time (A) | Tension (B) | A*B | Temp (C) | A*C | B*C | N1 | N2 | N3 | S/N |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 192.68 | 191.51 | 192.29 | 45.67 |
| 2 | 1 | 1 | 1 | 2 | 2 | 2 | 191.12 | 192.68 | 193.07 | 45.67 |
| 3 | 1 | 1 | 1 | 3 | 3 | 3 | 187.22 | 189.56 | 188.16 | 45.49 |
| 4 | 1 | 2 | 2 | 1 | 1 | 2 | 191.12 | 193.23 | 192.68 | 45.68 |
| 5 | 1 | 2 | 2 | 2 | 2 | 3 | 191.67 | 192.68 | 191.51 | 45.66 |
| 6 | 1 | 2 | 2 | 3 | 3 | 1 | 187.38 | 186.99 | 186.99 | 45.44 |
| 7 | 1 | 3 | 3 | 1 | 1 | 3 | 190.89 | 192.29 | 187.61 | 45.58 |
| 8 | 1 | 3 | 3 | 2 | 2 | 1 | 188.55 | 191.12 | 192.45 | 45.60 |
| 9 | 1 | 3 | 3 | 3 | 3 | 2 | 188.16 | 185.04 | 182.15 | 45.34 |
| 10 | 2 | 1 | 2 | 1 | 2 | 1 | 193.23 | 192.68 | 191.51 | 45.68 |
| 11 | 2 | 1 | 2 | 2 | 3 | 2 | 190.11 | 189.95 | 191.9 | 45.60 |
| 12 | 2 | 1 | 2 | 3 | 1 | 3 | 189.72 | 191.9 | 188.55 | 45.57 |
| 13 | 2 | 2 | 3 | 1 | 2 | 2 | 190.89 | 191.67 | 193.07 | 45.66 |
| 14 | 2 | 2 | 3 | 2 | 3 | 3 | 191.9 | 190.73 | 189.72 | 45.61 |
| 15 | 2 | 2 | 3 | 3 | 1 | 1 | 182.93 | 184.88 | 185.66 | 45.31 |
| 16 | 2 | 3 | 1 | 1 | 2 | 3 | 191.12 | 192.68 | 192.06 | 45.66 |
| 17 | 2 | 3 | 1 | 2 | 3 | 1 | 191.12 | 188.78 | 188.55 | 45.55 |
| 18 | 2 | 3 | 1 | 3 | 1 | 2 | 191.67 | 181.92 | 189.95 | 45.46 |

**Table 20** Analysis of variance for S/N ratios

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Time(A) | 1 | 0.000061 | 0.000061 | 0.000061 | 0.02 | 0.883 |
| Tension(B) | 2 | 0.021425 | 0.021425 | 0.010712 | 4.33 | 0.100 |
| Temperature(C) | 2 | 0.159813 | 0.159813 | 0.079906 | 32.30 | 0.003 |
| Time(A)*Tension(B) | 2 | 0.010043 | 0.010043 | 0.005021 | 2.03 | 0.246 |
| Time(A)*Temperature(C) | 2 | 0.007399 | 0.007399 | 0.003699 | 1.50 | 0.327 |
| Tension(B)*Temperature(C) | 4 | 0.014985 | 0.014985 | 0.003746 | 1.51 | 0.349 |
| Residual Error | 4 | 0.009896 | 0.009896 | 0.002474 | | |
| Total | 17 | 0.223622 | | | | |

The SN ratios for the three factors, time, tension, and temperature, are summarized in table 21, which shows that temperature and tension are the most influential factors.

**Table 21** Main effects for S/N ratios: tensile strength response table for signal to noise ratios larger is better

| Level | Time (A) | Tension (B) | Temp (C) |
|---|---|---|---|
| 1 | 45.58 | 45.62 | 45.66 |
| 2 | 45.57 | 45.56 | 45.62 |
| 3 | 45.54 | 45.44 | |
| Effect | 0.00 | 0.08 | 0.22 |
| Rank | 3 | 2 | 1 |

Figure 21 shows the effects plots for the three factors, time, tension, and temperature. It can be seen that time has no effect on the mean SN ratio. Temperature has the most effect on the SN ratio, which is at its highest when temperature is at the lower limit of 350$^{o}$C. Tension also effects the SN ratio when it is set at 30%.

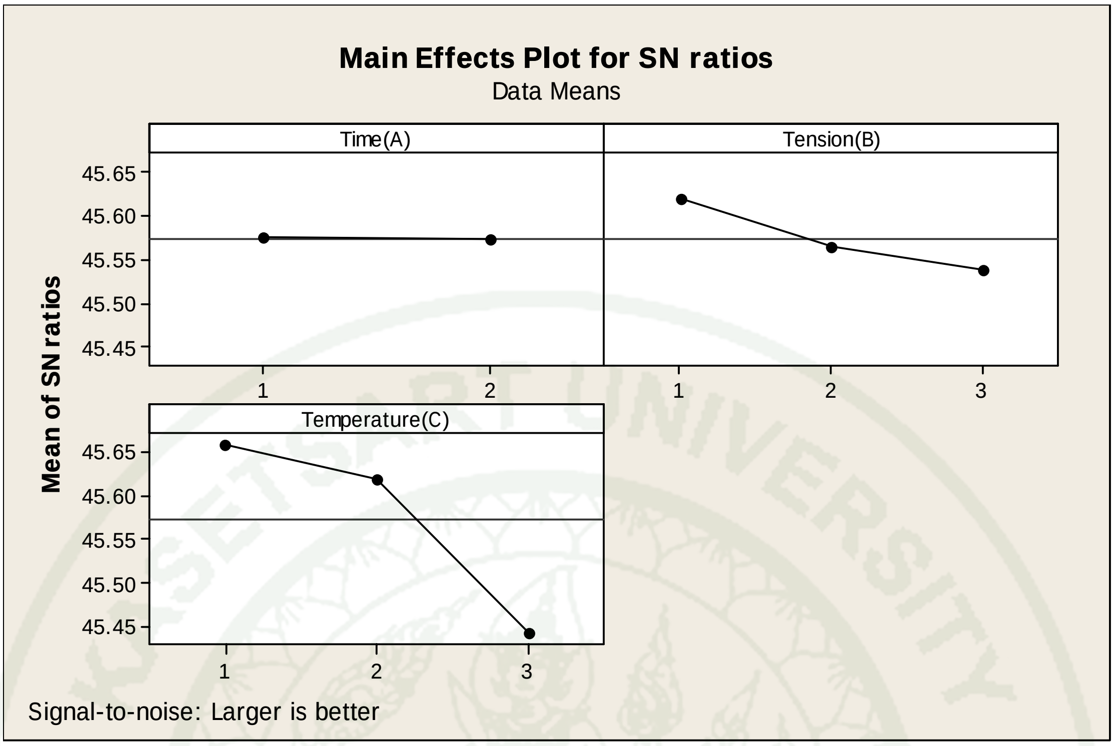



**Figure 28** S/N effects of time, tension and temperature on tensile strength

2.2 Effect of stress relieving treatments on yield strength

The experimental design and the results are shown in table 22.

**Table 22** Experiment design and data for yield strength

| Factors control and levels | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Run | Time (A) | Tension (B) | A*B | Temp (C) | A*C | B*C | N1 | N2 | N2 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 179.42 | 177.47 | 175.52 |
| 2 | 1 | 1 | 1 | 2 | 2 | 2 | 171.62 | 175.52 | 175.52 |
| 3 | 1 | 1 | 1 | 3 | 3 | 3 | 163.82 | 167.72 | 167.72 |
| 4 | 1 | 2 | 2 | 1 | 1 | 2 | 175.52 | 183.32 | 175.52 |
| 5 | 1 | 2 | 2 | 2 | 2 | 3 | 173.18 | 175.52 | 175.52 |
| 6 | 1 | 2 | 2 | 3 | 3 | 1 | 165.38 | 165.38 | 162.26 |

**Table 22** (Continued)

| Factors control and levels | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Run | Time (A) | Tension (B) | A*B | Temp (C) | A*C | B*C | N1 | N2 | N2 |
| 7 | 1 | 3 | 3 | 1 | 1 | 3 | 175.52 | 173.57 | 171.62 |
| 8 | 1 | 3 | 3 | 2 | 2 | 1 | 171.62 | 175.52 | 177.47 |
| 9 | 1 | 3 | 3 | 3 | 3 | 2 | 169.67 | 167.72 | 165.77 |
| 10 | 2 | 1 | 2 | 1 | 2 | 1 | 177.47 | 179.42 | 177.47 |
| 11 | 2 | 1 | 2 | 2 | 3 | 2 | 171.62 | 171.62 | 173.57 |
| 12 | 2 | 1 | 2 | 3 | 1 | 3 | 171.62 | 175.52 | 165.77 |
| 13 | 2 | 2 | 3 | 1 | 2 | 2 | 173.18 | 177.86 | 179.42 |
| 14 | 2 | 2 | 3 | 2 | 3 | 3 | 173.57 | 171.62 | 171.62 |
| 15 | 2 | 2 | 3 | 3 | 1 | 1 | 160.70 | 163.82 | 163.82 |
| 16 | 2 | 3 | 1 | 1 | 2 | 3 | 173.57 | 179.42 | 173.57 |
| 17 | 2 | 3 | 1 | 2 | 3 | 1 | 173.57 | 171.62 | 171.62 |
| 18 | 2 | 3 | 1 | 3 | 1 | 2 | 175.52 | 165.77 | 173.57 |

The resulting SN ratios are calculated and shown in table 23, and the ANOVA results, which show that temperature and the interaction of temperature and tension are the most significant factors, are shown in table 24.

**Table 23** The S/N yield strength for each row larger is better

| Run | Time (A) | Tension (B) | A*B | Temp (C) | A*C | B*C | N1 | N2 | N3 | S/N |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 179.42 | 177.47 | 175.52 | 44.982 |
| 2 | 1 | 1 | 1 | 2 | 2 | 2 | 171.62 | 175.52 | 175.52 | 44.821 |
| 3 | 1 | 1 | 1 | 3 | 3 | 3 | 163.82 | 167.72 | 167.72 | 44.423 |
| 4 | 1 | 2 | 2 | 1 | 1 | 2 | 175.52 | 183.32 | 175.52 | 45.009 |
| 5 | 1 | 2 | 2 | 2 | 2 | 3 | 173.18 | 175.52 | 175.52 | 44.847 |
| 6 | 1 | 2 | 2 | 3 | 3 | 1 | 165.38 | 165.38 | 162.26 | 44.314 |
| 7 | 1 | 3 | 3 | 1 | 1 | 3 | 175.52 | 173.57 | 171.62 | 44.788 |
| 8 | 1 | 3 | 3 | 2 | 2 | 1 | 171.62 | 175.52 | 177.47 | 44.852 |
| 9 | 1 | 3 | 3 | 3 | 3 | 2 | 169.67 | 167.72 | 165.77 | 44.491 |
| 10 | 2 | 1 | 2 | 1 | 2 | 1 | 177.47 | 179.42 | 177.47 | 45.014 |
| 11 | 2 | 1 | 2 | 2 | 3 | 2 | 171.62 | 171.62 | 173.57 | 44.724 |
| 12 | 2 | 1 | 2 | 3 | 1 | 3 | 171.62 | 175.52 | 165.77 | 44.651 |
| 13 | 2 | 2 | 3 | 1 | 2 | 2 | 173.18 | 177.86 | 179.42 | 44.948 |
| 14 | 2 | 2 | 3 | 2 | 3 | 3 | 173.57 | 171.62 | 171.62 | 44.724 |
| 15 | 2 | 2 | 3 | 3 | 1 | 1 | 160.7 | 163.82 | 163.82 | 44.231 |
| 16 | 2 | 3 | 1 | 1 | 2 | 3 | 173.57 | 179.42 | 173.57 | 44.883 |
| 17 | 2 | 3 | 1 | 2 | 3 | 1 | 173.57 | 171.62 | 171.62 | 44.724 |
| 18 | 2 | 3 | 1 | 3 | 1 | 2 | 175.52 | 165.77 | 173.57 | 44.683 |

**Table 24** Analysis of variance for S/N ratios

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Time (A) | 1 | 0.000179 | 0.000179 | 0.000179 | 0.05 | 0.838 |
| Tension (B) | 2 | 0.025071 | 0.025071 | 0.012535 | 3.34 | 0.140 |
| Temperature(C) | 2 | 0.693939 | 0.693939 | 0.346969 | 92.50 | 0.000 |
| Time (A)*Tension (B) | 2 | 0.020514 | 0.020514 | 0.010257 | 2.73 | 0.178 |
| Time (A)*Temperature (C) | 2 | 0.039864 | 0.039864 | 0.019932 | 5.31 | 0.075 |
| Tension (B)*Temperature (C) | 4 | 0.120695 | 0.120695 | 0.030174 | 8.04 | 0.034 |
| Residual Error | 4 | 0.015004 | 0.015004 | 0.003751 | | |
| Total | 17 | 0.915265 | | | | |

In table 25, the response table for SN ratios is shown for the three factors, time, tension, and temperature. Temperature has the greatest effect on the SN ratio, tension has little, and time none whatsoever. These effects can be clearly seen in the figure that follows (figure 29).

**Table 25** Response table for signal to noise ratios yield strength larger is better

| Level | Time (A) | Tension (B) | Temperature (C) |
|---|---|---|---|
| 1 | 44.73 | 44.77 | 44.94 |
| 2 | 44.73 | 44.68 | 44.78 |
| 3 | 44.74 | 44.47 | |
| Effect | 0.00 | 0.09 | 0.47 |
| Rank | 3 | 2 | 1 |

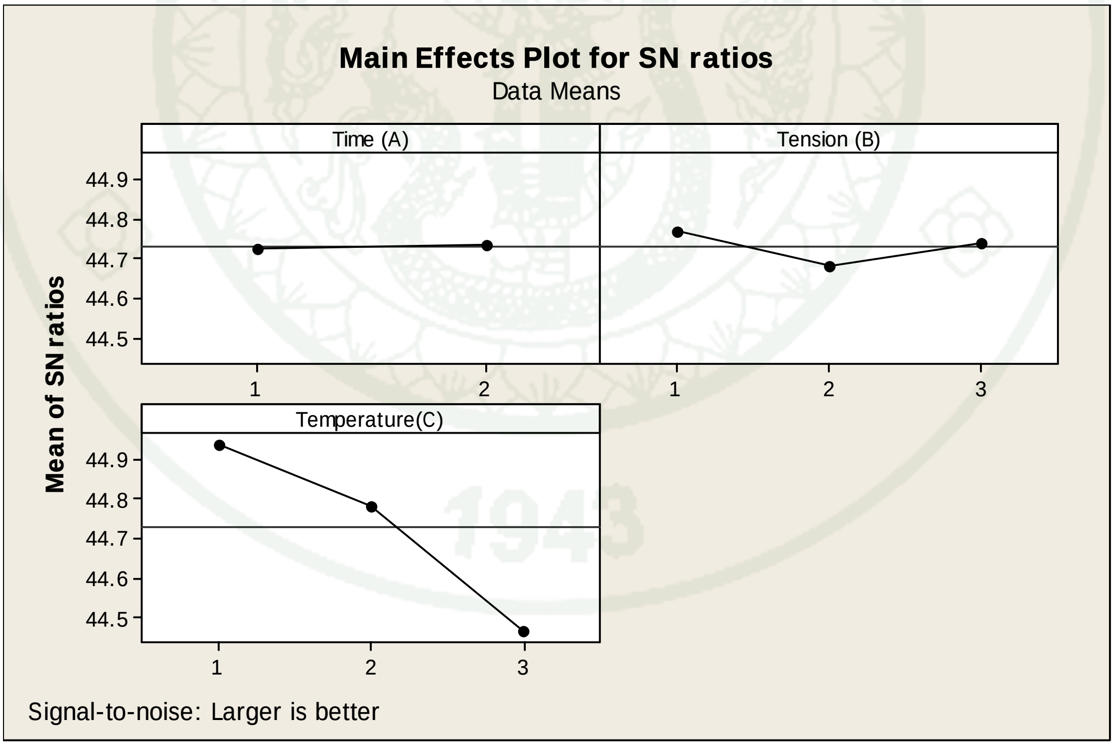



**Figure 29** S/N ratio effects of time, tension, and temperature on yield strength

The interaction effects of tension and temperature are shown in figure 30. The plot confirms that temperature is by the most influential with the highest SN ratios recorded at 350°C, irrespective of the tension setting. The most beneficial tension settings at this temperature are at 30 and 40%.

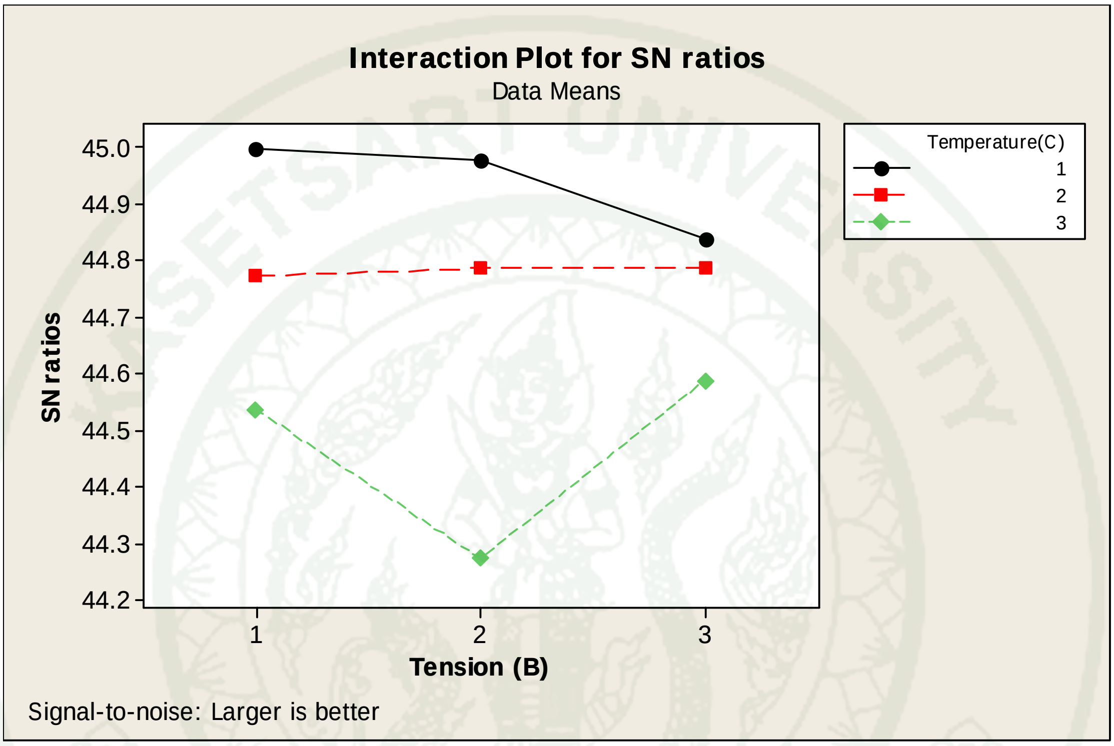



**Figure 30** Interaction effects of tension and temperature on yield strength

2.3 Effect of stress relieving treatments on elongation

The experimental design and the results are shown in table 26.

**Table 26** Experiment design and data for elongation

| Factors control and levels | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Run | Time (A) | Tension (B) | A*B | Temp (C) | A*C | B*C | Elong N1 | Elong N2 | Elong N3 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 6.8 | 6.8 | 7 |
| 2 | 1 | 1 | 1 | 2 | 2 | 2 | 4.4 | 4.5 | 4.5 |
| 3 | 1 | 1 | 1 | 3 | 3 | 3 | 7.3 | 7.2 | 7.2 |
| 4 | 1 | 2 | 2 | 1 | 1 | 2 | 5.5 | 5 | 6 |
| 5 | 1 | 2 | 2 | 2 | 2 | 3 | 4.7 | 4.7 | 4.7 |
| 6 | 1 | 2 | 2 | 3 | 3 | 1 | 7.1 | 7.1 | 7.1 |
| 7 | 1 | 3 | 3 | 1 | 1 | 3 | 8.6 | 8.6 | 8.4 |
| 8 | 1 | 3 | 3 | 2 | 2 | 1 | 4.6 | 5.6 | 4.7 |
| 9 | 1 | 3 | 3 | 3 | 3 | 2 | 6.5 | 6.5 | 5.5 |
| 10 | 2 | 1 | 2 | 1 | 2 | 1 | 6.7 | 6.8 | 6.6 |
| 11 | 2 | 1 | 2 | 2 | 3 | 2 | 3.9 | 3.9 | 3.9 |
| 12 | 2 | 1 | 2 | 3 | 1 | 3 | 6.5 | 7 | 7.7 |
| 13 | 2 | 2 | 3 | 1 | 2 | 2 | 7 | 7 | 6.7 |
| 14 | 2 | 2 | 3 | 2 | 3 | 3 | 5 | 5.1 | 5 |
| 15 | 2 | 2 | 3 | 3 | 1 | 1 | 6 | 7.1 | 7.2 |
| 16 | 2 | 3 | 1 | 1 | 2 | 3 | 6.6 | 6.8 | 7.1 |
| 17 | 2 | 3 | 1 | 2 | 3 | 1 | 4.5 | 4.5 | 4.2 |
| 18 | 2 | 3 | 1 | 3 | 1 | 2 | 6.4 | 6.2 | 6.6 |

The resulting SN ratios are calculated and shown in table 27, and the ANOVA results, which show that temperature is the most significant factor, are shown in table 28.

**Table 27** S/N for each row elongation - larger is better

| Run | Time (A) | Tension (B) | A*B | Temp (C) | A*C | B*C | Elong | Elong | Elong | S/N |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 6.8 | 6.8 | 7 | 16.73 |
| 2 | 1 | 1 | 1 | 2 | 2 | 2 | 4.4 | 4.5 | 4.5 | 13.00 |
| 3 | 1 | 1 | 1 | 3 | 3 | 3 | 7.3 | 7.2 | 7.2 | 17.19 |
| 4 | 1 | 2 | 2 | 1 | 1 | 2 | 5.5 | 5 | 6 | 14.74 |
| 5 | 1 | 2 | 2 | 2 | 2 | 3 | 4.7 | 4.7 | 4.7 | 13.44 |
| 6 | 1 | 2 | 2 | 3 | 3 | 1 | 7.1 | 7.1 | 7.1 | 17.03 |
| 7 | 1 | 3 | 3 | 1 | 1 | 3 | 8.6 | 8.6 | 8.4 | 18.62 |
| 8 | 1 | 3 | 3 | 2 | 2 | 1 | 4.6 | 5.6 | 4.7 | 13.82 |
| 9 | 1 | 3 | 3 | 3 | 3 | 2 | 6.5 | 6.5 | 5.5 | 15.72 |
| 10 | 2 | 1 | 2 | 1 | 2 | 1 | 6.7 | 6.8 | 6.6 | 16.52 |
| 11 | 2 | 1 | 2 | 2 | 3 | 2 | 3.9 | 3.9 | 3.9 | 11.82 |
| 12 | 2 | 1 | 2 | 3 | 1 | 3 | 6.5 | 7 | 7.7 | 16.92 |
| 13 | 2 | 2 | 3 | 1 | 2 | 2 | 7 | 7 | 6.7 | 16.77 |
| 14 | 2 | 2 | 3 | 2 | 3 | 3 | 5 | 5.1 | 5 | 14.04 |
| 15 | 2 | 2 | 3 | 3 | 1 | 1 | 6 | 7.1 | 7.2 | 16.52 |
| 16 | 2 | 3 | 1 | 1 | 2 | 3 | 6.6 | 6.8 | 7.1 | 16.68 |
| 17 | 2 | 3 | 1 | 2 | 3 | 1 | 4.5 | 4.5 | 4.2 | 12.86 |
| 18 | 2 | 3 | 1 | 3 | 1 | 2 | 6.4 | 6.2 | 6.6 | 16.12 |

**Table 28** Analysis of variance for S/N ratios

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Time(A) | 1 | 0.2319 | 0.2319 | 0.2319 | 0.30 | 0.614 |
| Tension(B) | 2 | 0.2470 | 0.2470 | 0.1235 | 0.16 | 0.858 |
| Temperature(C) | 2 | 48.0853 | 48.0853 | 24.0426 | 30.97 | 0.004 |
| Time(A)*Tension(B) | 2 | 2.0252 | 2.0252 | 1.0126 | 1.30 | 0.366 |
| Time(A)*Temperature(C) | 2 | 0.1945 | 0.1945 | 0.0972 | 0.13 | 0.886 |
| Tension(B)*Temperature(C) | 4 | 6.6233 | 6.6233 | 1.6558 | 2.13 | 0.241 |
| Residual Error | 4 | 3.1053 | 3.1053 | 0.7763 | | |
| Total | 17 | 60.5125 | | | | |

In table 29, the response table for SN ratios is shown for the three factors, time, tension, and temperature. Temperature has the greatest effect on the SN ratio, whilst the effect of time and tension are negligible. This can be clearly seen in figure 31.

**Table 29** Response table for signal to noise ratios elongation - larger is better

| Level | A | B | C |
|---|---|---|---|
| 1 | 15.59 | 15.36 | 16.68 |
| 2 | 15.36 | 15.42 | 13.16 |
| 3 | 15.64 | 16.58 | |
| Effect | 0.23 | 0.27 | 3.51 |
| Rank | 3 | 2 | 1 |

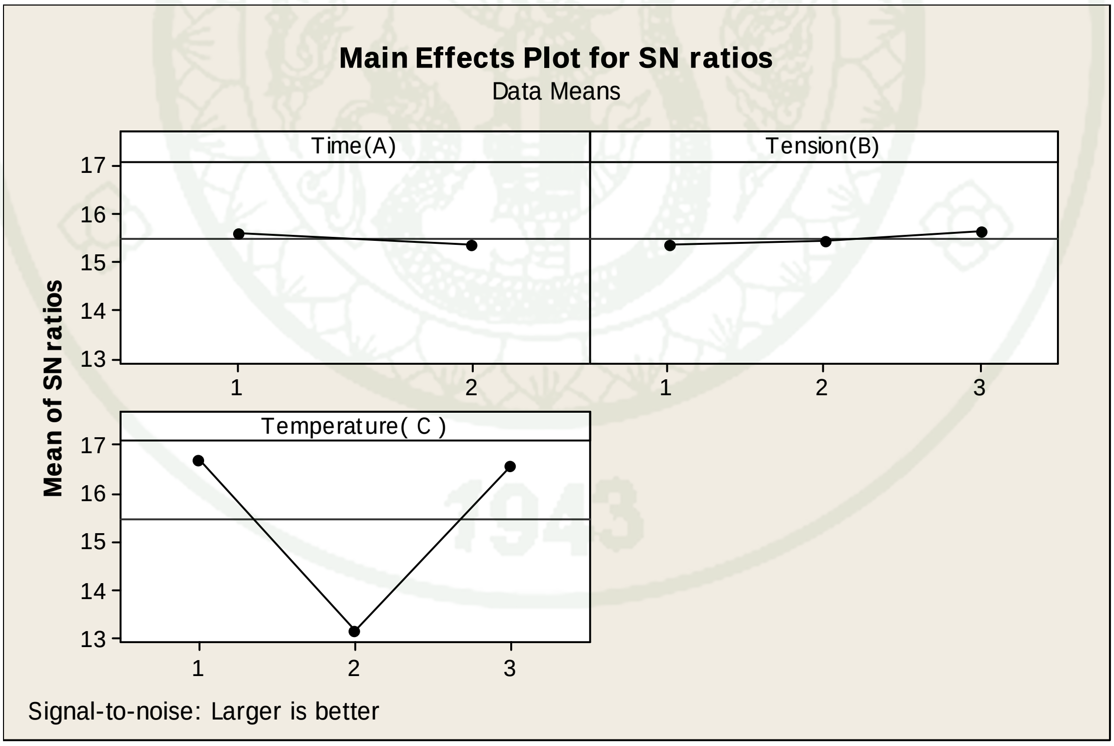



**Figure 31** S/N ratio effects of time, tension, and temperature on elongation

2.4 Effect of stress relieving treatments on relaxation

The experimental design and the results of the experiments are shown in table 30.

**Table 30** Experiment design and data Relaxation

| Run | Factors control and levels | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Time (A) | Tension (B) | A*B | Temp (C) | A*C | B*C | Relax N1 | Relax N |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 5.72 | 5.79 |
| 2 | 1 | 1 | 1 | 2 | 2 | 2 | 6.98 | 6.11 |
| 3 | 1 | 1 | 1 | 3 | 3 | 3 | 7.78 | 6.18 |
| 4 | 1 | 2 | 2 | 1 | 1 | 2 | 4.55 | 5.4 |
| 5 | 1 | 2 | 2 | 2 | 2 | 3 | 4.83 | 5.22 |
| 6 | 1 | 2 | 2 | 3 | 3 | 1 | 6.32 | 6.19 |
| 7 | 1 | 3 | 3 | 1 | 1 | 3 | 3.17 | 3.05 |
| 8 | 1 | 3 | 3 | 2 | 2 | 1 | 3.99 | 3.78 |
| 9 | 1 | 3 | 3 | 3 | 3 | 2 | 4.22 | 3.32 |
| 10 | 2 | 1 | 2 | 1 | 2 | 1 | 6.5 | 6.2 |
| 11 | 2 | 1 | 2 | 2 | 3 | 2 | 7.08 | 7.42 |
| 12 | 2 | 1 | 2 | 3 | 1 | 3 | 7.23 | 7.47 |
| 13 | 2 | 2 | 3 | 1 | 2 | 2 | 5.31 | 5.77 |
| 14 | 2 | 2 | 3 | 2 | 3 | 3 | 4.73 | 4.88 |
| 15 | 2 | 2 | 3 | 3 | 1 | 1 | 5.05 | 5.65 |
| 16 | 2 | 3 | 1 | 1 | 2 | 3 | 4.27 | 3.62 |
| 17 | 2 | 3 | 1 | 2 | 3 | 1 | 3.78 | 3.49 |
| 18 | 2 | 3 | 1 | 3 | 1 | 2 | 4.7 | 3 |

These results are used to calculate the SN ratios which are shown in table 31 and the analysis of variance is shown in table 32. The latter shows that the influential factors are primarily tension, followed by temperature.

**Table 31** S/N for each row relaxation - smaller is the better

| Run | Time (A) | Tension (B) | A*B | Temp (C) | A*C | B*C | N1 | N2 | S/N |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 5.72 | 5.79 | -15.20 |
| 2 | 1 | 1 | 1 | 2 | 2 | 2 | 6.98 | 6.11 | -16.34 |
| 3 | 1 | 1 | 1 | 3 | 3 | 3 | 7.78 | 6.18 | -16.93 |
| 4 | 1 | 2 | 2 | 1 | 1 | 2 | 4.55 | 5.4 | -13.97 |
| 5 | 1 | 2 | 2 | 2 | 2 | 3 | 4.83 | 5.22 | -14.03 |
| 6 | 1 | 2 | 2 | 3 | 3 | 1 | 6.32 | 6.19 | -15.93 |
| 7 | 1 | 3 | 3 | 1 | 1 | 3 | 3.17 | 3.05 | -9.86 |
| 8 | 1 | 3 | 3 | 2 | 2 | 1 | 3.99 | 3.78 | -11.79 |
| 9 | 1 | 3 | 3 | 3 | 3 | 2 | 4.22 | 3.32 | -11.59 |
| 10 | 2 | 1 | 2 | 1 | 2 | 1 | 6.5 | 6.2 | -16.06 |
| 11 | 2 | 1 | 2 | 2 | 3 | 2 | 7.08 | 7.42 | -17.21 |
| 12 | 2 | 1 | 2 | 3 | 1 | 3 | 7.23 | 7.47 | -17.33 |
| 13 | 2 | 2 | 3 | 1 | 2 | 2 | 5.31 | 5.77 | -14.88 |
| 14 | 2 | 2 | 3 | 2 | 3 | 3 | 4.73 | 4.88 | -13.63 |
| 15 | 2 | 2 | 3 | 3 | 1 | 1 | 5.05 | 5.65 | -14.58 |
| 16 | 2 | 3 | 1 | 1 | 2 | 3 | 4.27 | 3.62 | -11.95 |
| 17 | 2 | 3 | 1 | 2 | 3 | 1 | 3.78 | 3.49 | -11.22 |
| 18 | 2 | 3 | 1 | 3 | 1 | 2 | 4.7 | 3 | -11.92 |

**Table 32** Analysis of variance for S/N ratios

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Time(A) | 1 | 0.5479 | 0.5479 | 0.5479 | 1.84 | 0.247 |
| Tension(B) | 2 | 80.0071 | 80.0071 | 40.0035 | 134.02 | 0.000 |
| Temp(c) | 2 | 3.4547 | 3.4547 | 1.7273 | 5.79 | 0.066 |
| Time(A)*Tension(B) | 2 | 0.8854 | 0.8854 | 0.4427 | 1.48 | 0.330 |
| Time(A)*Temp(c) | 2 | 2.0024 | 2.0024 | 1.0012 | 3.35 | 0.140 |
| Tension(B)*Temp(c) | 4 | 1.8033 | 1.8033 | 0.4508 | 1.51 | 0.350 |
| Residual Error | 4 | 1.1940 | 1.1940 | 0.2985 | | |
| Total | 17 | 89.8948 | | | | |

In table 33, the response table for SN ratios is shown for the three factors, time, tension, and temperature. Tension has the greatest effect on the SN ratio, followed by temperature. The effect of time is negligible. This can be seen graphically in figure 32.

**Table 33** Response table for signal to noise ratios relaxation - smaller is better

| Level | Time (A) | Tension (B) | Temp (C) |
|---|---|---|---|
| 1 | -13.96 | -16.51 | -13.65 |
| 2 | -14.31 | -14.50 | -14.04 |
| 3 | -11.39 | -14.71 | |
| Effect | 0.35 | 5.12 | 1.06 |
| Rank | 3 | 1 | 2 |

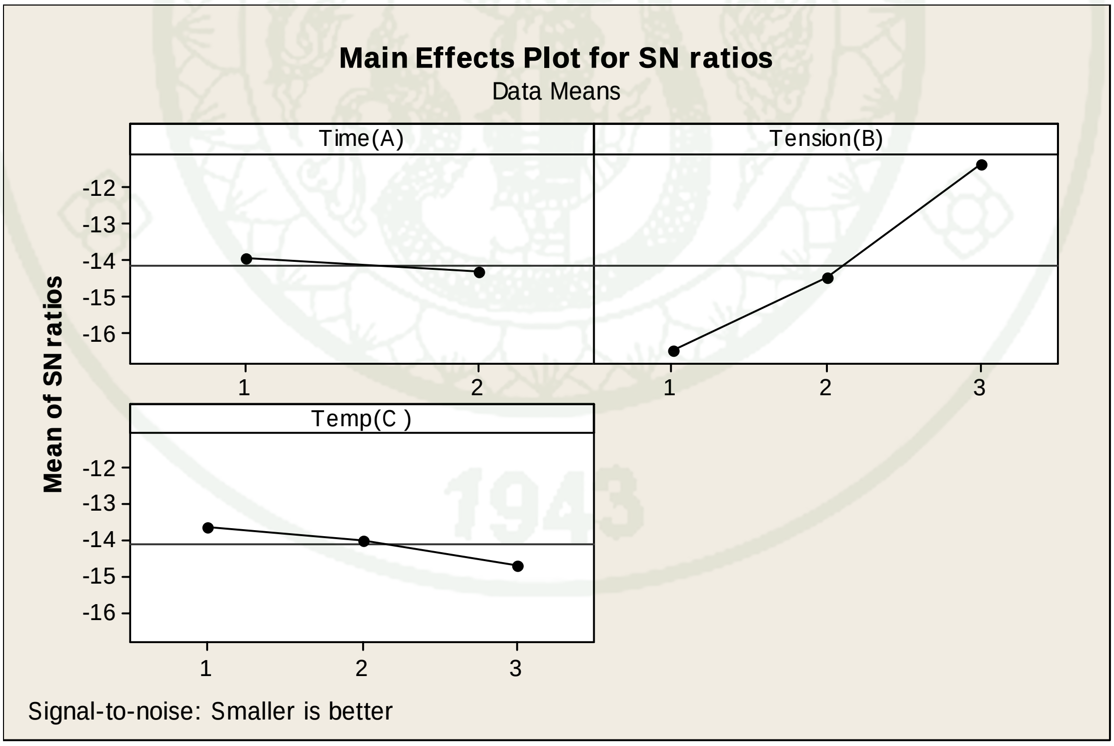


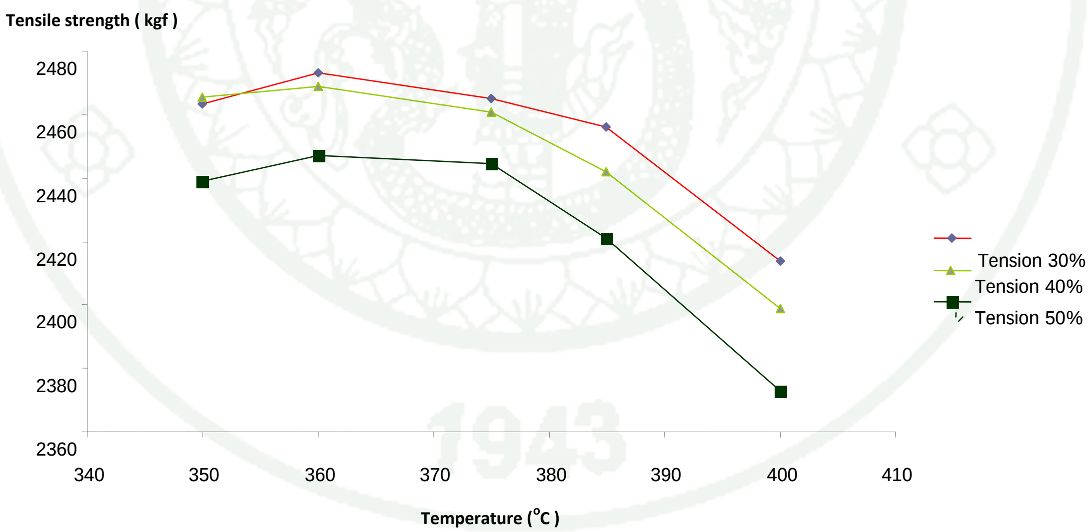

**Figure 32** S/N ratio effects of time, tension and temperature on relaxation

## 3. Additional Experiments

Having conducted and analyzed the initial experiments, temperature was seen to have the most significant effect on the mechanical properties, tensile strength, yield strength, and elongation. Tension had the most significant effect on relaxation. Therefore, additional experiments were designed and conducted (for data, see Appendix B) with an extended range of levels for these two factors.

### 3.1 The effect of temperature on tensile strength

Figure 33 shows the direct effect of temperature on tensile strength. Five temperature points are now shown for the original three tension levels. It can be seen that the optimal value for tensile strength is obtained when temperature is set at 360°C and tension at 30. When tension is increased and temperature is increased above 360°C tensile strength decreases.

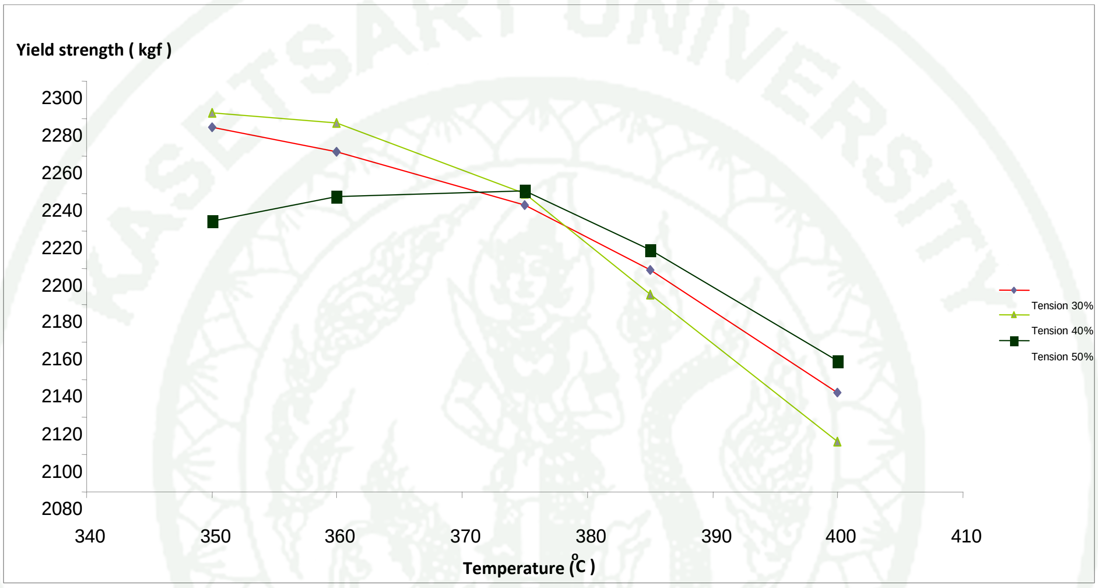



Hold values: Time: 15 sec

**Figure 33** Effect of temperature on tensile strength behavior

3.2 Effect of temperature on yield strength

The graph, shown in figure 34, indicates the yield strength at 5 temperature points when three sets of tension are used (30, 40 and 50%). It can be seen that yield strength is optimal when temperature is 375°C and tension is 30%. At higher temperatures, yield strength declines.

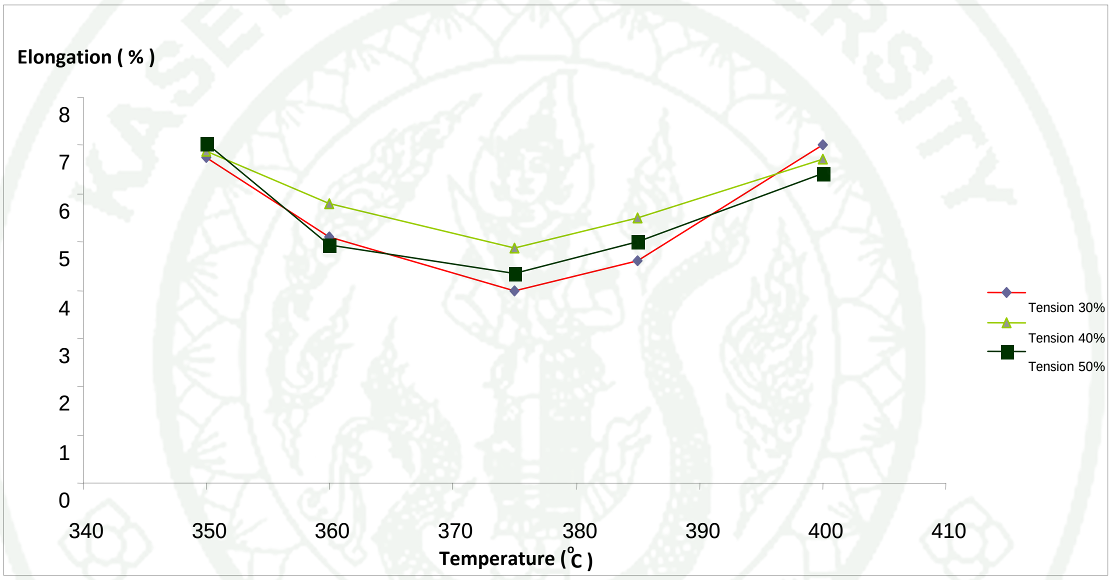



Hold values: Time: 15 sec

**Figure 34** Effect of temperature on yield strength behavior

3.3 Effect of temperature on elongation

The graph shown in figure 35 indicates the effects on elongation of temperature under three tension conditions, 30%, 40% and 50%. Elongation is reduced as temperature drops to 375°C and then increases steadily up to 400°C. Optimal elongation values are to be found with temperature at 400°C and tension at 30 or temperature at 350°C and tension at 50%, in other words, either high temperature, low tension or the reverse low temperature and high tension.

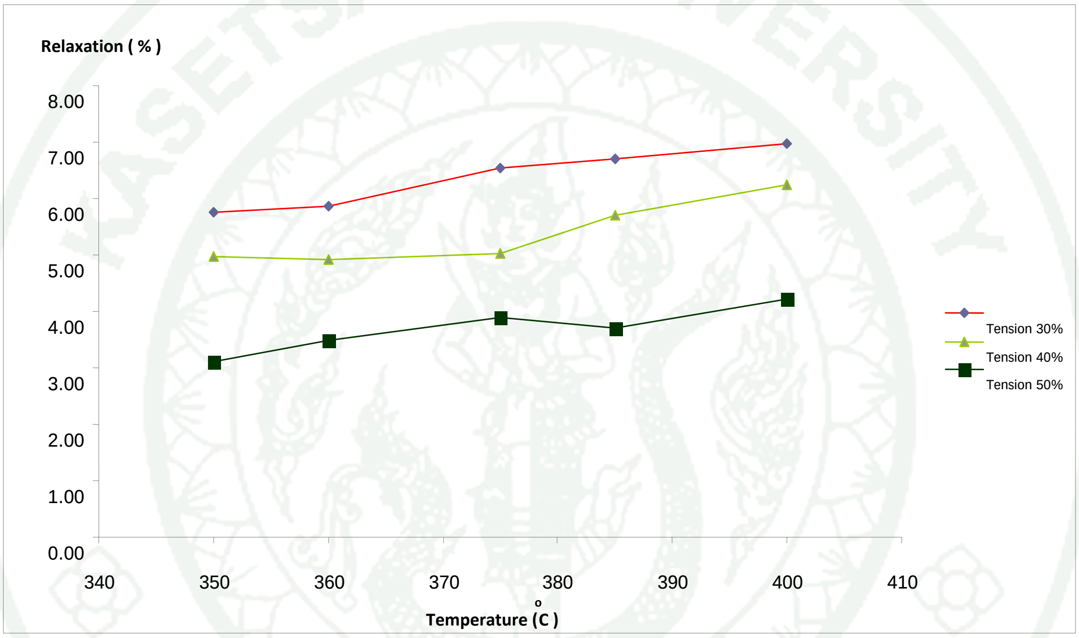



Hold values: Time: 15 sec

**Figure 35** Effect of temperature on elongation behavior

3.4 Effect of temperature and tension on relaxation

In figure 36, the relaxation percentage is measured against temperature at three different condition sets (tension at 30, 40 and 50%). It can be seen that tension has a pronounced effect on relaxation, the higher the tension, the lower the relaxation. The effect of temperature is more muted, but the optimal figure for relaxation occurs when tension is 50% and temperature is 350°C.




Hold values: Time: 15 sec

**Figure 36** Effect of temperature and tension on relaxation behavior

**4. Development of Mathematical Models**

Having conducted the experiments, collected the data, identified the influential factors in stress relieving treatments, and conducted additional experiments, we are able to use this information to develop mathematical models. Individual models are constructed for the four desirable properties, namely tensile strength, yield strength, elongation, and relaxation. The statistical program, MINITAB (version 15), is used to analyze the data and produce regression coefficients. Regression analysis on the significant coefficients, having eliminated the less significant coefficients using the t-test, enables a mathematical model to be constructed. The adequacy of the model is tested using the analysis of variance technique (ANOVA). Details are shown in Appendix D.

4.1 Mathematical Model for Tensile Strength

The following mathematical model was determined by regression analysis of the experimental data and then tested for adequacy (for details, see Appendix D):

$$\hat{Y} = -174.351-0.301(A)+0.269(B)+2.047(C)+0.002(B^2) -0.003(C^2)+0.005(A\times B)-0.002(B\times C) \quad (10)$$

Where: $\hat{Y}$ = Tensile strength

A = Time and $15 \leq A \leq 25$

B = Tension and $30 \leq B \leq 50$

C = Temperature and $350 \leq C \leq 400$

4.2 Mathematical Model for Yield Strength

The following final mathematical model was determined by regression analysis of the experimental data and then tested for adequacy (for details, see Appendix D):

$$\hat{Y} = -11.4403-1.2570(A) - 2.6375(B)+1.5328(C)+ 0.0118(B^2) - 0.0026(C^2) -0.0010(A\times B)+0.0033(A\times C)+ 0.0045(B\times C) \quad (11)$$

Where: $\hat{Y}$ = Yield strength

A = Time and $15 \leq A \leq 25$

B = Tension and $30 \leq B \leq 50$

C = Temperature and $350 \leq C \leq 400$

4.3 Mathematical Model for Elongation

The following final mathematical model was determined by regression analysis of the experimental data and then tested for adequacy (for details, see Appendix D):

$$\hat{Y} = -799.951+1.032B+3.993C-0.004B^2 -0.005C^2 + 0.001(A\times C)-0.002(B\times C) \quad (12)$$

Where: $\hat{Y}$ = Elongation

A = Time and $15 \leq A \leq 25$

B = Tension and $30 \leq B \leq 50$

C = Temperature and $375 \leq C \leq 400$

4.4 Mathematical Model for Relaxation

The following final mathematical model was determined by regression analysis of the experimental data and then tested for adequacy (for details, see Appendix D):

$$\hat{Y} = 6.43347+0.02150(A)-0.14979(B)+ 0.01175(C) \quad (13)$$

Where: $\hat{Y}$ = Relaxation

A = Time and $15 \leq A \leq 25$

B = Tension and $30 \leq B \leq 50$

C = Temperature and $350 \leq C \leq 400$

**5. Composite Optimization**

Using the response optimization feature of MINITAB, a composite optimum solution can be obtained for predefined input criteria. The predefined criteria are:

- Minimum values as defined by international standards
- The ranking of each property in order of perceived importance, i.e.
  1. Tensile strength
  2. Relaxation
  3. Yield Strength
  4. Elongation

The optimum composite solution indicated by the response optimization feature of MINITAB is shown in table 34.

**Table 34** Optimum composite solution for stress relieving treatments

| Treatments | | | Predicted Properties | | | |
|---|---|---|---|---|---|---|
| Time | Tension | Temperature | Tensile Strength | Yield Strength | Elongation | Relaxation |
| 15 | 41.3 | 350 | 192 | 177 | 6.6 | 3.4 |

This composite optimum solution is tested in a production setting to compare predicted results against actual results. To eliminate individual variations, five samples are used so that averages can be used for the comparison with the predicted results. The results are shown in tables 35 to 38.

**Table 35** Tensile strength - predicted v actual results

| Treatments | | | Results | | S. No. |
|---|---|---|---|---|---|
| Time | Tension | Temp | Predicted | Actual | |
| 15 | 41.3 | 350 | 192 | 190 | 1 |
| | | | | 189 | 2 |
| | | | | 189 | 3 |
| | | | | 190 | 4 |
| | | | | 190 | 5 |
| | | | Average 189.6 | | |

**Table 36** Yield strength - predicted v actual results

| Treatments | | | Results | | S. No |
|---|---|---|---|---|---|
| Time | Tension | Temp | Predicted | Actual | |
| 15 | 41.3 | 350 | 177 | 174 | 1 |
| | | | | 174 | 2 |
| | | | | 175 | 3 |
| | | | | 175 | 4 |
| | | | | 174 | 5 |
| | | | Average 174.4 | | |

**Table 37** Elongation - predicted v actual results

| Treatments | | | Results | | S. No |
|---|---|---|---|---|---|
| Time | Tension | Temp | Predicted | Actual | |
| 15 | 41.3 | 350 | 6.6 | 5.7 | 1 |
| | | | | 5.9 | 2 |
| | | | | 5.8 | 3 |
| | | | | 5.7 | 4 |
| | | | | 5.9 | 5 |
| | | | Average 5.80 | | |

**Table 38** Relaxation - predicted v actual results

| Treatments | | | Results | | S. No |
|---|---|---|---|---|---|
| Time | Tension | Temp | Predicted | Actual | |
| 15 | 41.3 | 350 | 3.4 | 3.7 | 1 |
| | | | | 3.8 | 2 |
| | | | | 3.8 | 3 |
| | | | | 3.7 | 4 |
| | | | | 3.7 | 5 |
| | | | Average 3.74 | | |

# CONCLUSION AND RECOMMENDATION

## Conclusion

The design and construction of an experimental stress relief unit for high tensile steel wire was critical for the experimental phase of this research project. A large volume of data was required for a wide range of parameter settings. The experimental unit enabled numerous experiments to be conducted without disrupting commercial production. Furthermore, it facilitated the fine-tuning of parameters to be achieved efficiently and economically to obtain a results database. This database is the corner stone of this research and could not have been obtained without a dedicated experimental machine.

Experiments were conducted using both the Classical and the Taguchi method. A comparison of the results was then made (see table 39 below).

**Table 39** The comparison between the classical method and taguchi method

| Response (Y) | Properties ranked by significance | | |
|---|---|---|---|
| | 1st | 2nd | 3rd |
| Classical method | | | |
| 1. Tensile strength | Temperature P = 0.000 | Tension P = 0.022 | Time*Tension P = 0.142 |
| 2. Yield strength | Temperature P = 0.000 | Tension*Temperature P = 0.004 | Time*Temperature P = 0.051 |
| 3. Elongation | Temperature P = 0.000 | Tension*Temperature P = 0.000 | Time*Tension P = 0.011 |
| 4. Relaxation | Tension P = 0.000 | Temperature P = 0.020 | Time*Temperature P = 0.158 |
| Taguchi method | | | |
| 1. Tensile strength | Temperature P = 0.003 | Tension P = 0.100 | Time*Tension P = 0.246 |
| 2. Yield strength | Temperature P = 0.000 | Tension*Temperature P = 0.034 | Time*Temperature P = 0.075 |
| 3. Elongation | Temperature P = 0.004 | Tension*Temperature P = 0.241 | Time*Tension P = 0.366 |
| 4. Relaxation | Tension P = 0.000 | Temperature P = 0.066 | Time*Temperature P = 0.148 |

The degree of significance differs in both methods, with greater certainty being attained with classical method. However, the ranking of the significant parameters that affect the quality of steel wire are identical in both methods. We can conclude, that, given the added complexity involved in using the Classical method, the use the Taguchi method is sufficient for identifying the significant parameters, saving both time and money.

The practical findings of this research project show the effects of stress relieving treatments on the resulting quality of progressively drawn pearlitic steel wire. The main findings are summarized below:

1. Tensile strength is high when temperature is in the low range of 350-370$^{o}$C and tension is set at the lower range of 30-40%.

2. Yield strength is high when temperature is at 350$^{o}$C and tension is in the range of 30-40%. After 375$^{o}$C, yield strength degrades rapidly.

3. Elongation is at it's highest when temperature is either low (300$^{o}$C) or high (400$^{o}$C), but is at it's lowest at 375$^{o}$C, irrespective of tension.

4. Relaxation has a strong inverse relationship with tension being at it's lowest when tension is at it's highest setting (50%).

5. Temperature is the most significant parameter for the mechanical properties of tensile strength, yield strength, and elongation. Lower temperature settings are the most beneficial.

6. Tension has a strong relationship with relaxation.

7. The length of time is not shown to be a significant parameter for enhancing any of the properties.

Mathematical models were also derived from the data and they enable us to predict with varying degrees of certainty the effects of treatments on the properties of steel wire.

Finally, the response optimization feature of MINITAB (version 15) has provided us with a recipe for the highest quality of steel wire, based on the extensive results database of this research study. Testing of the ingredients, i.e. the parameter settings, in a production setting has confirmed the veracity of the predicted properties.

## Recommendation

The influence of chemical compositions of samples such as Mn, Cr, etc, should be investigated and the influence of the reduction ratio on wire should be investigated. For future study, the researcher should perform the experiments using this study as base information.

# LITERATURE CITED

Allan, B. D. 1989. Lubrication of Ferrous wire. **Ferrous wire-volume 1.** The wire association international, inc., Guilfiord, Connecicut.

Berntsson, T. and M. Jarl. 2004. **Material Properties of induction tempered high tensile value spring wire.** Submitted for publication in ISIJ International, New York.

Caddell, R. M. and A. G. Atkins. 1968. "The Influence of Redundant Work When Drawing Rods Through Conical Dies". **Journal of Engineering for Industry** 90: 41-419.

Cho, S. K. and S. W. Choi. 1987. "Effect of Wire Rod Size and Its Packing Density on the Tensile Strength Deviation of High Carbon Steel Wire Rod in the Stanmore Process". **Proceedings: Annual Wire Association International Conference**. Atlanta, Georgia.

Eichinger and Lueg. 1941. **Mitteilungen aus dem Kaiser**. n.p.

Elices, M. 2004. Influence of residual stresses in stress relaxation of cold drawn wires. **Materials and Structures** 37(6): 301-304.

Enghang, P. 2002. **Steel Wire Technology.** Repro Orebro University, Orebro, Sweden.

Enghag, P. 2001. Investigation of force and friction in wire drawing. **Wire Industry** (5): 272-277.

Flanders, N. A. and E. M. Alexander. 1979. "Analysis of Wire Temperature and Power Requirements on Multi-pass Drawing Productivity". **Wire Journal International** l.12(4): 60-64.

George, E. 2003. **Handbook of workability and process design**. ASM International.

Golis, B. 1999. **Basic factors that effect the quality of steel tire cord**. Steel tire cord technology.

______. 2009. Analysis of different equations for calculations of wire tensile strength after patenting and drawing. **Wire Journal International** (8): 80-85.

Gregory, L. D. 1992. **SEM/EDS selection using a multi attribute decision making technique.** Georgetown steel corporation.

Hastings, P., and J. Heerema. 2001. "Influence of Test Method, Rolling Conditions, and Steel Chemistry on Tensile Variation for High Carbon Wire Rod". **Proceedings. Annual Wire Association International Conference**. Atlanta, Georgia.

Ivo, N. 2007. Effect of high-speed drawing on properties of high-carbon steel wires. **Wire Journal International** (12): 63-68.

Lange, K. 1985. **Handbook of Metal Forming**. McGraw-Hill, New York.

Kalpakjain, S. 2003. **Manufacturing Engineering and Technology.** Addison Wesley, Massachusetts.

Michael, R. B. 1992. **Practical Guide to Statistical Quality Improvement**. Springer.

Montgomery. 2001. **Design and Analysis of Experiment**. John Wiley and Sons, Inc., New York.

Murugan and V. Gunnaraj. 2002. The effects of process variables on the angular distortion of multipass GMA welded structural steel plates. **Welding Journal**, 4(81): n.p.

Norman, A. W. 1954. Cooling of Steel Wire During Continuous Drawing. **Wire & Wire Products** 29(10): 1160-1169.

Richard, V. M. and Y. Chia-Shun. 1971. **Advances in applied mechanics**. Academic Press, New York.

Richardson, F. D. and J. H. E. Jeffes. 1948 The Thermodynamics of Substances of Interest in Iron and Steel Making from 0 ºC to 2400 ºC: I-Oxides. **J. Iron and Steel Inst**. 160-261.

Robert, M. S. 2008. **Ferrous wire handbook**. n.p.

Ronald, D. M. 1990. **Improving Quality Through Planned Experimentation [Hardcover]**. McGraw-Hill, New York.

Schmid, E. 1968. "Plasticity of Insonated Metals". **Transactions of the Japanese Intitute of Metals** (9): 798-804.

Shermenski, R. M. 1999. Wire drawing by computer simulation. **Wire Journal International** (4): 166-183.

Shemenski, R. M., M. A. Foster and J. Walter. 2002. "Finite Element Analysis of Die Geometry for Drawing Steel Wire". **Conference Proceedings, 74th Wire & Cable Technical Symposium,** pp. 42; 55, Cleveland, Ohio, The Wire Association International, Inc., Guilford, Connecticut.

Siebel, E. 1947. Der derzeitige Stand der Erkenntisse uber mechanischen Vorgange Beim Drahtziehen. **Stahl Eisen** 11/12: 171-180.

Stebbins, R. A. 1954. "The effects of coiling temperature on hot rolled rod". **Wire & Wire Products.**

Thompson, J. A. and T. W. Clyne. 2001. The effect of heat treatment on the stiffness of zirconia top coats in plasma-sprayed TBCs. **Acta Materialia.** n.p.

Toribio, J. and F. J Ayaso. 2002. Fracture process zone in notched samples of cold drawn pearlitic steels. **ISIJ International** 42: 1049-1055.

Vitelli, V. 1972. "The Application of Stelmor Rod to high-Carbon Wire Commodities". **Wire journal International** 12(4): 52-60.

William, D. and J. Callister. 1997. Material Science and Engineering. **An Introduction**. 4th ed. John Wiley & Sons Inc, USA.

Wistreich, J. G. 1958. **The fundamentals of wire drawing. Metal**. n.p.

Wright, R. N. 1977. "Factors to Consider in Wire Die and Pass Schedule Design: Technicial Paper MF77-960". p.10. *In* **Society of Manufacturing Engineers**, Dearborn, Michigan.

Annealing of Steel. 1981. **Metals Handbook Ninth Edition-volume 4 Heat Treating.** ASM International, Materials Park, Ohio.

Kasawasaki Steel & JFE. 2003. **21st Century Foundation, An Introduction to Iron and Steel Processing 2003**. Available Source: http://www.JFE-21s-cf.or.jp/ chapter_ 202b_1.html, December 12, 2010.

# APPENDICES

**Appendix A**

Data for the Experiments

**Appendix Table A1** Data for tensile strength, yield strength, and elongation

| Run Order | Time | Tension | Temp | Sample No. | Tensile | Yield | Elongation |
|---|---|---|---|---|---|---|---|
| 1 | 15 | 30 | 375 | 801533702 | 2470 | 2250 | 4.5 |
| 2 | 15 | 50 | 375 | 801553703 | 2467 | 2275 | 4.7 |
| 3 | 25 | 30 | 375 | 802533703 | 2460 | 2225 | 4.2 |
| 4 | 15 | 50 | 350 | 801553501 | 2447 | 2250 | 8.6 |
| 5 | 25 | 30 | 400 | 802534003 | 2417 | 2125 | 7.7 |
| 6 | 25 | 50 | 400 | 802554001 | 2457 | 2250 | 6.5 |
| 7 | 15 | 30 | 375 | 801533703 | 2475 | 2250 | 4.5 |
| 8 | 15 | 40 | 350 | 801543501 | 2450 | 2250 | 4.9 |
| 9 | 15 | 30 | 350 | 801533502 | 2455 | 2275 | 6.8 |
| 10 | 25 | 30 | 375 | 802533702 | 2435 | 2200 | 3.9 |
| 11 | 25 | 40 | 400 | 802544002 | 2370 | 2100 | 7.0 |
| 12 | 15 | 40 | 400 | 801544003 | 2397 | 2080 | 7.1 |
| 13 | 15 | 40 | 375 | 801543702 | 2470 | 2250 | 4.8 |
| 14 | 15 | 40 | 350 | 801543502 | 2477 | 2350 | 4.8 |
| 15 | 25 | 50 | 400 | 802554003 | 2435 | 2225 | 6.7 |
| 16 | 25 | 40 | 400 | 802544001 | 2345 | 2060 | 5.9 |
| 17 | 15 | 30 | 400 | 801534001 | 2400 | 2100 | 7.2 |
| 18 | 15 | 40 | 400 | 801544002 | 2397 | 2120 | 7.1 |
| 19 | 15 | 50 | 350 | 801553502 | 2465 | 2225 | 8.6 |
| 20 | 25 | 30 | 400 | 802534002 | 2460 | 2250 | 7.0 |
| 21 | 15 | 50 | 400 | 801554002 | 2372 | 2150 | 6.4 |
| 22 | 15 | 30 | 350 | 801533503 | 2465 | 2250 | 7.1 |
| 23 | 25 | 50 | 375 | 802553703 | 2417 | 2200 | 4 |

**Appendix Table A1** (Continued)

| Run Order | Time | Tension | Temp | Sample No. | Tensile | Yield | Elongation |
|---|---|---|---|---|---|---|---|
| 24 | 25 | 30 | 350 | 802533501 | 2477 | 2275 | 6.7 |
| 25 | 25 | 50 | 375 | 802553702 | 2420 | 2200 | 4.5 |
| 26 | 15 | 30 | 400 | 801534002 | 2430 | 2150 | 7.2 |
| 27 | 25 | 40 | 350 | 802543503 | 2475 | 2300 | 6.7 |
| 28 | 15 | 50 | 400 | 801554001 | 2412 | 2175 | 6.6 |
| 29 | 15 | 40 | 400 | 801544001 | 2402 | 2120 | 7.2 |
| 30 | 15 | 50 | 400 | 801554003 | 2335 | 2125 | 5.5 |
| 31 | 15 | 50 | 350 | 801553503 | 2405 | 2200 | 8.2 |
| 32 | 25 | 40 | 350 | 802543502 | 2457 | 2280 | 6.9 |
| 33 | 25 | 40 | 350 | 802543501 | 2447 | 2220 | 7.0 |
| 34 | 15 | 40 | 375 | 801543703 | 2455 | 2250 | 4.8 |
| 35 | 15 | 50 | 375 | 801553702 | 2450 | 2250 | 5.4 |
| 36 | 25 | 50 | 400 | 802554002 | 2332 | 2125 | 6.1 |
| 37 | 25 | 40 | 375 | 802543702 | 2445 | 2200 | 5.1 |
| 38 | 25 | 40 | 375 | 802543703 | 2432 | 2200 | 5.0 |
| 39 | 25 | 50 | 350 | 802553503 | 2462 | 2225 | 7.2 |
| 40 | 25 | 50 | 375 | 802553701 | 2450 | 2225 | 4.5 |
| 41 | 15 | 30 | 375 | 801533701 | 2450 | 2200 | 4.3 |
| 42 | 25 | 40 | 400 | 802544003 | 2380 | 2100 | 7.2 |
| 43 | 25 | 30 | 350 | 802533503 | 2455 | 2275 | 6.7 |
| 44 | 25 | 50 | 350 | 802553502 | 2470 | 2300 | 6.8 |
| 45 | 25 | 40 | 375 | 802543701 | 2460 | 2225 | 4.6 |
| 46 | 15 | 30 | 350 | 801533501 | 2470 | 2300 | 6.7 |
| 47 | 15 | 50 | 375 | 801553701 | 2417 | 2200 | 4.7 |
| 48 | 25 | 30 | 400 | 802534001 | 2432 | 2200 | 6.3 |
| 49 | 15 | 30 | 400 | 801534003 | 2412 | 2150 | 7.2 |
| 50 | 25 | 30 | 375 | 802533701 | 2437 | 2200 | 3.9 |

**Appendix Table A1** (Continued)

| Run Order | Time | Tension | Temp | Sample No. | Tensile | Yield | Elongation |
|---|---|---|---|---|---|---|---|
| 52 | 15 | 40 | 375 | 801543701 | 2457 | 2220 | 4.7 |
| 53 | 25 | 50 | 350 | 802553501 | 2450 | 2225 | 6.7 |
| 54 | 25 | 30 | 350 | 802533502 | 2470 | 2300 | 6.8 |

**Appendix Table A2** Data for relaxation

| | | Condition Set | | | Relaxation |
|---|---|---|---|---|---|
| Run number | Sample number | Tension (%) | Temp $^{o}C$ | Time (sec) | Result (%) |
| 1 | 801533504 | 30 | 350 | 15 | 6.02 |
| 2 | 801533505 | 30 | 350 | 15 | 6.09 |
| 3 | 802533504 | 30 | 350 | 25 | 6.50 |
| 4 | 802533505 | 30 | 350 | 25 | 6.20 |
| 5 | 802543504 | 40 | 350 | 25 | 5.31 |
| 6 | 802543505 | 40 | 350 | 25 | 5.77 |
| 7 | 801543504 | 40 | 350 | 15 | 4.55 |
| 8 | 801543505 | 40 | 350 | 15 | 4.40 |
| 9 | 801553504 | 50 | 350 | 15 | 3.17 |
| 10 | 801553505 | 50 | 350 | 15 | 3.05 |
| 11 | 802553504 | 50 | 350 | 25 | 4.27 |
| 12 | 802553505 | 50 | 350 | 25 | 3.62 |
| 13 | 801533704 | 30 | 375 | 15 | 6.68 |
| 14 | 801533705 | 30 | 375 | 15 | 6.11 |
| 15 | 802533704 | 30 | 375 | 25 | 7.08 |
| 16 | 802533705 | 30 | 375 | 25 | 7.42 |
| 17 | 802543704 | 40 | 375 | 25 | 4.97 |
| 18 | 802543705 | 40 | 375 | 25 | 5.08 |

**Appendix Table A2** (Continued)

| | | Condition Set | | | Relaxation |
|---|---|---|---|---|---|
| Run number | Sample number | Tension (%) | Temp •C | Time (sec) | Result (%) |
| 19 | 801543704 | 40 | 375 | 15 | 4.83 |
| 20 | 801543705 | 40 | 375 | 15 | 5.22 |
| 21 | 801553704 | 50 | 375 | 15 | 3.99 |
| 22 | 801553705 | 50 | 375 | 15 | 3.78 |
| 23 | 802553704 | 50 | 375 | 25 | 3.78 |
| 24 | 802553705 | 50 | 375 | 25 | 3.49 |
| 25 | 801534004 | 30 | 400 | 15 | 7.08 |
| 26 | 801534005 | 30 | 400 | 15 | 6.18 |
| 27 | 802534004 | 30 | 400 | 25 | 7.23 |
| 28 | 802534005 | 30 | 400 | 25 | 7.47 |
| 29 | 801544004 | 40 | 400 | 15 | 6.32 |
| 30 | 801544005 | 40 | 400 | 15 | 6.19 |
| 31 | 802544004 | 40 | 400 | 25 | 5.05 |
| 32 | 802544005 | 40 | 400 | 25 | 5.65 |
| 33 | 801554004 | 50 | 400 | 15 | 4.22 |
| 34 | 801554005 | 50 | 400 | 15 | 3.32 |
| 35 | 802554004 | 50 | 400 | 25 | 4.7 |
| 36 | 802554005 | 50 | 400 | 25 | 3.59 |

# Appendix B

Additional Experiments

**Additional Experiments**

Samples used in these experiments were produced using the same processing conditions as before. Tension settings were extended to be 30, 35, 40, 45 and 50%. Temperature settings were extended to be 350, 360, 375, 385 and 400C$^{o}$. Time settings remained the same at 15 and 25 seconds.

**Appendix Table B1** Results for tensile strength, yield strength, and elongation

| Factor Condition | | | | | Result | | |
|---|---|---|---|---|---|---|---|
| Run Number | Code Number | Tension (%) | Temp. ($^{o}$C) | Time (sec) | Tensile (Kgf) | Yield (Kgf) | Elong (%) |
| 1 | 8015303601 | 30 | 360 | 15 | 2473 | 2262 | 6.00 |
| 2 | 8025303601 | 30 | 360 | 25 | 2455 | 2257 | 6.66 |
| 3 | 8015303801 | 30 | 385 | 15 | 2456 | 2199 | 7.00 |
| 4 | 8025303801 | 30 | 385 | 25 | 2437 | 2203 | 6.47 |
| 5 | 8015353501 | 35 | 350 | 15 | 2467 | 2287 | 5.92 |
| 6 | 8025353501 | 35 | 350 | 25 | 2459 | 2279 | 6.72 |
| 7 | 8015353601 | 35 | 360 | 15 | 2481 | 2276 | 5.00 |
| 8 | 8025353601 | 35 | 360 | 25 | 2459 | 2250 | 3.70 |
| 9 | 8015353701 | 35 | 375 | 15 | 2476 | 2237 | 4.31 |
| 10 | 8025353701 | 35 | 375 | 25 | 2446 | 2202 | 4.64 |
| 11 | 8015353801 | 35 | 385 | 15 | 2456 | 2195 | 7.00 |
| 12 | 8025353801 | 35 | 385 | 25 | 2428 | 2167 | 6.80 |
| 13 | 8015354001 | 35 | 400 | 15 | 2402 | 2108 | 7.52 |
| 14 | 8025354001 | 35 | 400 | 25 | 2389 | 2111 | 7.12 |
| 15 | 8015403601 | 40 | 360 | 15 | 2469 | 2278 | 5.81 |
| 16 | 8025403601 | 40 | 360 | 25 | 2468 | 2243 | 7.00 |
| 17 | 8015403801 | 40 | 385 | 15 | 2442 | 2186 | 6.28 |
| 18 | 8025403801 | 40 | 385 | 25 | 2431 | 2165 | 7.00 |
| 19 | 8015453501 | 45 | 350 | 15 | 2461 | 2262 | 6.42 |
| 20 | 8025453501 | 45 | 350 | 25 | 2453 | 2248 | 6.78 |

**Appendix Table B1** (Continued)

| Factor Condition | | | | | Result | | |
|---|---|---|---|---|---|---|---|
| Run Number | Code Number | Tension (%) | Temp. ($^o$C) | Time (sec) | Tensile (Kgf) | Yield (Kgf) | Elong (%) |
| 21 | 8015453601 | 45 | 360 | 15 | 2470 | 2268 | 5.20 |
| 22 | 8025453601 | 45 | 360 | 25 | 2455 | 2241 | 6.45 |
| 23 | 8015453701 | 45 | 375 | 15 | 2458 | 2245 | 4.97 |
| 24 | 8025453701 | 45 | 375 | 25 | 2441 | 2213 | 4.57 |
| 25 | 8015453801 | 45 | 385 | 15 | 2434 | 2209 | 5.70 |
| 26 | 8025453801 | 45 | 385 | 25 | 2419 | 2182 | 5.99 |
| 27 | 8015454001 | 45 | 400 | 15 | 2373 | 2123 | 7.21 |
| 28 | 8025454001 | 45 | 400 | 25 | 2369 | 2119 | 6.35 |
| 29 | 8015503601 | 50 | 360 | 15 | 2447 | 2238 | 6.90 |
| 30 | 8025503601 | 50 | 360 | 25 | 2450 | 2221 | 4.93 |
| 31 | 8015053801 | 50 | 385 | 15 | 2421 | 2210 | 5.80 |
| 32 | 8025503801 | 50 | 385 | 25 | 2423 | 2200 | 5.00 |

**Appendix Table B2** Results for Relaxation

| Factor Condition | | | | | Result |
|---|---|---|---|---|---|
| Run Number | Code Number | Tension (%) | Temp. ($^o$C) | Time (sec) | Relaxation (%) |
| 1 | 8015353501 | 35 | 350 | 15 | 5.13 |
| 2 | 8025353501 | 35 | 350 | 25 | 5.83 |
| 3 | 8015453501 | 45 | 350 | 15 | 3.80 |
| 4 | 8025453501 | 45 | 350 | 25 | 4.77 |
| 5 | 8015303601 | 30 | 360 | 15 | 5.12 |
| 6 | 8025303601 | 30 | 360 | 25 | 8.13 |
| 7 | 8015353602 | 35 | 360 | 15 | 2.91 |
| 8 | 8025353601 | 35 | 360 | 25 | 4.11 |
| 9 | 8015403601 | 40 | 360 | 15 | 2.17 |

**Appendix Table B2** (Continued)

| Factor Condition | | | | | Result |
|---|---|---|---|---|---|
| Run Number | Code Number | Tension (%) | Temp. (°C) | Time (sec) | Relaxation (%) |
| 10 | 8025403601 | 40 | 360 | 25 | 2.73 |
| 11 | 8015453601 | 45 | 360 | 15 | 2.94 |
| 12 | 8025453601 | 45 | 360 | 25 | 4.21 |
| 13 | 8015503601 | 50 | 360 | 15 | 5.32 |
| 14 | 8025503601 | 50 | 360 | 25 | 7.62 |
| 15 | 8015353701 | 35 | 375 | 15 | 5.70 |
| 16 | 8025353701 | 35 | 375 | 25 | 6.13 |
| 17 | 8015453701 | 45 | 375 | 15 | 4.20 |
| 18 | 8025453701 | 45 | 375 | 25 | 4.08 |
| 19 | 8015303801 | 30 | 385 | 15 | 3.49 |
| 20 | 8025303801 | 30 | 385 | 25 | 8.38 |
| 21 | 8015353801 | 35 | 385 | 15 | 2.13 |
| 22 | 8025353801 | 35 | 385 | 25 | 4.06 |
| 23 | 8015403801 | 40 | 385 | 15 | 1.89 |
| 24 | 8025403801 | 40 | 385 | 25 | 2.45 |
| 25 | 8015453801 | 45 | 385 | 15 | 3.57 |
| 26 | 8025453801 | 45 | 385 | 25 | 3.81 |
| 27 | 8015503801 | 50 | 385 | 15 | 6.10 |
| 28 | 8025503801 | 50 | 385 | 25 | 7.89 |

# Appendix C

Relaxation Data

**Appendix Table C1** Test results for temperature (relaxation period - 1,000 hours)

| hr | 350°C | 375°C | 400°C | Untreat |
|---|---|---|---|---|
| 2 | 0.21% | 0.47% | 0.62% | 0.75% |
| 3 | 0.21% | 0.63% | 0.79% | 1.70% |
| 4 | 0.38% | 0.86% | 0.95% | 1.86% |
| 5 | 0.49% | 0.97% | 1.06% | 1.91% |
| 6 | 0.60% | 1.02% | 1.17% | 1.91% |
| 7 | 0.88% | 1.08% | 1.28% | 2.23% |
| 8 | 0.71% | 1.14% | 1.34% | 2.44% |
| 9 | 0.94% | 1.30% | 1.40% | 2.44% |
| 10 | 1.05% | 1.36% | 1.45% | 2.50% |
| 11 | 0.99% | 1.36% | 1.51% | 2.50% |
| 12 | 0.99% | 1.41% | 1.56% | 2.56% |
| 13 | 1.05% | 1.47% | 1.56% | 2.56% |
| 14 | 1.10% | 1.52% | 1.62% | 2.63% |
| 15 | 1.10% | 1.52% | 1.62% | 2.56% |
| 16 | 1.10% | 1.52% | 1.67% | 2.63% |
| 17 | 1.22% | 1.58% | 1.67% | 2.69% |
| 18 | 1.33% | 1.58% | 1.78% | 2.69% |
| 19 | 1.22% | 1.69% | 1.78% | 2.76% |
| 20 | 1.27% | 1.64% | 1.84% | 2.76% |
| 21 | 1.38% | 1.75% | 1.89% | 2.76% |
| 22 | 1.55% | 1.75% | 1.89% | 2.69% |
| 23 | 1.33% | 1.75% | 1.95% | 2.76% |
| 24 | 1.49% | 1.75% | 1.89% | 2.76% |
| 25 | 1.61% | 1.80% | 2.01% | 2.76% |
| 26 | 1.49% | 1.86% | 1.95% | 2.76% |
| 27 | 1.61% | 1.91% | 1.95% | 2.76% |
| 28 | 1.61% | 1.86% | 2.01% | 2.82% |
| 29 | 1.61% | 1.86% | 1.95% | 2.76% |

**Appendix Table C1** (Continued)

| hr | 350°C | 375°C | 400°C | Untreat |
|---|---|---|---|---|
| 30 | 1.72% | 1.91% | 2.06% | 2.82% |
| 31 | 1.66% | 1.91% | 2.01% | 2.82% |
| 32 | 1.61% | 1.91% | 2.06% | 2.88% |
| 33 | 1.66% | 1.91% | 2.06% | 2.88% |
| 34 | 1.77% | 2.03% | 2.12% | 2.88% |
| 35 | 1.83% | 2.03% | 2.12% | 2.88% |
| 36 | 1.77% | 2.03% | 2.17% | 2.88% |
| 37 | 1.72% | 2.03% | 2.12% | 2.88% |
| 40 | 1.83% | 2.14% | 2.23% | 2.88% |
| 41 | 1.66% | 2.03% | 2.23% | 2.88% |
| 42 | 1.83% | 2.14% | 2.23% | 2.95% |
| 43 | 1.72% | 2.14% | 2.23% | 2.95% |
| 44 | 1.83% | 2.14% | 2.23% | 2.95% |
| 45 | 1.77% | 2.19% | 2.23% | 2.95% |
| 46 | 1.72% | 2.14% | 2.28% | 2.95% |
| 47 | 1.94% | 2.19% | 2.28% | 2.95% |
| 48 | 1.94% | 2.19% | 2.28% | 2.95% |
| 49 | 1.88% | 2.14% | 2.28% | 2.95% |
| 50 | 1.94% | 2.25% | 2.34% | 2.95% |
| 51 | 1.88% | 2.19% | 2.28% | 3.01% |
| 52 | 2.00% | 2.25% | 2.34% | 3.01% |
| 53 | 1.94% | 2.25% | 2.34% | 3.01% |
| 54 | 2.00% | 2.30% | 2.39% | 3.01% |
| 55 | 1.94% | 2.30% | 2.39% | 3.01% |
| 56 | 1.94% | 2.25% | 2.39% | 3.01% |
| 57 | 1.83% | 2.30% | 2.45% | 3.01% |
| 58 | 1.94% | 2.25% | 2.39% | 3.08% |
| 59 | 1.94% | 2.30% | 2.39% | 3.08% |
| 60 | 2.00% | 2.25% | 2.45% | 3.08% |

**Appendix Table C1** (Continued)

| hr | 350°C | 375°C | 400°C | Untreat |
|---|---|---|---|---|
| 61 | 2.00% | 2.30% | 2.45% | 3.08% |
| 62 | 2.00% | 2.36% | 2.45% | 3.08% |
| 63 | 2.00% | 2.36% | 2.45% | 3.08% |
| 64 | 2.00% | 2.36% | 2.45% | 3.08% |
| 65 | 2.05% | 2.36% | 2.45% | 3.08% |
| 66 | 2.05% | 2.36% | 2.50% | 3.08% |
| 67 | 2.05% | 2.41% | 2.50% | 3.08% |
| 68 | 2.16% | 2.41% | 2.50% | 3.08% |
| 69 | 2.16% | 2.41% | 2.50% | 3.08% |
| 70 | 2.05% | 2.41% | 2.50% | 3.14% |
| 71 | 2.05% | 2.41% | 2.50% | 3.14% |
| 72 | 2.00% | 2.41% | 2.50% | 3.14% |
| 73 | 2.16% | 2.41% | 2.56% | 3.21% |
| 74 | 2.05% | 2.41% | 2.56% | 3.21% |
| 75 | 2.22% | 2.41% | 2.56% | 3.14% |
| 76 | 2.05% | 2.47% | 2.56% | 3.14% |
| 77 | 2.05% | 2.41% | 2.56% | 3.14% |
| 78 | 2.16% | 2.47% | 2.62% | 3.14% |
| 79 | 2.27% | 2.53% | 2.56% | 3.21% |
| 80 | 2.16% | 2.47% | 2.56% | 3.14% |
| 81 | 2.05% | 2.53% | 2.56% | 3.21% |
| 82 | 2.16% | 2.47% | 2.56% | 3.14% |
| 83 | 2.22% | 2.53% | 2.62% | 3.14% |
| 84 | 2.22% | 2.53% | 2.67% | 3.21% |
| 85 | 2.27% | 2.53% | 2.67% | 3.14% |
| 86 | 2.16% | 2.53% | 2.62% | 3.21% |
| 87 | 2.22% | 2.53% | 2.62% | 3.27% |
| 88 | 2.27% | 2.53% | 2.67% | 3.21% |

**Appendix Table C1** (Continued)

| hr | 350°C | 375°C | 400°C | Untreat |
|---|---|---|---|---|
| 89 | 2.22% | 2.58% | 2.67% | 3.21% |
| 90 | 2.22% | 2.58% | 2.67% | 3.21% |
| 91 | 2.22% | 2.58% | 2.67% | 3.27% |
| 92 | 2.27% | 2.53% | 2.67% | 3.27% |
| 93 | 2.33% | 2.58% | 2.67% | 3.21% |
| 94 | 2.22% | 2.64% | 2.73% | 3.21% |
| 95 | 2.27% | 2.58% | 2.73% | 3.21% |
| 96 | 2.33% | 2.64% | 2.73% | 3.27% |
| 97 | 2.22% | 2.58% | 2.73% | 3.21% |
| 98 | 2.27% | 2.64% | 2.67% | 3.21% |
| 99 | 2.27% | 2.64% | 2.67% | 3.27% |
| 100 | 2.22% | 2.64% | 2.73% | 3.21% |
| 101 | 2.27% | 2.64% | 2.73% | 3.27% |
| 102 | 2.33% | 2.64% | 2.73% | 3.33% |
| 103 | 2.33% | 2.64% | 2.78% | 3.21% |
| 104 | 2.27% | 2.69% | 2.78% | 3.21% |
| 105 | 2.39% | 2.64% | 2.73% | 3.21% |
| 106 | 2.44% | 2.64% | 2.73% | 3.27% |
| 107 | 2.44% | 2.64% | 2.78% | 3.29% |
| 108 | 2.27% | 2.69% | 2.73% | 3.33% |
| 109 | 2.39% | 2.69% | 2.78% | 3.33% |
| 110 | 2.44% | 2.75% | 2.78% | 3.33% |
| 111 | 2.33% | 2.69% | 2.84% | 3.33% |
| 112 | 2.33% | 2.69% | 2.84% | 3.33% |
| 113 | 2.44% | 2.69% | 2.84% | 3.33% |
| 114 | 2.39% | 2.75% | 2.84% | 3.33% |
| 115 | 2.44% | 2.69% | 2.84% | 3.33% |
| 116 | 2.39% | 2.80% | 2.84% | 3.33% |
| 117 | 2.50% | 2.75% | 2.84% | 3.40% |

**Appendix Table C1** (Continued)

| hr | 350°C | 375°C | 400°C | Untreat |
|---|---|---|---|---|
| 118 | 2.39% | 2.69% | 2.84% | 3.40% |
| 119 | 2.33% | 2.75% | 2.84% | 3.40% |
| 120 | 2.39% | 2.75% | 2.89% | 3.40% |
| 121 | 2.39% | 2.75% | 2.84% | 3.40% |
| 122 | 2.44% | 2.75% | 2.84% | 3.40% |
| 123 | 2.39% | 2.80% | 2.84% | 3.40% |
| 124 | 2.50% | 2.75% | 2.89% | 3.40% |
| 125 | 2.50% | 2.75% | 2.89% | 3.40% |
| 126 | 2.50% | 2.80% | 2.84% | 3.27% |
| 127 | 2.55% | 2.75% | 2.84% | 3.33% |
| 128 | 2.39% | 2.75% | 2.89% | 3.33% |
| 129 | 2.55% | 2.75% | 2.89% | 3.33% |
| 130 | 2.55% | 2.80% | 2.84% | 3.40% |
| 131 | 2.55% | 2.75% | 2.89% | 3.40% |
| 132 | 2.44% | 2.80% | 2.89% | 3.33% |
| 133 | 2.55% | 2.80% | 2.89% | 3.33% |
| 134 | 2.55% | 2.75% | 2.89% | 3.33% |
| 135 | 2.61% | 2.80% | 2.95% | 3.46% |
| 136 | 2.50% | 2.86% | 2.95% | 3.33% |
| 137 | 2.44% | 2.80% | 2.95% | 3.40% |
| 138 | 2.50% | 2.80% | 2.95% | 3.46% |
| 139 | 2.44% | 2.80% | 2.95% | 3.46% |
| 140 | 2.61% | 2.80% | 2.95% | 3.46% |
| 141 | 2.61% | 2.80% | 2.95% | 3.46% |
| 142 | 2.61% | 2.80% | 2.95% | 3.46% |
| 143 | 2.61% | 2.86% | 2.95% | 3.46% |
| 144 | 2.55% | 2.80% | 2.95% | 3.40% |
| 145 | 2.55% | 2.92% | 3.00% | 3.33% |

**Appendix Table C1** (Continued)

| hr | 350°C | 375°C | 400°C | Untreat |
|---|---|---|---|---|
| 146 | 2.66% | 2.92% | 3.00% | 3.33% |
| 147 | 2.66% | 2.86% | 2.95% | 3.33% |
| 148 | 2.61% | 2.86% | 2.95% | 3.40% |
| 149 | 2.61% | 2.86% | 2.95% | 3.40% |
| 150 | 2.55% | 2.92% | 2.95% | 3.40% |
| 152 | 2.66% | 2.86% | 2.95% | 3.40% |
| 153 | 2.66% | 2.92% | 3.06% | 3.40% |
| 154 | 2.66% | 2.92% | 3.00% | 3.40% |
| 155 | 2.66% | 2.92% | 3.00% | 3.40% |
| 156 | 2.66% | 2.92% | 3.00% | 3.40% |
| 157 | 2.66% | 2.92% | 3.00% | 3.40% |
| 158 | 2.61% | 2.92% | 3.06% | 3.40% |
| 159 | 2.66% | 2.92% | 3.06% | 3.46% |
| 160 | 2.66% | 2.92% | 3.06% | 3.46% |
| 161 | 2.66% | 2.92% | 3.00% | 3.46% |
| 162 | 2.61% | 2.92% | 3.06% | 3.46% |
| 163 | 2.66% | 2.97% | 3.06% | 3.46% |
| 164 | 2.61% | 2.92% | 3.06% | 3.46% |
| 165 | 2.72% | 2.92% | 3.06% | 3.46% |
| 166 | 2.66% | 2.97% | 3.06% | 3.46% |
| 167 | 2.55% | 2.92% | 3.00% | 3.46% |
| 168 | 2.72% | 3.03% | 3.06% | 3.46% |
| 169 | 2.61% | 2.97% | 3.06% | 3.46% |
| 170 | 2.61% | 2.97% | 3.00% | 3.46% |
| 171 | 2.61% | 3.03% | 3.06% | 3.40% |
| 172 | 2.66% | 2.97% | 3.11% | 3.46% |
| 173 | 2.61% | 2.97% | 3.11% | 3.46% |
| 174 | 2.72% | 2.97% | 3.06% | 3.46% |

**Appendix Table C1** (Continued)

| hr | 350°C | 375°C | 400°C | Untreat |
|---|---|---|---|---|
| 175 | 2.61% | 2.97% | 3.11% | 3.46% |
| 176 | 2.66% | 2.97% | 3.06% | 3.53% |
| 177 | 2.61% | 2.97% | 3.11% | 3.46% |
| 178 | 2.77% | 3.03% | 3.06% | 3.53% |
| 179 | 2.66% | 3.03% | 3.11% | 3.46% |
| 180 | 2.77% | 3.03% | 3.11% | 3.46% |
| 181 | 2.72% | 2.97% | 3.17% | 3.46% |
| 182 | 2.72% | 3.03% | 3.11% | 3.46% |
| 183 | 2.61% | 2.97% | 3.11% | 3.46% |
| 184 | 2.66% | 3.03% | 3.11% | 3.53% |
| 185 | 2.72% | 3.08% | 3.11% | 3.53% |
| 186 | 2.83% | 3.08% | 3.17% | 3.53% |
| 187 | 2.72% | 3.08% | 3.17% | 3.53% |
| 188 | 2.66% | 3.03% | 3.17% | 3.59% |
| 189 | 2.77% | 3.03% | 3.17% | 3.59% |
| 190 | 2.83% | 3.03% | 3.17% | 3.59% |
| 191 | 2.77% | 3.08% | 3.11% | 3.59% |
| 192 | 2.72% | 3.08% | 3.11% | 3.53% |
| 193 | 2.83% | 3.03% | 3.17% | 3.40% |
| 194 | 2.72% | 3.03% | 3.11% | 3.46% |
| 195 | 2.83% | 3.08% | 3.11% | 3.46% |
| 196 | 2.72% | 3.03% | 3.22% | 3.40% |
| 199 | 2.72% | 3.03% | 3.17% | 3.46% |
| 200 | 2.72% | 3.08% | 3.22% | 3.53% |
| 250 | 2.89% | 3.11% | 3.31% | 3.62% |
| 300 | 2.98% | 3.15% | 3.29% | 3.73% |
| 350 | 3.08% | 3.20% | 3.41% | 3.79% |
| 400 | 3.16% | 3.31% | 3.43% | 3.82% |
| 450 | 3.17% | 3.34% | 3.47% | 3.84% |

**Appendix Table C1** (Continued)

| hr | 350°C | 375°C | 400°C | Untreat |
|---|---|---|---|---|
| 500 | 3.31% | 3.36% | 3.47% | 3.85% |
| 550 | 3.32% | 3.45% | 3.51% | 3.91% |
| 600 | 3.35% | 3.51% | 3.59% | 3.95% |
| 650 | 3.37% | 3.54% | 3.60% | 3.98% |
| 700 | 3.41% | 3.58% | 3.62% | 4.01% |
| 750 | 3.47% | 3.68% | 3.68% | 4.03% |
| 800 | 3.50% | 3.66% | 3.72% | 4.04% |
| 850 | 3.53% | 3.69% | 3.74% | 4.07% |
| 900 | 3.58% | 3.72% | 3.77% | 4.14% |
| 950 | 3.59% | 7.40% | 3.81% | 4.19% |
| 1000 | 3.62% | 3.78% | 3.82% | 4.22% |

**Appendix Table C2** Test results for tension (relaxation period - 1,000 hours)

| hr | 30% | 40% | 50% | Untreat |
|---|---|---|---|---|
| 2 | 1.01% | 0.89% | 0.09% | 0.94% |
| 3 | 1.17% | 1.16% | 0.11% | 1.20% |
| 4 | 1.51% | 1.27% | 0.22% | 1.73% |
| 5 | 1.67% | 1.55% | 0.33% | 1.92% |
| 6 | 1.84% | 1.72% | 0.33% | 2.30% |
| 7 | 1.84% | 1.83% | 0.39% | 2.30% |
| 8 | 1.95% | 1.94% | 0.61% | 2.44% |
| 9 | 2.12% | 2.00% | 0.56% | 2.44% |
| 10 | 2.18% | 2.11% | 0.56% | 2.50% |
| 11 | 2.29% | 2.16% | 0.67% | 2.50% |
| 12 | 2.34% | 2.22% | 0.67% | 2.56% |
| 13 | 2.40% | 2.27% | 0.67% | 2.56% |
| 14 | 2.51% | 2.23% | 0.84% | 2.63% |
| 15 | 2.57% | 2.28% | 0.78% | 2.56% |

**Appendix Table C2** (Continued)

| hr | 30% | 40% | 50% | Untreat |
|---|---|---|---|---|
| 16 | 2.57% | 2.28% | 0.95% | 2.63% |
| 17 | 2.62% | 2.39% | 0.89% | 2.69% |
| 18 | 2.73% | 2.45% | 1.00% | 2.69% |
| 19 | 2.73% | 2.45% | 0.89% | 2.76% |
| 20 | 2.84% | 2.51% | 1.06% | 2.76% |
| 21 | 2.79% | 2.36% | 1.06% | 2.76% |
| 22 | 2.90% | 2.42% | 1.06% | 2.69% |
| 23 | 2.90% | 2.42% | 1.06% | 2.76% |
| 24 | 2.90% | 2.47% | 1.11% | 2.76% |
| 25 | 2.90% | 2.47% | 1.06% | 2.76% |
| 26 | 3.01% | 2.53% | 1.11% | 2.76% |
| 27 | 3.07% | 2.58% | 1.11% | 2.76% |
| 28 | 3.12% | 2.58% | 1.11% | 2.82% |
| 29 | 3.12% | 2.64% | 1.17% | 2.76% |
| 30 | 3.12% | 2.64% | 1.11% | 2.82% |
| 31 | 3.23% | 2.69% | 1.17% | 2.82% |
| 32 | 3.12% | 2.69% | 1.17% | 2.88% |
| 33 | 3.18% | 2.69% | 1.17% | 2.88% |
| 34 | 3.12% | 2.75% | 1.22% | 2.88% |
| 35 | 3.35% | 2.69% | 1.22% | 2.88% |
| 36 | 3.29% | 2.75% | 1.22% | 2.88% |
| 37 | 3.35% | 2.75% | 1.22% | 2.88% |
| 38 | 3.35% | 2.80% | 1.22% | 2.88% |
| 39 | 3.40% | 3.00% | 1.28% | 2.88% |
| 40 | 3.35% | 3.06% | 1.28% | 2.88% |
| 41 | 3.40% | 2.86% | 1.39% | 2.88% |
| 42 | 3.40% | 2.86% | 1.34% | 2.95% |
| 43 | 3.40% | 2.92% | 1.34% | 2.95% |

**Appendix Table C2** (Continued)

| hr | 30% | 40% | 50% | Untreat |
|---|---|---|---|---|
| 44 | 3.46% | 2.92% | 1.28% | 2.95% |
| 45 | 3.46% | 2.92% | 1.34% | 2.95% |
| 46 | 3.46% | 2.92% | 1.45% | 2.95% |
| 47 | 3.51% | 2.97% | 1.34% | 2.95% |
| 48 | 3.51% | 2.97% | 1.39% | 2.95% |
| 49 | 3.57% | 3.03% | 1.45% | 2.95% |
| 50 | 3.57% | 3.03% | 1.39% | 2.95% |
| 51 | 3.51% | 3.08% | 1.39% | 3.01% |
| 52 | 3.62% | 3.08% | 1.50% | 3.01% |
| 53 | 3.68% | 3.11% | 1.39% | 3.01% |
| 54 | 3.57% | 3.11% | 1.39% | 3.01% |
| 55 | 3.57% | 3.11% | 1.45% | 3.01% |
| 56 | 3.51% | 3.13% | 1.45% | 3.01% |
| 57 | 3.62% | 3.13% | 1.45% | 3.01% |
| 58 | 3.69% | 3.13% | 1.45% | 3.08% |
| 59 | 3.62% | 3.14% | 1.45% | 3.08% |
| 60 | 3.74% | 3.14% | 1.50% | 3.08% |
| 61 | 3.79% | 3.17% | 1.61% | 3.08% |
| 62 | 3.79% | 3.19% | 1.50% | 3.08% |
| 63 | 3.75% | 3.19% | 1.61% | 3.08% |
| 64 | 3.79% | 3.23% | 1.61% | 3.08% |
| 65 | 3.74% | 3.23% | 1.50% | 3.08% |
| 66 | 3.79% | 3.25% | 1.56% | 3.08% |
| 67 | 3.79% | 3.25% | 1.56% | 3.08% |
| 68 | 3.79% | 3.27% | 1.56% | 3.08% |
| 69 | 3.85% | 3.27% | 1.56% | 3.08% |
| 70 | 3.79% | 3.27% | 1.61% | 3.14% |
| 71 | 3.85% | 3.28% | 1.67% | 3.14% |
| 72 | 3.90% | 3.28% | 1.56% | 3.14% |

**Appendix Table C2** (Continued)

| hr | 30% | 40% | 50% | Untreat |
|---|---|---|---|---|
| 73 | 3.96% | 3.28% | 1.61% | 3.21% |
| 74 | 3.90% | 3.28% | 1.61% | 3.21% |
| 75 | 3.90% | 3.28% | 1.73% | 3.14% |
| 76 | 3.90% | 3.28% | 1.73% | 3.14% |
| 77 | 3.90% | 3.30% | 1.61% | 3.14% |
| 78 | 4.01% | 3.30% | 1.61% | 3.14% |
| 79 | 4.07% | 3.30% | 1.61% | 3.21% |
| 80 | 4.07% | 3.29% | 1.73% | 3.14% |
| 81 | 3.96% | 3.29% | 1.73% | 3.21% |
| 82 | 4.01% | 3.30% | 1.67% | 3.14% |
| 83 | 3.96% | 3.31% | 1.73% | 3.14% |
| 84 | 4.07% | 3.31% | 1.67% | 3.21% |
| 85 | 4.01% | 3.32% | 1.67% | 3.14% |
| 86 | 4.01% | 3.37% | 1.67% | 3.21% |
| 87 | 4.01% | 3.31% | 1.67% | 3.27% |
| 88 | 4.07% | 3.31% | 1.73% | 3.21% |
| 89 | 4.07% | 3.41% | 1.73% | 3.21% |
| 90 | 4.13% | 3.41% | 1.67% | 3.21% |
| 91 | 4.07% | 3.37% | 1.67% | 3.27% |
| 92 | 4.13% | 3.37% | 1.73% | 3.27% |
| 93 | 4.18% | 3.41% | 1.78% | 3.21% |
| 94 | 4.18% | 3.41% | 1.84% | 3.21% |
| 95 | 4.13% | 3.41% | 1.78% | 3.21% |
| 96 | 4.13% | 3.41% | 1.78% | 3.27% |
| 97 | 4.13% | 3.41% | 1.78% | 3.21% |
| 98 | 4.13% | 3.41% | 1.73% | 3.21% |
| 99 | 4.07% | 3.41% | 1.78% | 3.27% |
| 100 | 4.18% | 3.43% | 1.73% | 3.21% |
| 101 | 4.07% | 3.43% | 1.78% | 3.27% |

**Appendix Table C2** (Continued)

| hr | 30% | 40% | 50% | Untreat |
|---|---|---|---|---|
| 102 | 4.13% | 3.39% | 1.84% | 3.33% |
| 103 | 4.29% | 3.38% | 1.78% | 3.21% |
| 104 | 4.29% | 3.41% | 1.84% | 3.21% |
| 105 | 4.35% | 3.42% | 1.73% | 3.21% |
| 106 | 4.18% | 3.42% | 1.78% | 3.27% |
| 107 | 4.24% | 3.42% | 1.78% | 3.29% |
| 108 | 4.24% | 3.42% | 1.78% | 3.33% |
| 109 | 4.29% | 3.42% | 1.84% | 3.33% |
| 110 | 4.24% | 3.42% | 1.89% | 3.33% |
| 111 | 4.18% | 3.41% | 1.84% | 3.33% |
| 112 | 4.29% | 3.41% | 1.78% | 3.33% |
| 113 | 4.35% | 3.41% | 1.89% | 3.33% |
| 114 | 4.24% | 3.41% | 1.78% | 3.33% |
| 115 | 4.40% | 3.41% | 1.89% | 3.33% |
| 116 | 4.40% | 3.41% | 1.84% | 3.33% |
| 117 | 4.35% | 3.41% | 1.84% | 3.40% |
| 118 | 4.35% | 3.41% | 2.00% | 3.40% |
| 119 | 4.40% | 3.41% | 1.89% | 3.40% |
| 120 | 4.29% | 3.41% | 1.89% | 3.40% |
| 121 | 4.29% | 3.43% | 1.84% | 3.40% |
| 122 | 4.35% | 3.42% | 1.89% | 3.40% |
| 123 | 4.35% | 3.45% | 1.95% | 3.40% |
| 124 | 4.40% | 3.44% | 1.89% | 3.40% |
| 125 | 4.46% | 3.44% | 1.84% | 3.40% |
| 126 | 4.29% | 3.44% | 1.95% | 3.27% |
| 127 | 4.35% | 3.45% | 1.95% | 3.33% |
| 128 | 4.35% | 3.45% | 1.84% | 3.33% |
| 129 | 4.35% | 3.44% | 1.95% | 3.33% |
| 130 | 4.40% | 3.45% | 1.89% | 3.40% |

**Appendix Table C2** (Continued)

| hr | 30% | 40% | 50% | Untreat |
|---|---|---|---|---|
| 131 | 4.40% | 3.45% | 1.95% | 3.40% |
| 132 | 4.52% | 3.46% | 1.95% | 3.33% |
| 148 | 4.52% | 3.47% | 2.00% | 3.40% |
| 149 | 4.52% | 3.47% | 2.10% | 3.40% |
| 150 | 4.57% | 3.46% | 2.20% | 3.40% |
| 151 | 4.68% | 3.46% | 2.20% | 3.40% |
| 152 | 4.52% | 3.46% | 2.23% | 3.40% |
| 153 | 4.63% | 3.47% | 2.10% | 3.40% |
| 154 | 4.63% | 3.47% | 1.95% | 3.40% |
| 155 | 4.52% | 3.47% | 1.95% | 3.40% |
| 156 | 4.63% | 3.46% | 2.06% | 3.40% |
| 157 | 4.63% | 3.46% | 2.00% | 3.40% |
| 158 | 4.57% | 3.46% | 2.00% | 3.40% |
| 159 | 4.68% | 3.46% | 2.06% | 3.46% |
| 160 | 4.57% | 3.50% | 2.06% | 3.46% |
| 161 | 4.57% | 3.50% | 2.11% | 3.46% |
| 162 | 4.52% | 3.50% | 2.11% | 3.46% |
| 163 | 4.68% | 3.50% | 2.06% | 3.46% |
| 164 | 4.74% | 3.57% | 2.06% | 3.46% |
| 165 | 4.63% | 3.57% | 2.11% | 3.46% |
| 166 | 4.63% | 3.55% | 2.06% | 3.46% |
| 167 | 4.68% | 3.55% | 2.17% | 3.46% |
| 168 | 4.68% | 3.55% | 2.06% | 3.46% |
| 169 | 4.63% | 3.55% | 2.11% | 3.46% |
| 170 | 4.74% | 3.56% | 2.06% | 3.46% |
| 171 | 4.63% | 3.55% | 2.11% | 3.40% |
| 172 | 4.63% | 3.55% | 2.11% | 3.46% |
| 173 | 4.68% | 3.61% | 2.11% | 3.46% |
| 174 | 4.63% | 3.61% | 2.11% | 3.46% |

**Appendix Table C2** (Continued)

| hr | 30% | 40% | 50% | Untreat |
|---|---|---|---|---|
| 175 | 4.68% | 3.61% | 2.17% | 3.46% |
| 176 | 4.74% | 3.61% | 2.11% | 3.53% |
| 177 | 4.68% | 3.62% | 2.17% | 3.46% |
| 178 | 4.68% | 3.62% | 2.11% | 3.53% |
| 179 | 4.68% | 3.62% | 2.11% | 3.46% |
| 180 | 4.68% | 3.65% | 2.11% | 3.46% |
| 181 | 4.74% | 3.67% | 2.11% | 3.46% |
| 182 | 4.68% | 3.65% | 2.11% | 3.46% |
| 183 | 4.79% | 3.62% | 2.17% | 3.46% |
| 184 | 4.68% | 3.62% | 2.11% | 3.53% |
| 185 | 4.68% | 3.62% | 2.17% | 3.53% |
| 186 | 4.79% | 3.62% | 2.11% | 3.53% |
| 188 | 4.79% | 3.62% | 2.17% | 3.59% |
| 189 | 4.79% | 3.62% | 2.17% | 3.59% |
| 190 | 4.74% | 3.55% | 2.17% | 3.59% |
| 191 | 4.74% | 3.55% | 2.17% | 3.59% |
| 192 | 4.74% | 3.55% | 2.17% | 3.53% |
| 193 | 4.79% | 3.55% | 2.17% | 3.40% |
| 194 | 4.79% | 3.55% | 2.11% | 3.46% |
| 195 | 4.79% | 3.55% | 2.17% | 3.46% |
| 196 | 4.79% | 3.55% | 2.23% | 3.40% |
| 197 | 4.80% | 3.55% | 2.17% | 3.46% |
| 198 | 4.80% | 3.55% | 2.17% | 3.53% |
| 199 | 4.74% | 3.57% | 2.28% | 3.46% |
| 200 | 4.83% | 3.67% | 2.17% | 3.53% |
| 250 | 4.86% | 3.79% | 2.32% | 3.62% |
| 300 | 4.88% | 3.82% | 2.53% | 3.73% |
| 350 | 4.92% | 3.94% | 2.64% | 3.79% |
| 400 | 5.07% | 4.05% | 2.79% | 3.82% |

**Appendix Table C2** (Continued)

| hr | 30% | 40% | 50% | Untreat |
|---|---|---|---|---|
| 450 | 5.11% | 4.11% | 2.84% | 3.84% |
| 500 | 5.23% | 4.19% | 2.83% | 3.85% |
| 550 | 5.24% | 4.22% | 2.92% | 3.91% |
| 600 | 5.27% | 4.27% | 2.93% | 3.95% |
| 650 | 5.36% | 4.29% | 2.95% | 3.98% |
| 700 | 5.42% | 4.37% | 3.02% | 4.01% |
| 750 | 5.47% | 4.44% | 2.99% | 4.03% |
| 800 | 5.51% | 4.43% | 3.17% | 4.04% |
| 850 | 5.56% | 4.45% | 3.10% | 4.07% |
| 900 | 5.59% | 4.49% | 3.12% | 4.14% |
| 950 | 5.64% | 4.51% | 3.14% | 4.19% |
| 1000 | 5.68% | 4.55% | 3.17% | 4.22% |

**Appendix D**

Mathematical Modeling

# Mathematical Modeling

## 1. Optimization Model for Tensile Strength

The estimated regression coefficients for tensile strength are determined on the basis of the data shown in appendix table D1 below. From the calculated coefficients of the full quadratic equation, less significant coefficients were eliminated without affecting the accuracy of the developed model by using the t-test. The final mathematical model was constructed using the significant coefficients, shown in D2.

**Appendix Table D1** Tensile strength - calculation of regression coefficients

Tensile strength versus Time, Tension, Temperature (Full Quadratic Equation)

| Term | Coef | SE Coef | T | P |
|---|---|---|---|---|
| Constant | -174.351 | 88.8099 | -1.963 | 0.053 |
| Time | -0.301 | 0.7058 | -0.427 | 0.671 |
| Tension | 0.269 | 0.5498 | 0.490 | 0.626 |
| Temperature | 2.047 | 0.4627 | 4.424 | 0.000 |
| Tension*Tension | 0.002 | 0.0038 | 0.449 | 0.655 |
| Temperature*Temperature | -0.003 | 0.0006 | -4.542 | 0.000 |
| Time*Tension | 0.005 | 0.0046 | 1.189 | 0.238 |
| Time*Temperature | 0.000 | 0.0018 | 0.063 | 0.950 |
| Tension*Temperature | -0.002 | 0.0012 | -1.350 | 0.181 |

S = 1.59400 R-Sq = 67.15% R-Sq(adj) = 63.73%

**Appendix Table D2** Significant regression coefficients for tensile strength

| Term | Coefficient |
|---|---|
| Constant | -174.351 |
| Time | -0.301 |
| Tension | 0.269 |
| Temperature | 2.047 |
| Tension*Tension | 0.002 |
| Temperature*Temperature | -0.003 |
| Time*Tension | 0.005 |
| Time*Temperature | 0.000 |
| Tension*Temperature | -0.002 |

The final mathematical models determined by the regression analysis are as follows:

$$\hat{Y} = -174.351-0.301(A)+0.269(B)+2.047(C)+0.002(B^2)-0.003(C^2)+0.005(A\times B)-0.002(B\times C)$$

Where $\hat{Y}$ = Tensile strength

A = Time and $15\leq A\leq 25$ and $A>0$

B = Tension and $30\leq B\leq 50$ and $B>0$

C = Temperature and $350\leq C15\leq 400$ and $C>0$

1.1 Checking the adequacy of the developed model

The adequacy of the models so developed is then tested by using the analysis of variance technique (ANOVA). Using this technique it is found that calculated P ratios are lower than the tabulated values at a 95% confidence level. Hence, the models are considered to be adequate.

The results of the ANOVA are given in appendix table D3.

**Appendix Table D3** Analysis of variance for tensile strength

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 8 | 399.845 | 399.845 | 49.981 | 19.67 | 0.000 |
| Linear | 3 | 338.978 | 51.344 | 17.115 | 6.74 | 0.000 |
| Square | 2 | 52.637 | 52.637 | 26.319 | 10.36 | 0.000 |
| Interaction | 3 | 8.230 | 8.230 | 2.743 | 1.08 | 0.363 |
| Residual Error | 77 | 195.644 | 195.644 | 2.541 | | |
| Lack-of-Fit | 41 | 71.315 | 71.315 | 1.739 | 0.50 | 0.983 |
| Pure Error | 36 | 124.330 | 124.330 | 3.454 | | |
| Total | 85 | 595.489 | | | | |

## 2. Optimization Model for Yield Strength

The estimated regression coefficients for yield strength are determined on the basis of the data shown in appendix table D4. From the calculated coefficients of the full quadratic equation, less significant coefficients were eliminated without affecting the accuracy of the developed model by using the t-test. The final mathematical model was constructed using the significant coefficients, shown in appendix table D5.

**Appendix Table D4** Calculation of regression coefficients

Yield strength versus Time, Tension, Temperature (Full Quadratic Equation)

| Term | Coef | SE Coef | T | P |
|---|---|---|---|---|
| Constant | -11.4403 | 144.750 | -0.079 | 0.937 |
| Time | -1.2570 | 1.150 | -1.093 | 0.278 |
| Tension | -2.6375 | 0.896 | -2.943 | 0.004 |
| Temperature | 1.5328 | 0.754 | 2.033 | 0.046 |
| Tension*Tension | 0.0118 | 0.006 | 1.895 | 0.062 |
| Temperature*Temperature | -0.0026 | 0.001 | -2.642 | 0.010 |
| Time*Tension | -0.0010 | 0.007 | -0.133 | 0.895 |
| Time*Temperature | 0.0033 | 0.003 | 1.129 | 0.262 |
| Tension*Temperature | 0.0045 | 0.002 | 2.305 | 0.024 |

S = 2.59803 R-Sq = 71.51% R-Sq(adj) = 68.55%

**Appendix Table D5** Significant regression coefficients for yield strength

| Term | Coefficient |
|---|---|
| Constant | -11.4403 |
| Time | -1.2570 |
| Tension | -2.6375 |
| Temperature | 1.5328 |
| Tension*Tension | 0.0118 |
| Temperature*Temperature | -0.0026 |
| Time*Tension | -0.0010 |
| Time*Temperature | 0.0033 |
| Tension*Temperature | 0.0045 |

The final mathematical model determined by the regression analysis is as follows:

$$\hat{Y} = -11.4403-1.2570(A)-2.6375(B)+1.5328(C)+0.0118(B^2) -0.0026(C^2)-0.0010(A\times B)+0.0033(A\times C)+ 0.0045(B\times C)$$

Where: $\hat{Y}$ = Yield strength

A = Time and $15\leq A\leq 25$ and $A>0$

B = Tension and $30\leq B\leq 50$ and $B>0$

C = Temperature and $350\leq C\leq 400$ and $C>0$

2.1 Checking the adequacy of the developed model

The adequacy of the model so developed is then tested by using the analysis of variance technique (ANOVA). Using this technique it is found that calculated P ratios are lower than the tabulated values at a 95% confidence level. Hence, the models are considered to be adequate.

The results of the ANOVA are given in Appendix Table D6.

**Appendix Table D6** Analysis of variance for yield strength

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 8 | 1304.54 | 1304.54 | 163.067 | 24.16 | 0.000 |
| Linear | 3 | 1190.71 | 100.76 | 33.586 | 4.98 | 0.003 |
| Square | 2 | 69.23 | 69.23 | 34.613 | 5.13 | 0.008 |
| Interaction | 3 | 44.60 | 44.60 | 14.867 | 2.20 | 0.095 |
| Residual Error | 77 | 519.73 | 519.73 | 6.750 | | |
| Lack-of-Fit | 41 | 246.19 | 246.19 | 6.005 | 0.79 | 0.768 |
| Pure Error | 36 | 273.54 | 273.54 | 7.598 | | |
| Total | 85 | 1824.27 | | | | |

**3. Optimization Model for Elongation**

The estimated regression coefficients for elongation are determined on the basis of the data shown in appendix table D7. From the calculated coefficients of the full quadratic equation, less significant coefficients were eliminated without affecting the accuracy of the developed model by using the t-test. The final mathematical model was constructed using the significant coefficients, shown appendix table D8.

**Appendix Table D7** Elongation - calculation of regression coefficients

Elongation versus Time, Tension, Temperature (Full Quadratic Equation)

| Term | Coef | SE Coef | T | P |
|---|---|---|---|---|
| Constant | -799.951 | 140.425 | -5.697 | 0.000 |
| Time | -0.420 | 0.373 | -1.125 | 0.267 |
| Tension | 1.032 | 0.260 | 3.967 | 0.000 |
| Temperature | 3.993 | 0.724 | 5.518 | 0.000 |
| Tension*Tension | -0.004 | 0.001 | -3.134 | 0.003 |
| Temperature*Temperature | -0.005 | 0.001 | -5.318 | 0.000 |
| Time*Tension | 0.001 | 0.001 | 0.625 | 0.535 |
| Time*Temperature | 0.001 | 0.001 | 0.983 | 0.331 |
| Tension*Temperature | -0.002 | 0.001 | -3.219 | 0.002 |

S = 0.396469 R-Sq = 89.95% R-Sq(adj) = 88.17%

**Appendix Table D8** Significant regression coefficients for elongation

| Term | Coefficient |
|---|---|
| Constant | -799.951 |
| Tension (B) | 1.032 |
| Temperature (C) | 3.993 |
| Tension*Tension | -0.004 |
| Temperature*Temperature | -0.005 |
| Time*Temperature | 0.001 |
| Tension*Temperature | -0.002 |

The final mathematical model determined by the regression analysis is as follows:

$$\hat{Y} = -799.951+1.032B+3.993C-0.004B^2 -0.005C^2 +0.001(A\times C) -0.002(B\times C)$$

When $15 \leq A \leq 25$, $30 \leq B \leq 50$, $375 \leq C \leq 400$, and $A,B,C > 0$

Where: $\hat{Y}$ = Elongation

A = Time and $15 \leq A \leq 25$ and $A>0$

B = Tension and $30 \leq B \leq 50$ and $B>0$

C = Temperature and $375 \leq C \leq 400$ and $C>0$

3.1 Checking the adequacy of the developed model

The adequacy of the model so developed is then tested by using the analysis of variance technique (ANOVA). Using this technique it is found that calculated P ratios are lower than the tabulated values at a 95% confidence level. Hence, the models are considered to be adequate.

The results of the ANOVA are given in appendix table D9.

**Appendix Table D9** Analysis of variance for elongation

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 8 | 63.333 | 63.333 | 7.9166 | 50.36 | 0.000 |
| Linear | 3 | 55.053 | 7.521 | 2.5069 | 15.95 | 0.000 |
| Square | 2 | 6.438 | 6.438 | 3.2190 | 20.48 | 0.000 |
| Interaction | 3 | 1.842 | 1.842 | 0.6139 | 3.91 | 0.015 |
| Residual Error | 45 | 7.073 | 7.073 | 0.1572 | | |
| Lack-of-Fit | 21 | 4.327 | 4.327 | 0.2060 | 1.80 | 0.083 |
| Pure Error | 24 | 2.747 | 2.747 | 0.1144 | | |
| Total | 53 | 70.406 | | | | |

**4. Optimization Model for Relaxation**

The estimated regression coefficients for relaxation are determined on the basis of the data shown in appendix table D10. From the calculated coefficients of the full quadratic equation, less significant coefficients were eliminated without affecting the accuracy of the developed model by using the t-test. The final mathematical model was constructed using the significant coefficients, shown in appendix table D11.

**Appendix Table D10** Relaxation - calculation of regression coefficients

Relaxation versus Time, Tension, Temperature (Linear)

| Term | Coef | SE Coef | T | P |
|---|---|---|---|---|
| Constant | 6.43347 | 1.48175 | 4.342 | 0.000 |
| Time | 0.02150 | 0.01523 | 1.411 | 0.168 |
| Tension | -0.14979 | 0.00933 | -16.058 | 0.000 |
| Temp | 0.01175 | 0.00373 | 3.149 | 0.004 |

S = 0.456977 R-Sq = 89.40% R-Sq(adj) = 88.40%

**Appendix Table D11** Significant regression coefficients for relaxation

| Term | Coefficients |
|---|---|
| Constant | 6.43347 |
| Time | 0.02150 |
| Tension | -0.14979 |
| Temperature | 0.01175 |

The final mathematical models determined by the regression analysis are as follows:

$$\hat{Y} = 6.43347+0.02150(A)-0.14979(B)+ 0.01175(C)$$

Where: $\hat{Y}$ = Relaxation

A = Time and $15 \leq A \leq 25$ and $A>0$

B = Tension and $30 \leq B \leq 50$ and $B>0$

C = Temperature and $350 \leq C \leq 400$ and $C>0$

4.1 Checking the adequacy of the developed model

The adequacy of the model so developed is then tested by using the analysis of variance technique (ANOVA). Using this technique it is found that calculated P ratios are lower than the tabulated values at a 95% confidence level. Hence, the models are considered to be adequate.

The results of the ANOVA are given in appendix table D12.

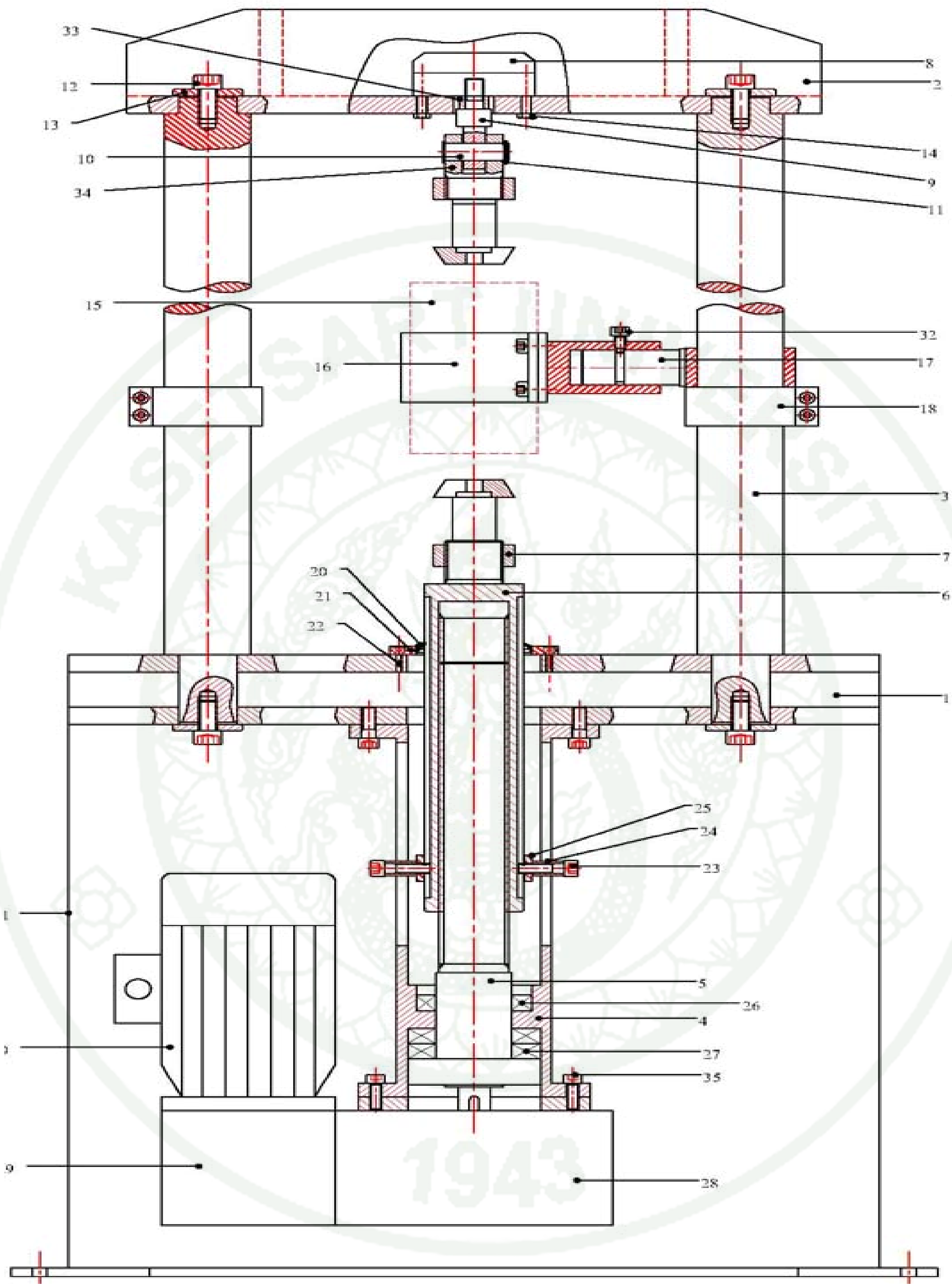
**Appendix Table D12** Analysis of variance for relaxation

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 3 | 56.337 | 56.337 | 18.7790 | 89.93 | 0.000 |
| Linear | 3 | 56.337 | 56.337 | 18.7790 | 89.93 | 0.000 |
| Residual Error | 32 | 6.682 | 6.682 | 0.2088 | | |
| Lack-of-Fit | 14 | 4.002 | 4.002 | 0.2859 | 1.92 | 0.097 |
| Pure Error | 18 | 2.680 | 2.680 | 0.1489 | | |
| Total | 35 | 63.020 | | | | |

**Appendix E**

The Experimental Stress Relief Unit

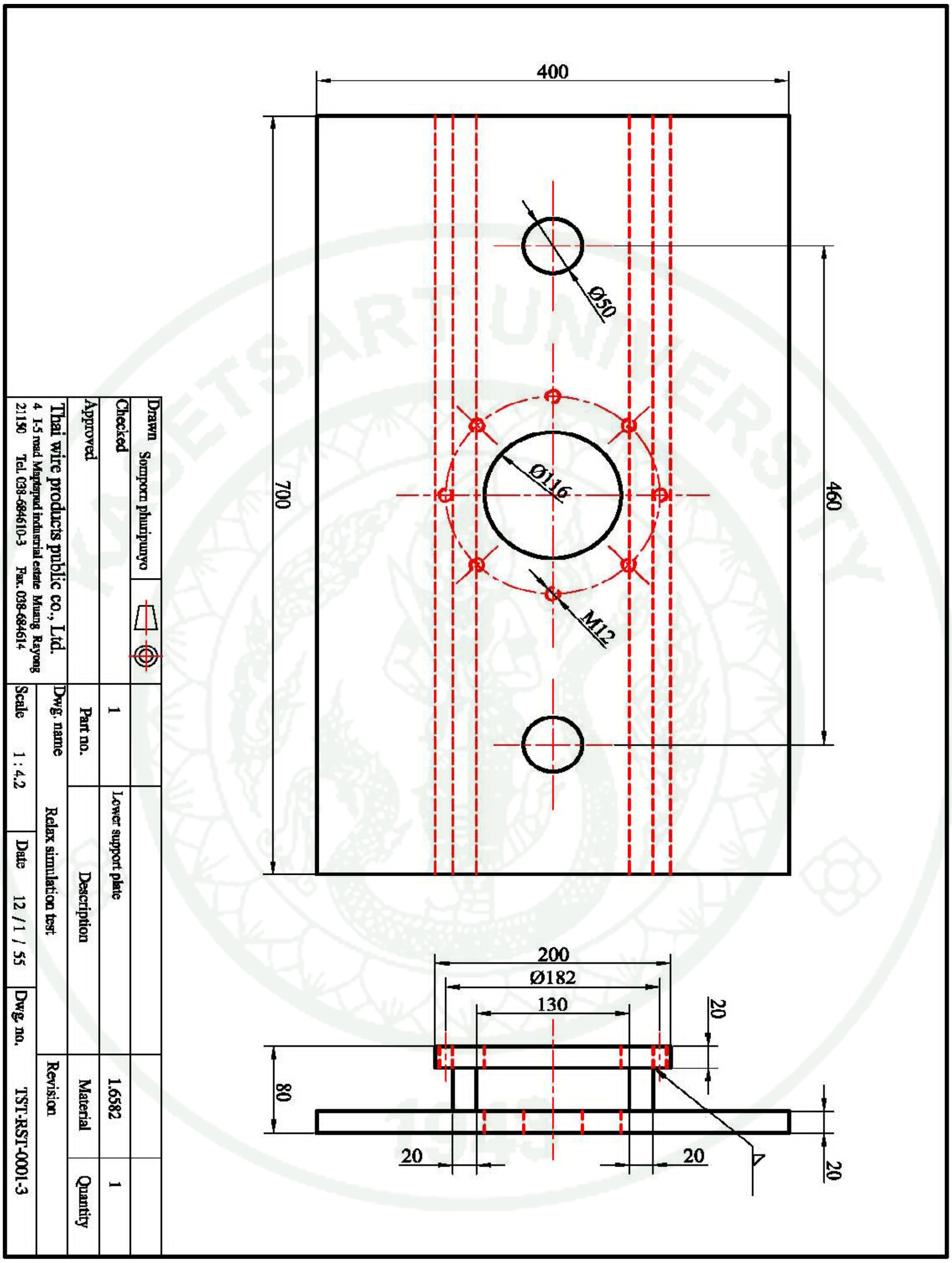
**Appendix Figure E1** The experimental stress relief unit



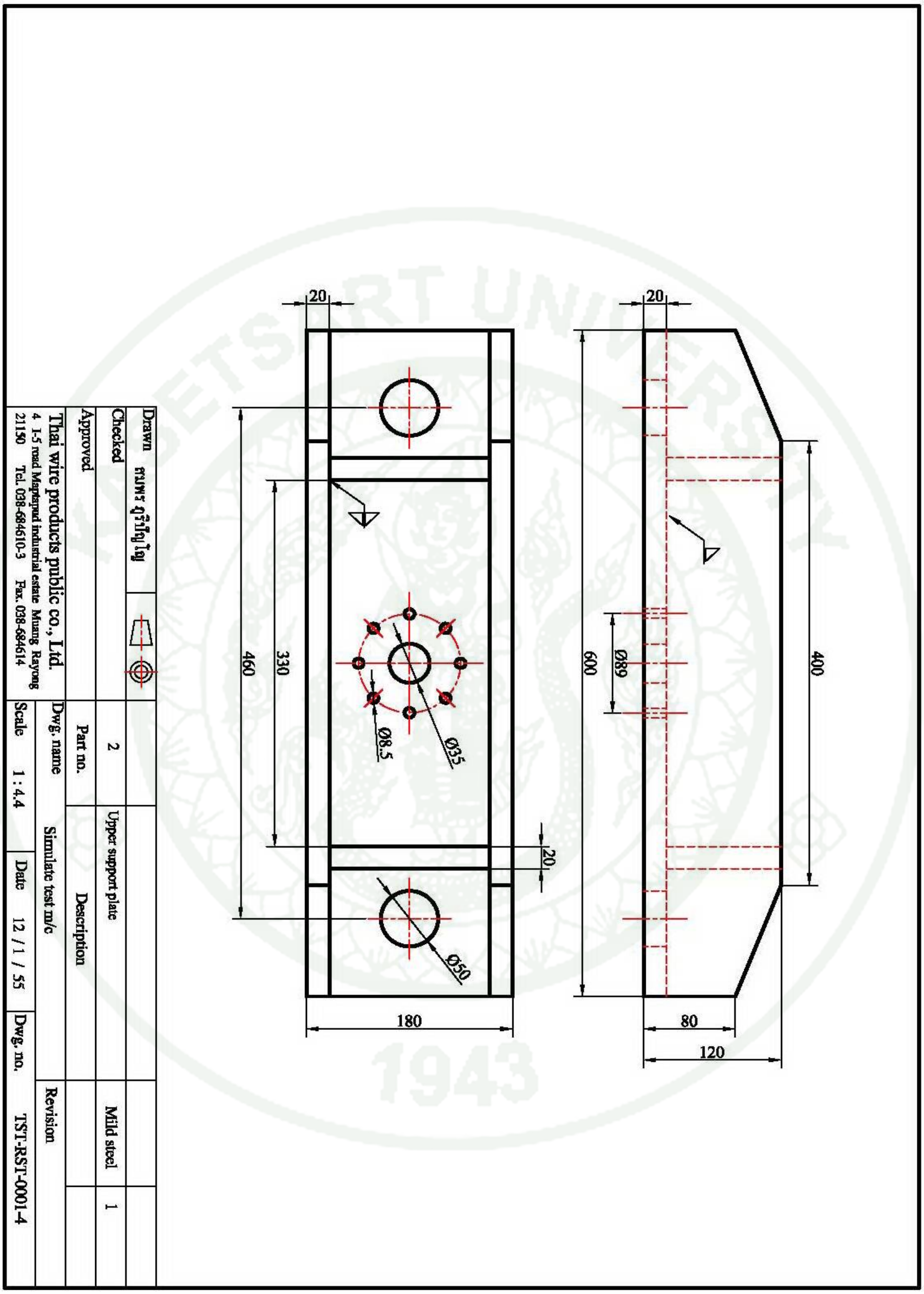

**Appendix Figure E2** Blueprint of the experimental stress relief unit

| | | | |
|---|---|---|---|
| 34 | Joint load cell | 1.6582 | 1 |
| 30 | AC Motor 3.7 Kw. 1430 rpm. | Standard | 1 |
| 29 | Reduce gear 1:10 | Standard | 1 |
| 28 | Reduce gear 1:60 | Standard | 1 |
| 27 | Bearing 51313 | FAG | 2 |
| 26 | Bearing 6013 2RS | SKF | 1 |
| 21 | Seal cover | Mild steel | 1 |
| 18 | Column clamp | Mild steel | 1 |
| 17 | Adjust pin heater | Mild steel | 1 |
| 16 | Heater clamp | Mild steel | 1 |
| 15 | Heater 4 Kw. 220 V. | - | 1 |
| 13 | Spacer Ø 60*8 | Mild steel | 4 |
| 10 | Shaft lock | scm4 | 1 |
| 9 | Screw lock load cell | 1.6582 | 1 |
| 8 | Load cell Interface 50 Kn. | Standard | 1 |
| 7 | Load fixture | 1.6582 | 2 |
| 6 | Pull nut S60*4 | 1.6582 | 1 |
| 5 | Shaft screw S 60*4 | 1.6582 | 1 |
| 4 | Housing shaft bearing | scm4 | 1 |
| 3 | Column | Mild steel | 2 |
| 2 | Upper support plate | Mild steel | 1 |
| 1 | Lower support plate | Mild steel | 1 |

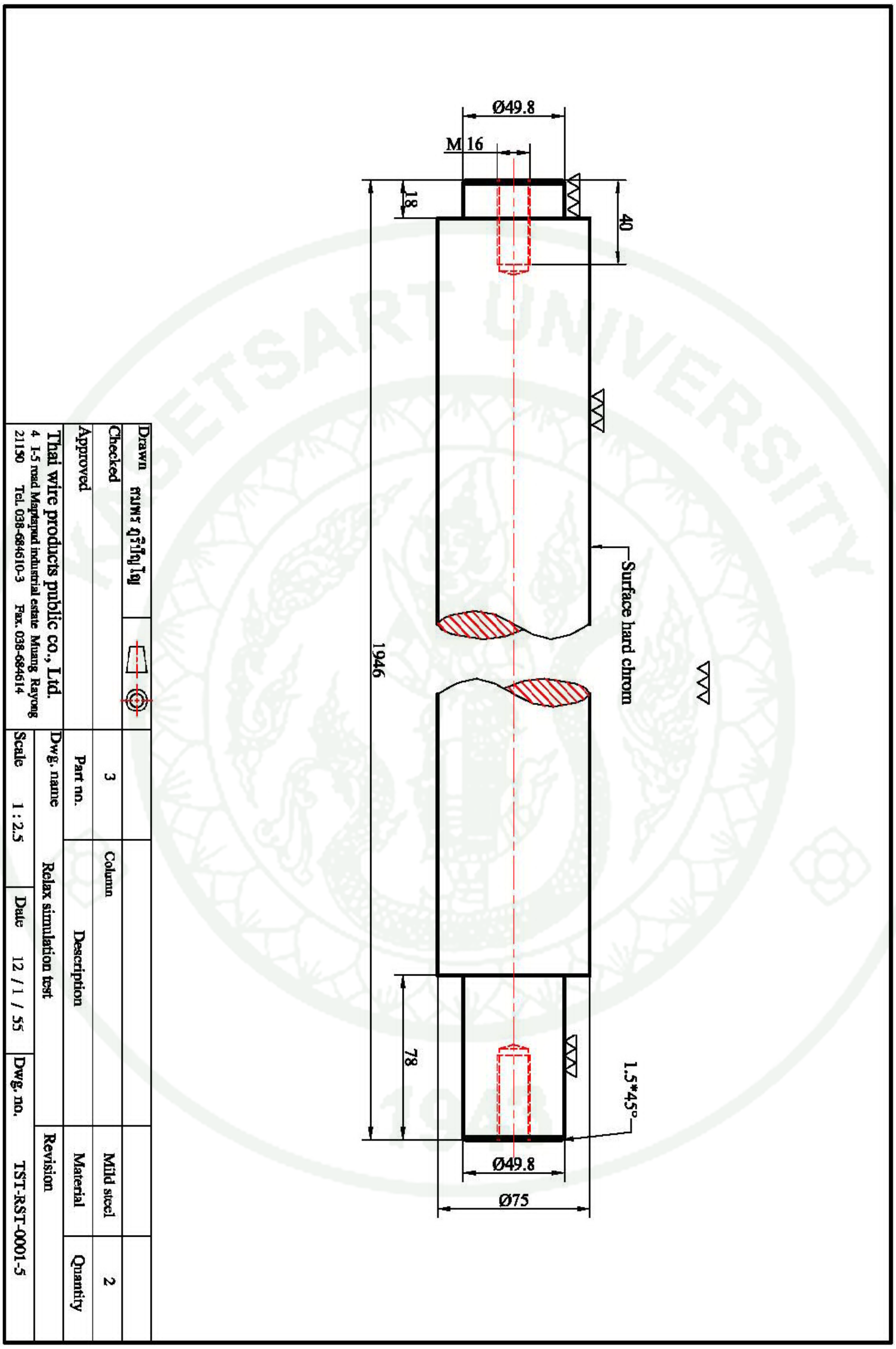
**Appendix Figure E3** List of numbered parts



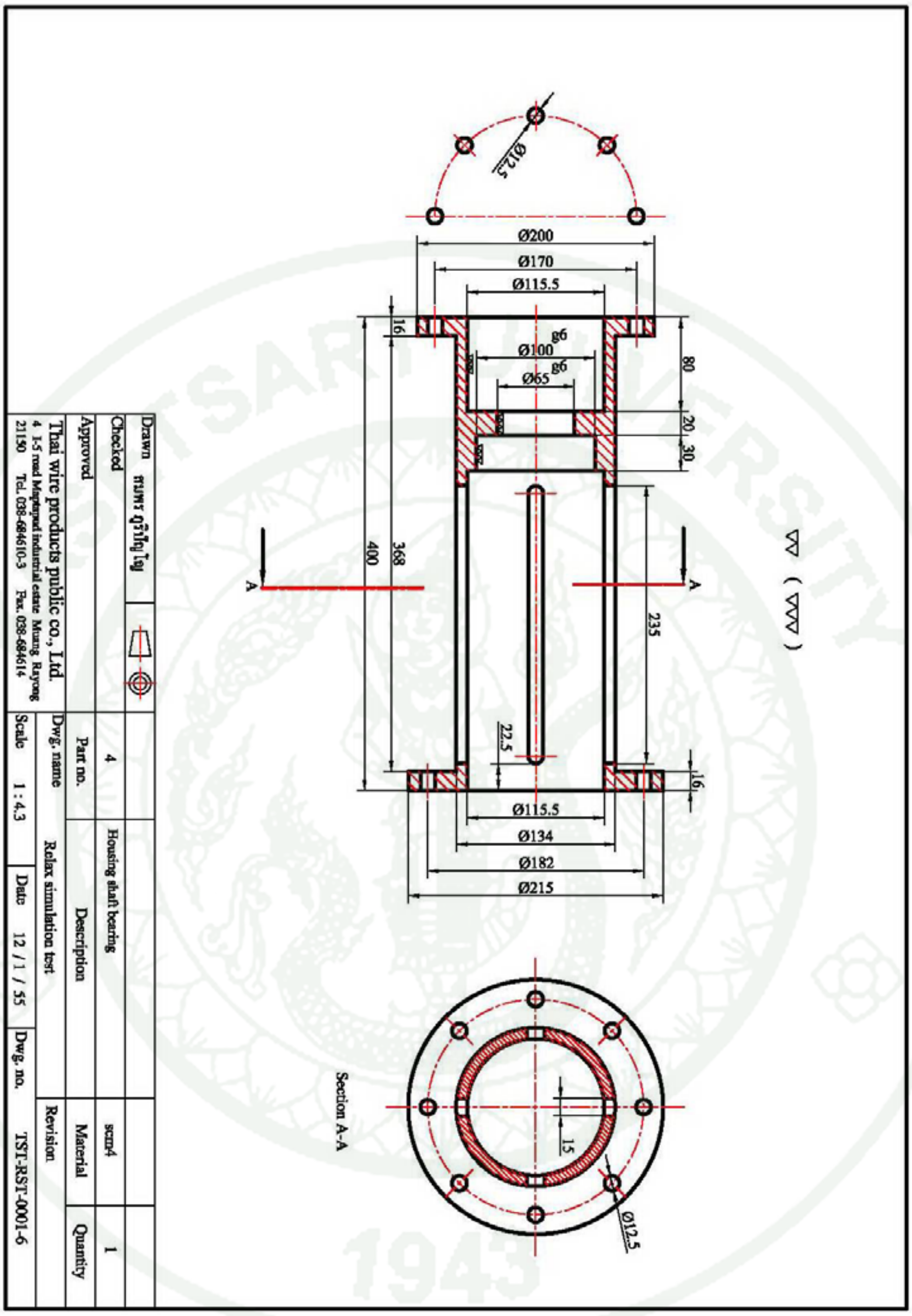

**Appendix Figure E4** Breakdown of parts (1) - lower support plate



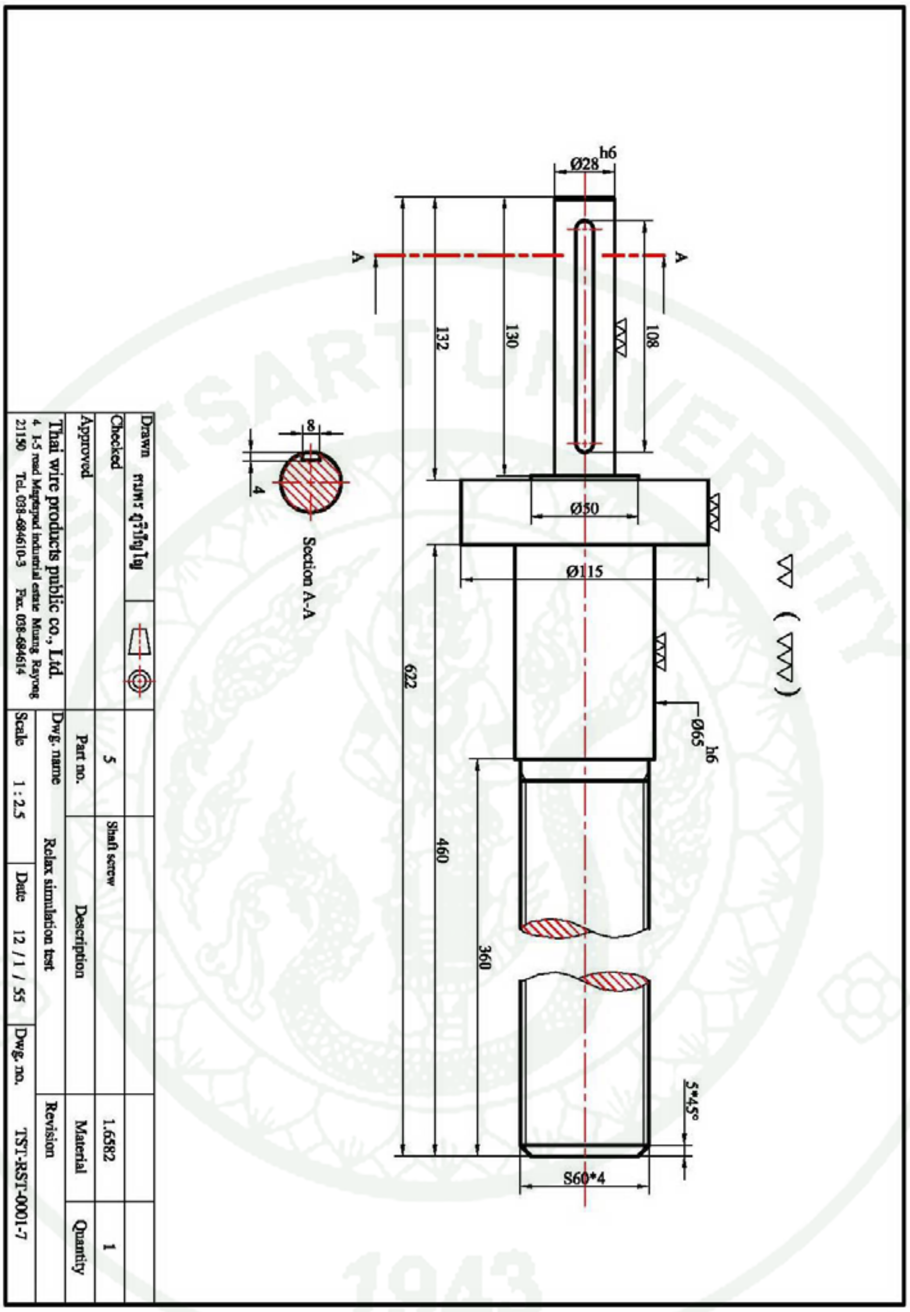

**Appendix Figure E5** Breakdown of parts (2) - upper support plate



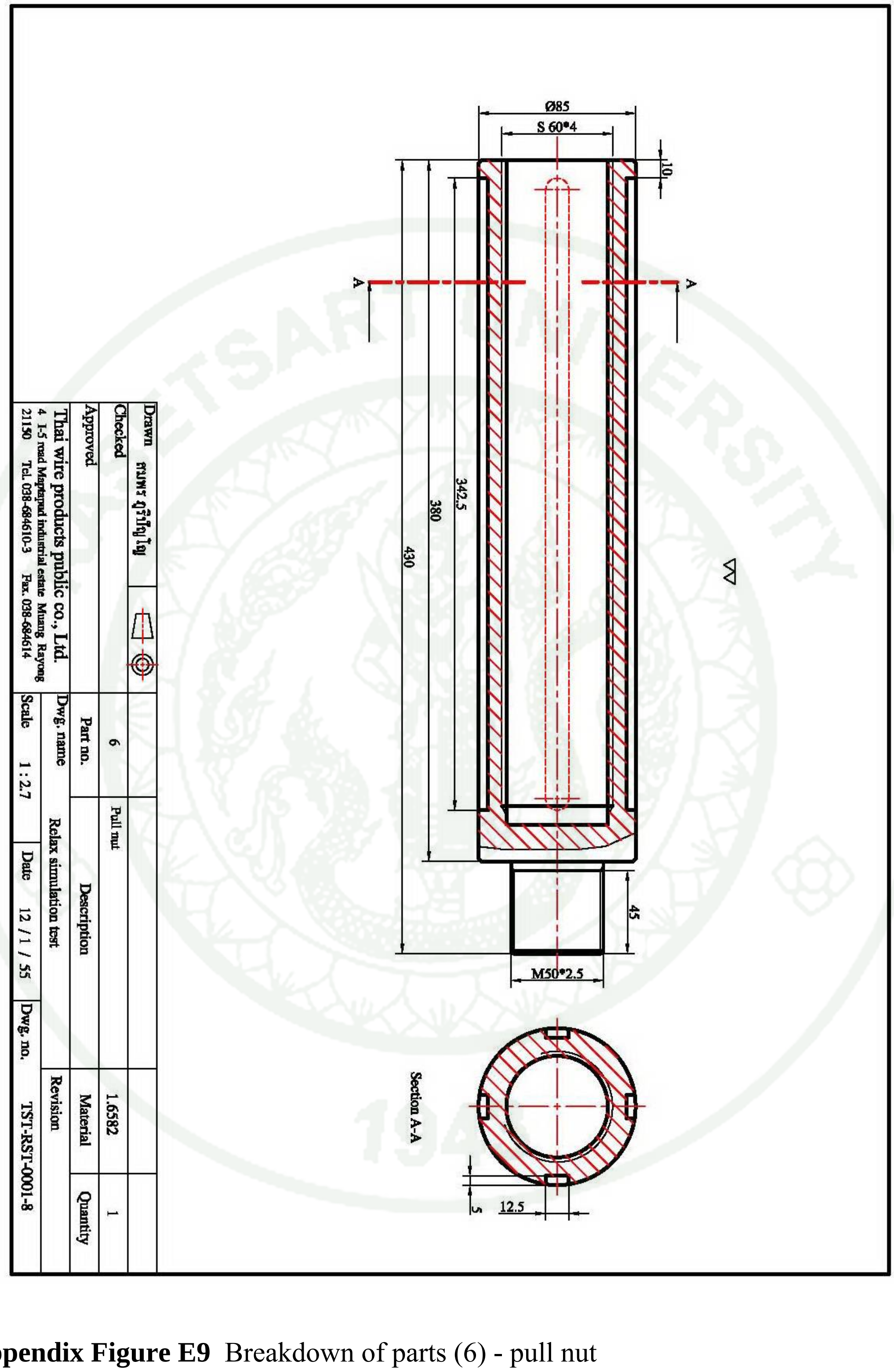

**Appendix Figure E6** Breakdown of parts (3) - column



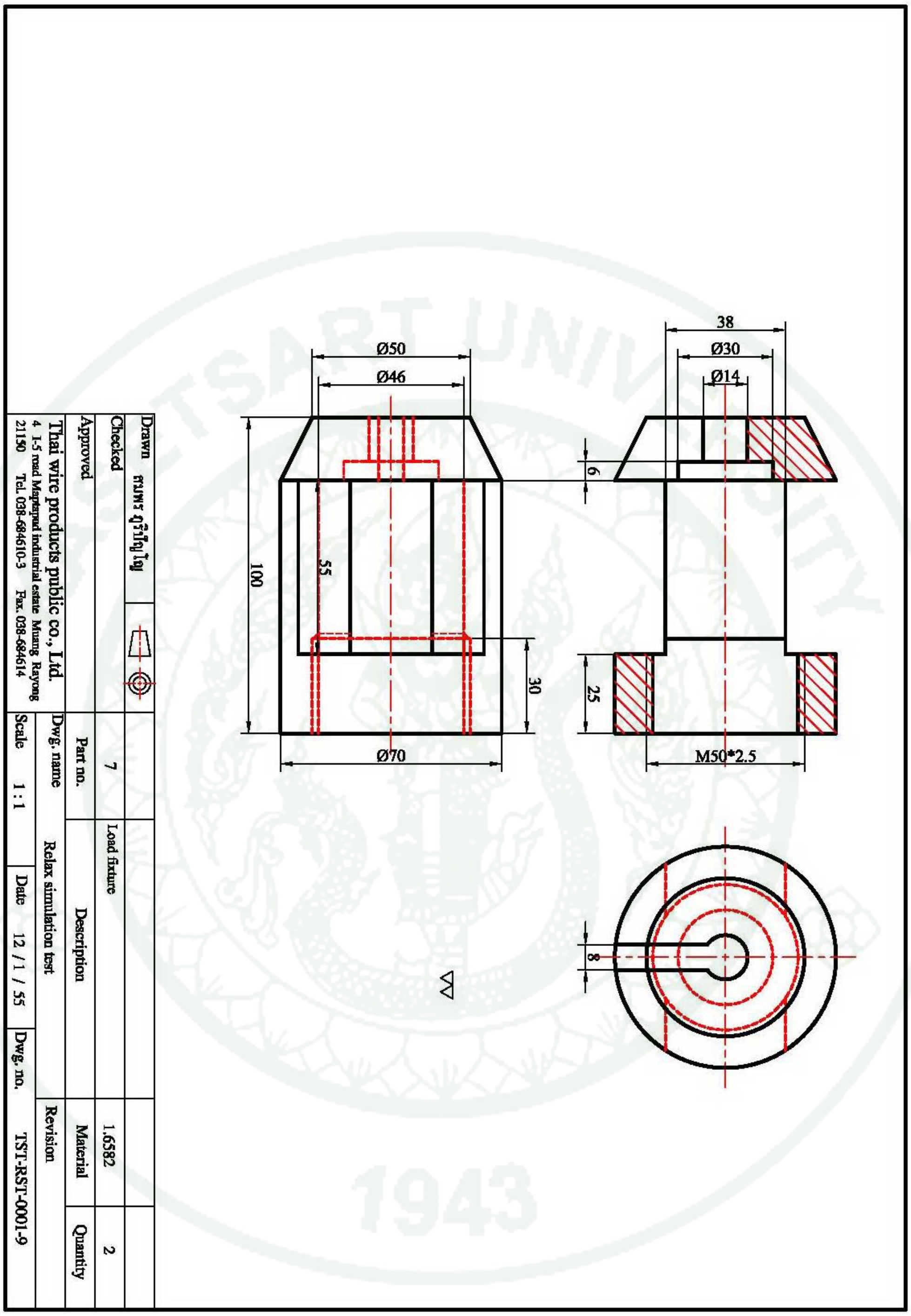

**Appendix Figure E7** Breakdown of parts (4) - housing shaft bearing



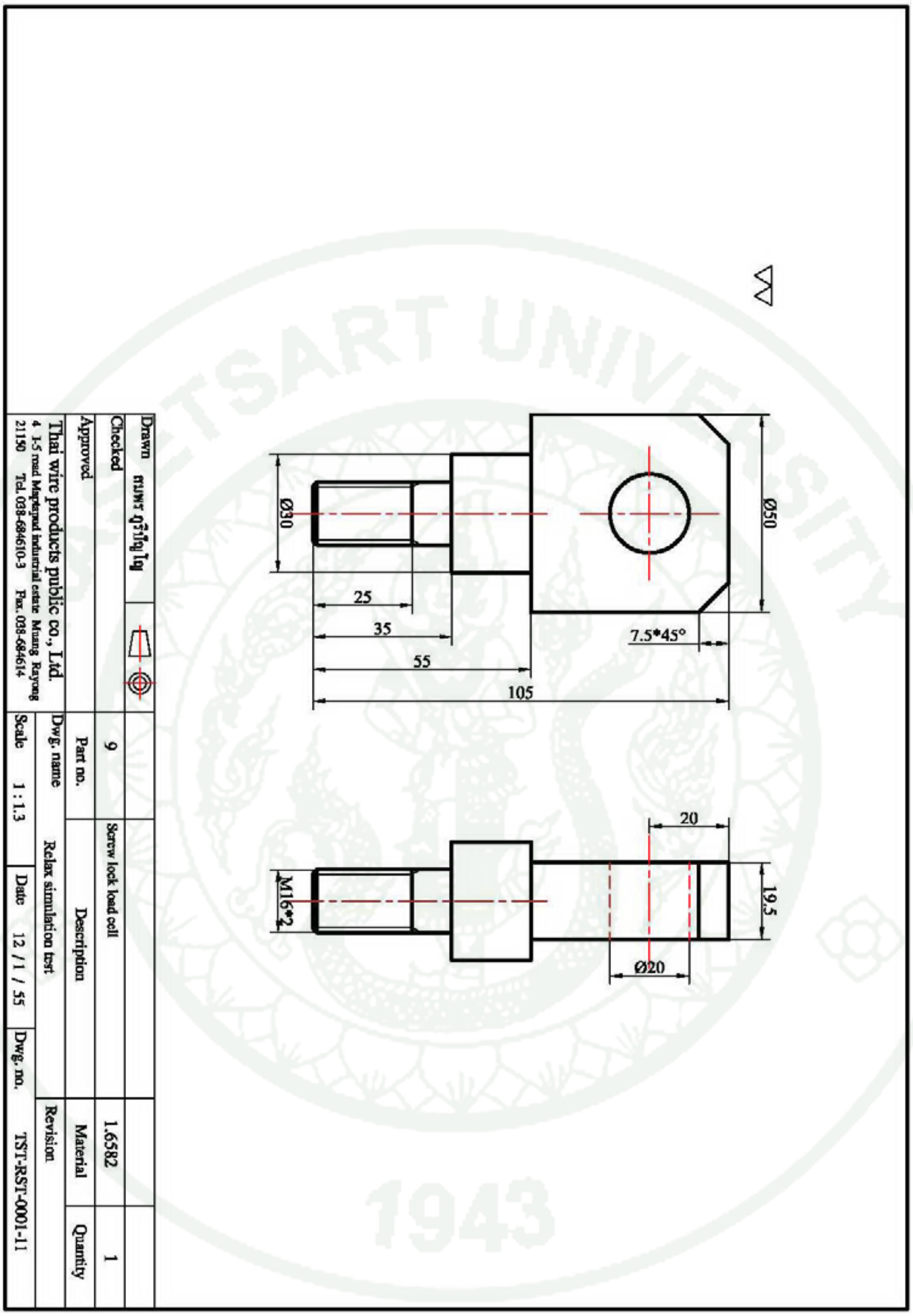

**Appendix Figure E8** Breakdown of Parts (5) - shaft screw



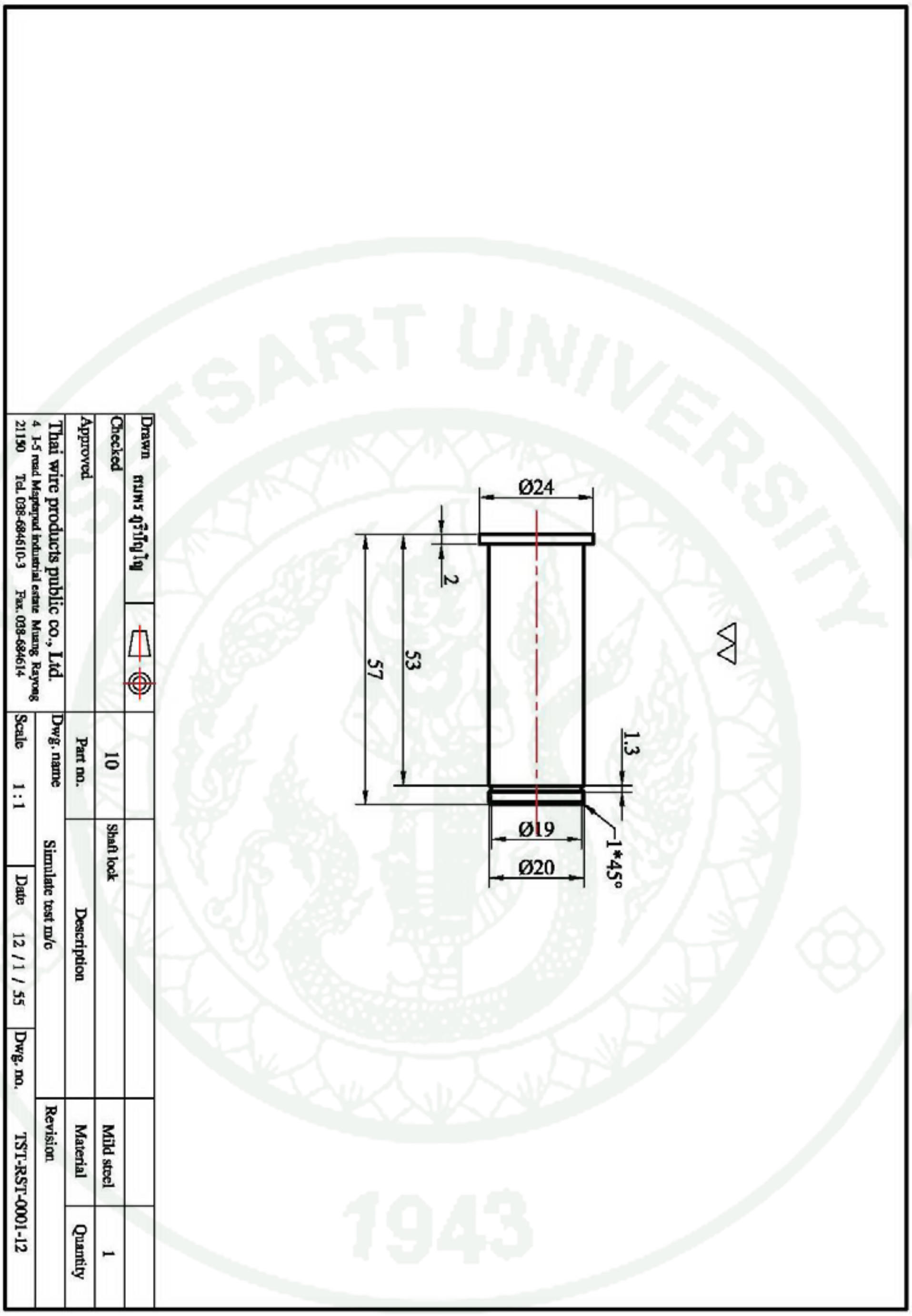

**Appendix Figure E9** Breakdown of parts (6) - pull nut



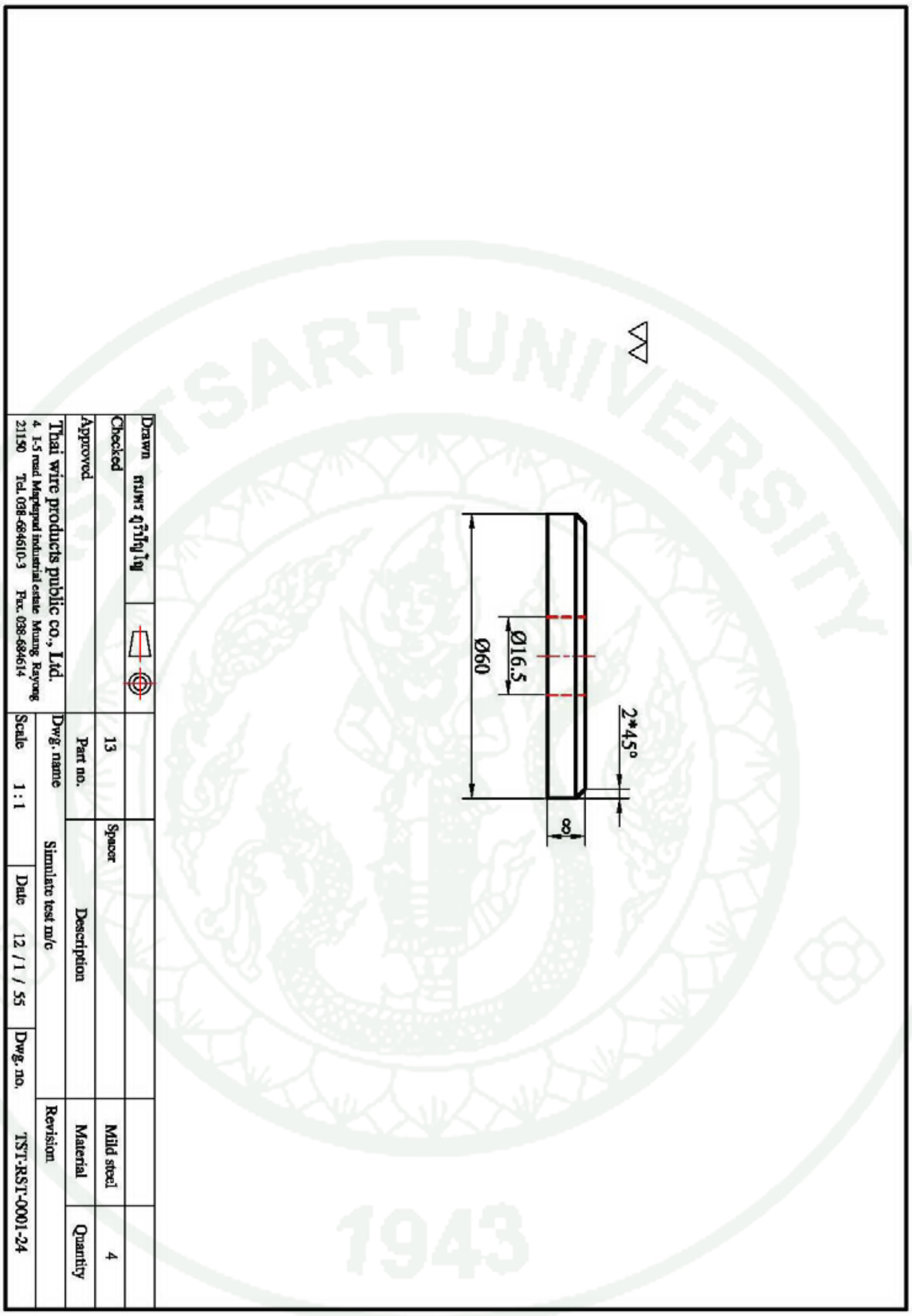

**Appendix Figure E10** Breakdown of parts (7) - load fixture



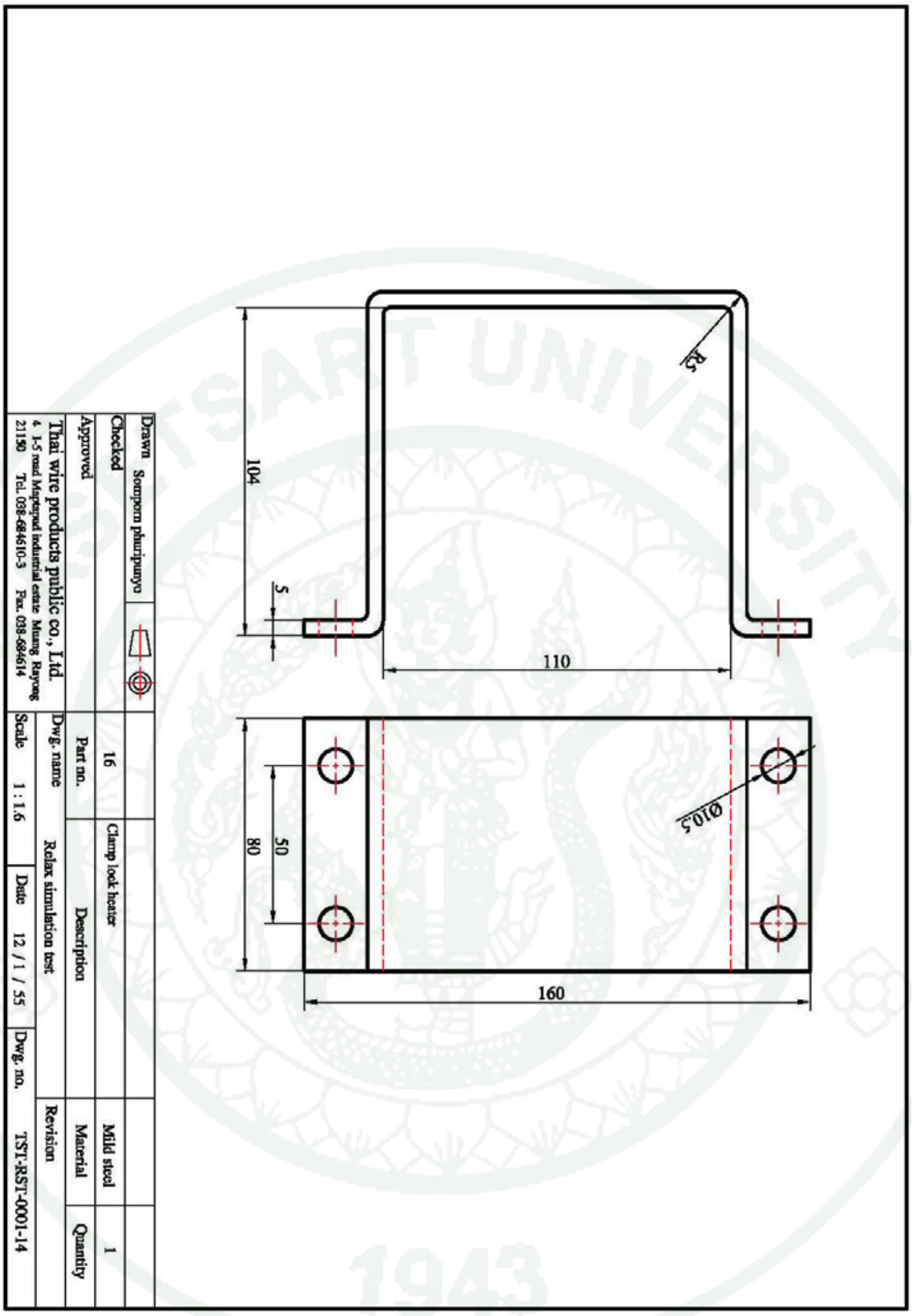

**Appendix Figure E11** Breakdown of parts (9) - screw lock load cell



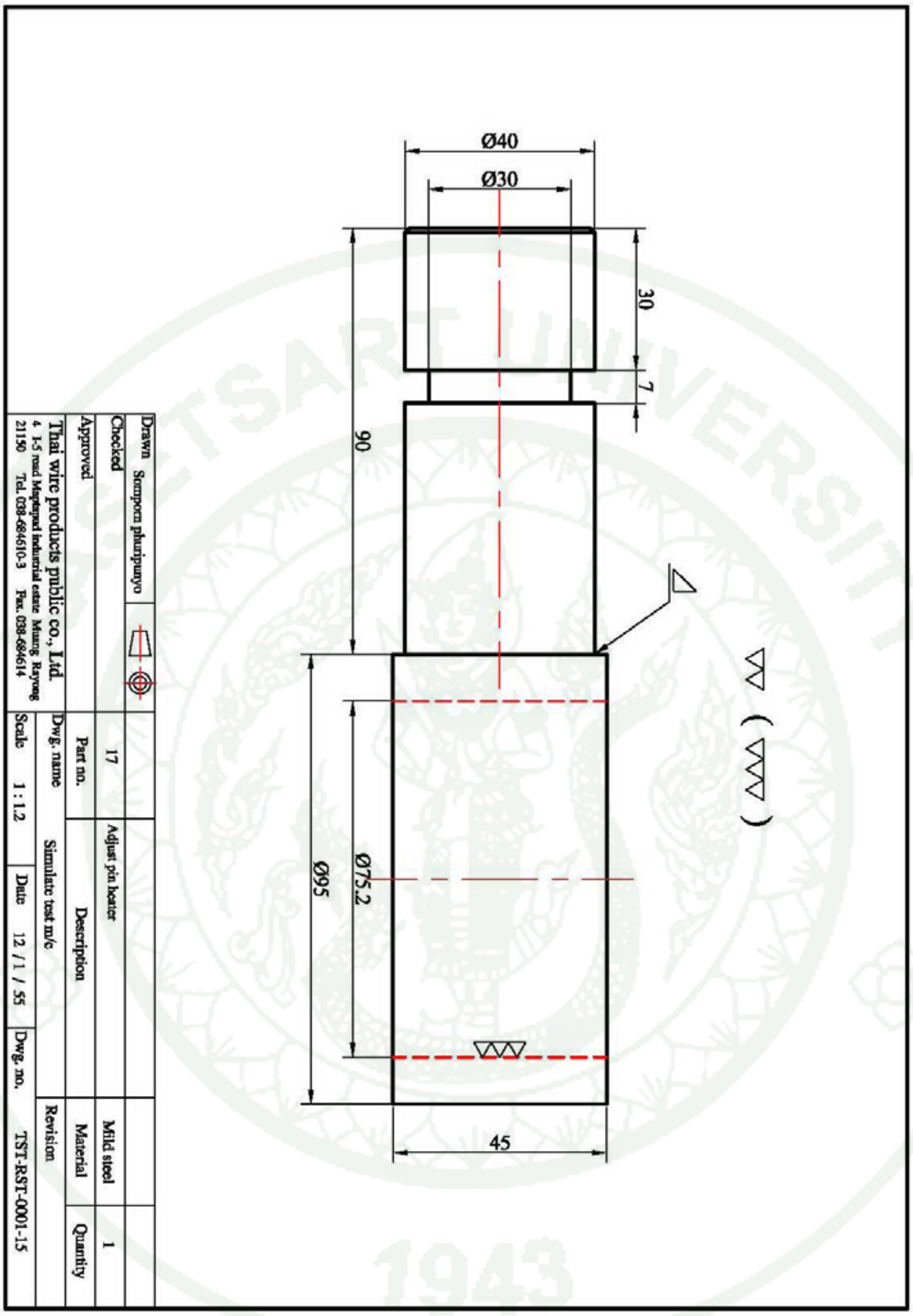

**Appendix Figure E12** Breakdown of parts (10) - shaft lock



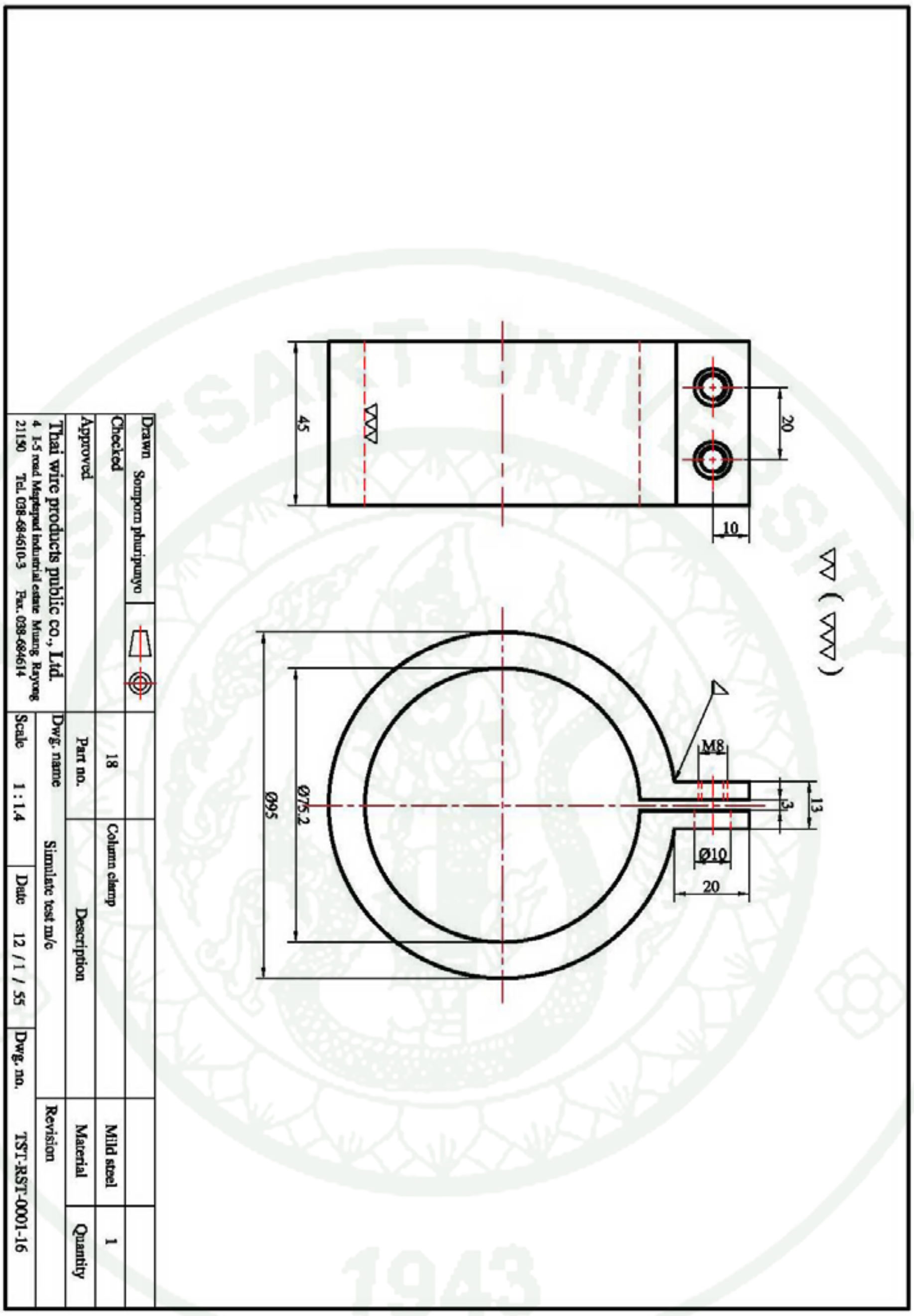

**Appendix Figure E13** Breakdown of parts (13) - spacer



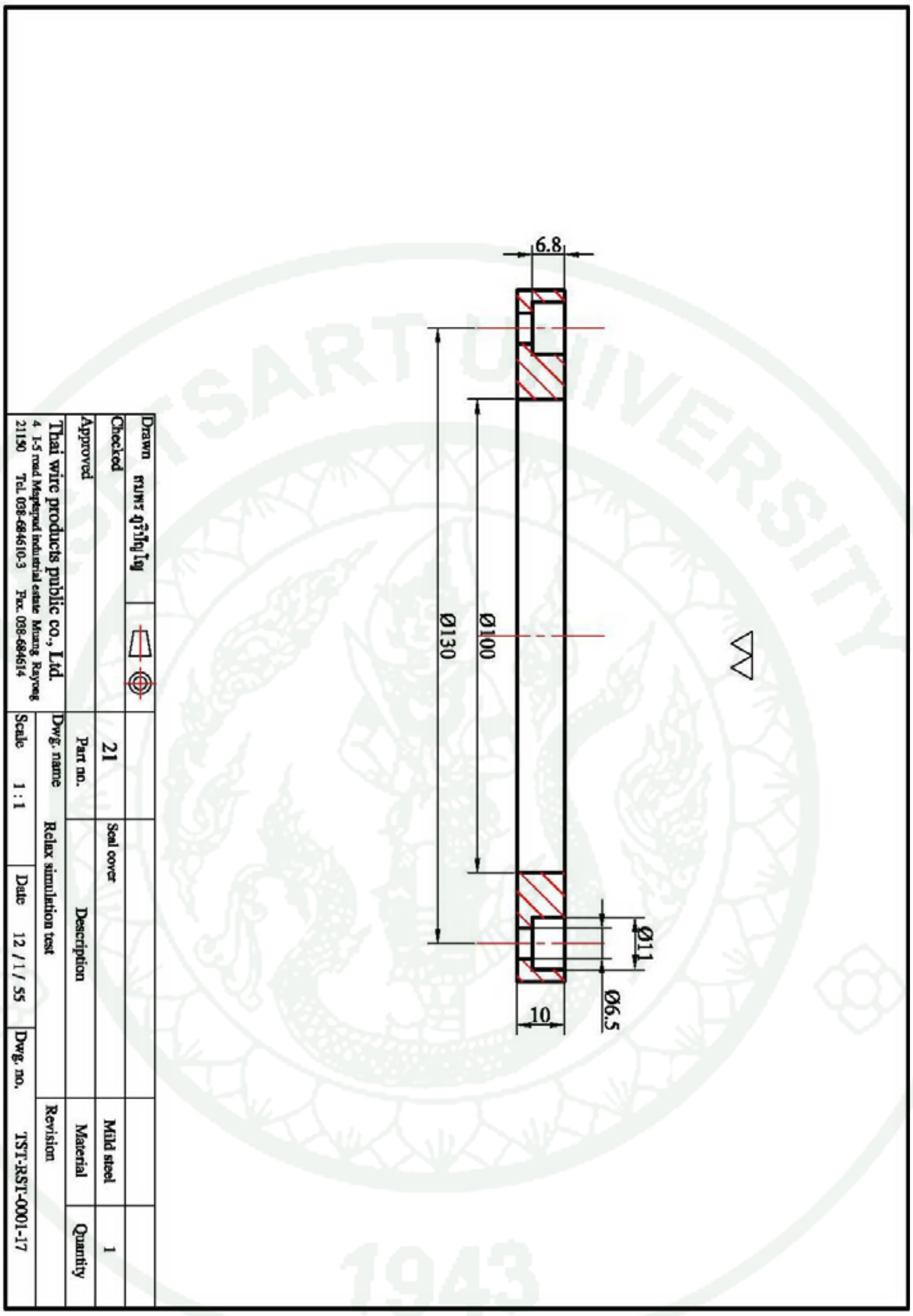

**Appendix Figure E14** Breakdown of parts (16) - heater clamp



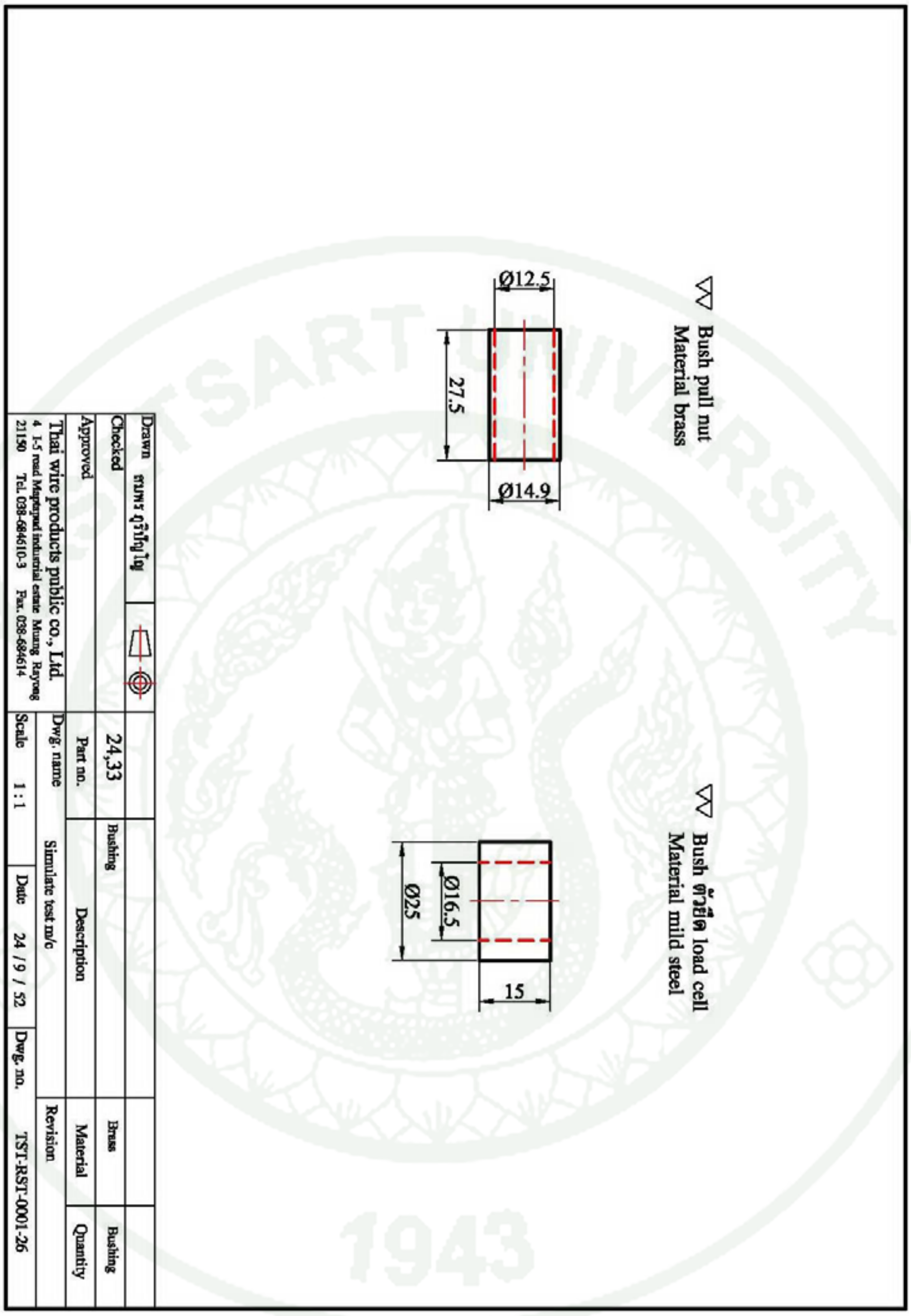

**Appendix Figure E15** Breakdown of parts (17) - adjust pin heater



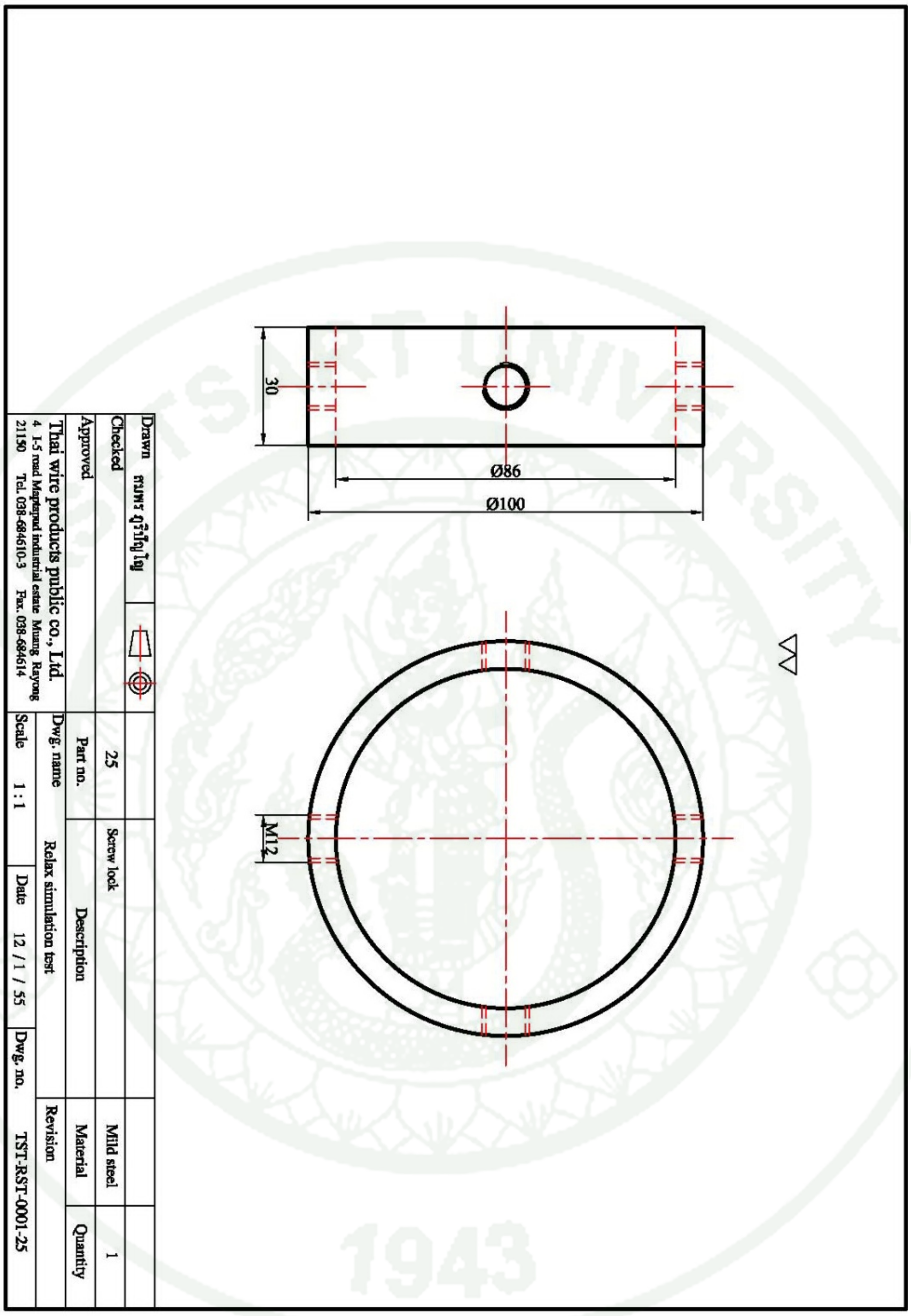

**Appendix Figure E16** Breakdown of parts (18) - column clamp



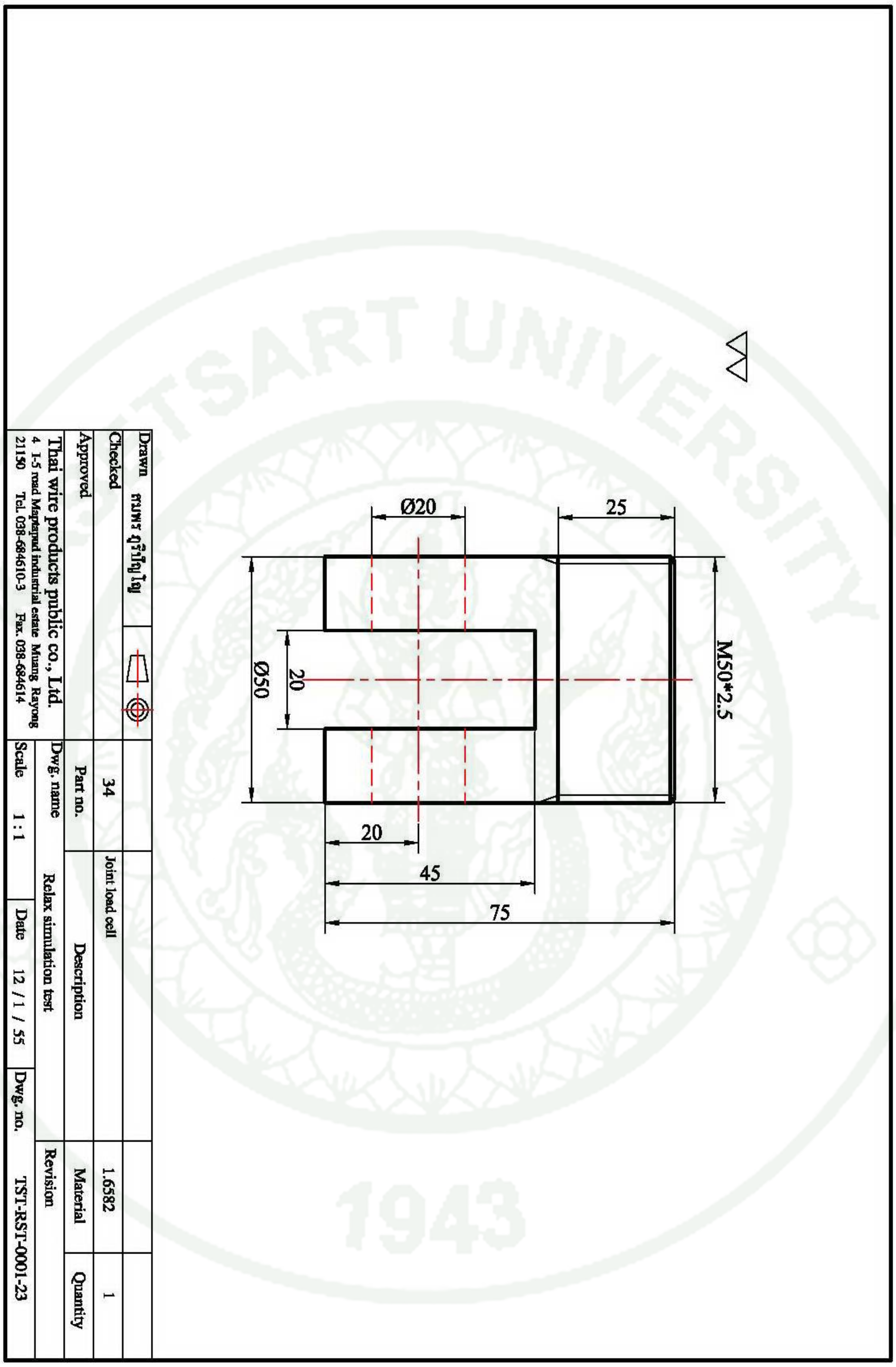

**Appendix Figure E17** Breakdown of parts (21) - seal cover




**Appendix Figure E18** Breakdown of parts (24, 33) - bushing




**Appendix Figure E19** Breakdown of parts (25) - screw lock




**Appendix Figure E20** Breakdown of parts (34) - joint load cell

**Appendix F**

Verification of the Experimental Stress Relief Unit

## Verification of the Experimental Stress Relief Unit

Having constructed an experimental stress relief unit for the purposes of this research project, it is necessary to verify that both the production unit and the experimental unit are equivalent in terms of performance. The treatment parameters of temperature and tension should be the same using both units. This is achieved by subjecting both units to statistical T-testing.

### 1. T-test for Temperature

The temperature settings of both units are independently tested to provide the data shown in Appendix Table F1 below.

**Appendix Table F1** Temperature observations

| Observation Number | Production line temperature | Stress reliefe unit temperature |
|---|---|---|
| 1 | 355 | 354 |
| 2 | 354 | 355 |
| 3 | 354 | 353 |
| 4 | 353 | 352 |
| 5 | 403 | 403 |
| 6 | 400 | 402 |
| 7 | 401 | 402 |
| 8 | 402 | 403 |

The temperature data is then be subjected to statistical T-testing to confirm the equivalence of both units as shown in appendix table F2.

**Appendix Table F2** T-test for temperature

Two-sample T for Production line temperature vs Stress relief unit temperature

| | N | Mean | St Dev | SE Mean |
|---|---|---|---|---|
| Production line temp | 8 | 376.3 | 27.0 | 9.6 |
| Stress relive unit temp | 8 | 376.8 | 27.3 | 9.6 |

Difference = mu(Production line temp)- mu(Stress relive unit temp)
Estimate for difference: -0.5
95% CI for difference: (-29.8, 28.8)
T-Test of difference = 0(vs not=): T-Value = -0.04 P-Value = 0.971 DF = 13

Because the p-value is more than 0.05, the null hypothesis cannot be rejected and we can conclude that the mean temperature of the production line unit is equivalent to that of the experimental unit.

**2. T-test for Tension**

The tension settings of both units are independently tested to provide the data shown in Appendix Table F3 below.

**Appendix Table F3** Tension observations

| Observation Number | Production Line tension (kgf) | Stress Relief Unit tension (kgf) |
|---|---|---|
| 1 | 2300 | 2301 |
| 2 | 2301 | 2301 |
| 3 | 2300 | 2302 |
| 4 | 2301 | 2303 |
| 5 | 1200 | 1200 |
| 6 | 1200 | 1201 |
| 7 | 1202 | 1203 |
| 8 | 1201 | 1202 |

The tension data is then be subjected to statistical T-testing to confirm the equivalence of both units as shown in appendix table F4.

**Appendix Table F4** T-test for tension

Two-sample Test for Production line tension vs Stress relive unit tension

| | N | Mean | St Dev | SE Mean |
|---|---|---|---|---|
| Production line | 8 | 1751 | 588 | 208 |
| Stress relive unit | 8 | 1752 | 588 | 208 |

Difference = mu (Production line tension) - mu (Stress relive unit tension)
Estimate for difference: -1
95% CI for difference: (-636, 634)
T-Test of difference = 0(vs not =): T-Value = -0.00 P-Value = 0.997 DF = 13

Because the p-value is more than 0.05, the null hypothesis cannot be rejected and we can conclude that the mean tension of the production line unit is equivalent to that of the experimental unit.

**Appendix G**

Investigation of the Microstructure

TISTR

## MATERIAL PROPERTIES ANALYSIS AND DEVELOPMENT CENTRE (MPAD)

**Request No. :** MAL 1455/54

**Date :** 3 October 2011

**Date of request :** 29 September 2011

**Page :** 1 of 6

### REPORT ON ANALYSIS / TESTING

**For**

**Thai Wire Products Public Company Limited**
**4 I-5 Road, Maptaphud Industrial Estate, T. Maptaphud A. Muang Rayong 21150**

**Testing/analysis/investigation of :** SG005700-0014-T390-45-250, SG005700-0013-T375-45-250, and SG005700-0012-T350-45-250

**Method of testing/analysis/investigation :** Microstructure analysis according to ASM Handbook Vol. 9-2004 and Hardness test (HV10) according to ASTM E 384-10$^{\varepsilon_2}$

**Result of testing/analysis/investigation :**

The test results are attached.

**Tested/analyzed/investigated by**

1. Preecha K.
2. ..........
3. ..........
4. ..........

**Approved by**

S. Poo...

(Sumate Poomiapiradee, Ph. D.)
Director of Material Property Analysis Laboratory

TISTR

**Examined by**

P. Thapnuy
(Mrs. Pachanee Thapnuy)

**This report contains 6 pages.**

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**Remark :** The above results are valid exclusively for tested/analysed samples as mentioned in this report. Publication of the results on testing and analysis is prohibited unless written permission is obtained from the governor of TISTR

Thailand Institute of Scientific and Technological Research
35 Moo 3, Technopolis Tambol Klong 5 Amphoe Khlong Luang Pathum Thani 12120 Thailand
Tel. (66) 0 2577 9000 Fax 0 2577 9009
E-mail : tistr@tistr.or.th Website : www.tistr.or.th

TISTR

**MATERIAL PROPERTIES ANALYSIS AND DEVELOPMENT CENTRE (MPAD)**
**MATERIAL PROPERTY ANALYSIS LABORATORY (MAL)**

**Request No. :** MAL 1455/54 **Date :** 3 October 2011

**REPORT**

**Customer:** Thai Wire Products Public Company Limited **Page :** 2 of 6

Thai Wire Products Public Company Limited has commissioned the Material Properties Analysis and Development Centre, Thailand Institute of Scientific and Technological Research (MPAD/TISTR) to carry out microstructure analysis, and hardness test (HV10) of the specimens of SG005700-0014-T390-45-250, SG005700-0013-T375-45-250, and SG005700-0012-T350-45-250.

The results are as follows:

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35 Moo 3, Technopolis Tambol Klong 5 Amphoe Khlong Luang Pathum Thani 12120 Thailand
Tel. (66) 0 2577 9000 Fax 0 2577 9009
E-mail : tistr@tistr.or.th Website : www.tistr.or.th

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**MATERIAL PROPERTIES ANALYSIS AND DEVELOPMENT CENTRE (MPAD)**

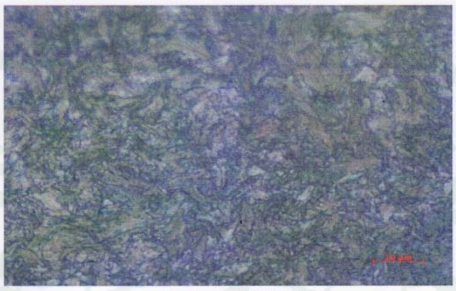
**MATERIAL PROPERTY ANALYSIS LABORATORY (MAL)**

**Request No. :** MAL 1455/54 **Date :** 3 October 2011

**REPORT**

**Customer:** Thai Wire Products Public Company Limited **Page :** 3 of 6

**Analysis date :** 30 September 2011



≈ 1000X

Etchant : 3% Nital

Fig. 1 Microstructure of a cross-section of the specimen of SG005700-0014-T390-45-250 shows

- Patented structure : Pearlite.

≈ 1000X

Etchant : 3% Nital

Fig. 2 Microstructure of a longitudinal section of the specimen of SG005700-0014-T390-45-250 shows

- Patented structure : Stretched pearlite.

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35 Moo 3, Technopolis Tambol Klong 5 Amphoe Khlong Luang Pathum Thani 12120 Thailand
Tel. (66) 0 2577 9000 Fax 0 2577 9009
E-mail : tistr@tistr.or.th Website : www.tistr.or.th

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**MATERIAL PROPERTIES ANALYSIS AND DEVELOPMENT CENTRE (MPAD)**

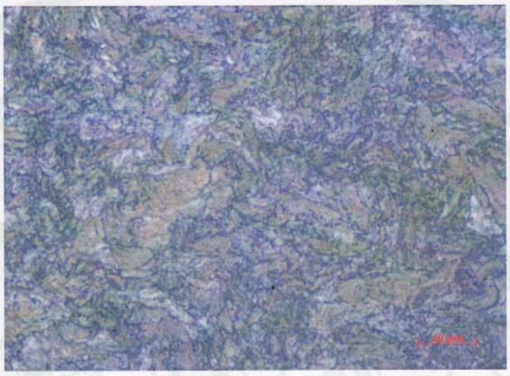
**MATERIAL PROPERTY ANALYSIS LABORATORY (MAL)**

**Request No. :** MAL 1455/54 **Date :** 3 October 2011

**REPORT**

**Customer:** Thai Wire Products Public Company Limited **Page :** 4 of 6

**Analysis date :** 30 September 2011

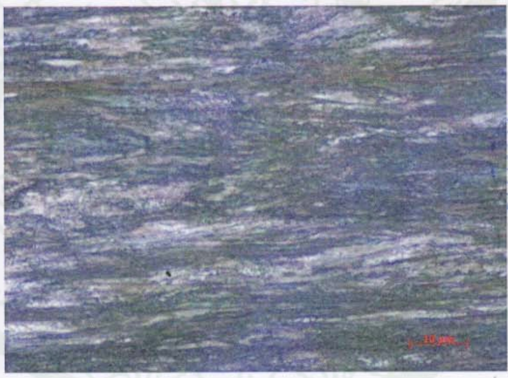


≈ 1000X

Etchant : 3% Nital

Fig. 3 Microstructure of a cross-section of the specimen of SG005700-0013-T375-45-250 shows

- Patented structure : pearlite.



≈ 1000X

Etchant : 3% Nital

Fig. 4 Microstructure of a longitudinal section of the specimen of SG005700-0013-T375-45-250 shows

- Patented structure : Stretched pearlite.

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35 Moo 3, Technopolis Tambol Klong 5 Amphoe Khlong Luang Pathum Thani 12120 Thailand
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E-mail : tistr@tistr.or.th Website : www.tistr.or.th

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**MATERIAL PROPERTIES ANALYSIS AND DEVELOPMENT CENTRE (MPAD)**

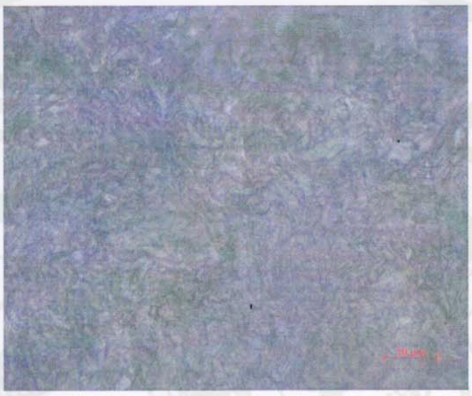
**MATERIAL PROPERTY ANALYSIS LABORATORY (MAL)**

**Request No. :** MAL 1455/54 **Date :** 3 October 2011

**REPORT**

**Customer:** Thai Wire Products Public Company Limited **Page :** 5 of 6

**Analysis date :** 30 September 2011



≈ 1000X

Etchant : 3% Nital

Fig. 5 Microstructure of a cross-section of the specimen of SG005700-0012-T350-45-250 shows

- Patented structure : pearlite.

≈ 1000X

Etchant : 3% Nital

Fig. 6 Microstructure of a longitudinal section of the specimen of SG005700-0012-T350-45-250 shows

- Patented structure : Stretched pearlite.

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35 Moo 3, Technopolis Tambol Klong 5 Amphoe Khlong Luang Pathum Thani 12120 Thailand
Tel. (66) 0 2577 9000 Fax 0 2577 9009
E-mail : tistr@tistr.or.th Website : www.tistr.or.th

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**MATERIAL PROPERTIES ANALYSIS AND DEVELOPMENT CENTRE (MPAD)**

**MATERIAL PROPERTY ANALYSIS LABORATORY (MAL)**

**Request No. :** MAL 1455/54 **Date :** 3 October 2011

**REPORT**

**Customer:** Thai Wire Products Public Company Limited **Page :** 6 of 6

**Test date :** 30 September 2011

**Hardness survey location of**

**SG005700-0014-T390-45-250, SG005700-0013-T375-45-250, and SG005700-0012-T350-45-250.**


**Cross-section** **Longitudinal section**

**The results of Vickers hardness test (HV10) of**

**SG005700-0014-T390-45-250, SG005700-0013-T375-45-250, and SG005700-0012-T350-45-250.**

| Sample \ Test point | | 1 | 2 | 3 |
|---|---|---|---|---|
| SG005700-0014-T390-45-250 | cross-section | 508 | 498 | 508 |
| | longitudinal section | 503 | 508 | 508 |
| SG005700-0013-T375-45-250 | cross-section | 514 | 498 | 503 |
| | longitudinal section | 508 | 503 | 508 |
| SG005700-0012-T350-45-250 | cross-section | 508 | 498 | 503 |
| | longitudinal section | 508 | 514 | 503 |

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35 Moo 3, Technopolis Tambol Klong 5 Amphoe Khlong Luang Pathum Thani 12120 Thailand
Tel. (66) 0 2577 9000 Fax 0 2577 9009
E-mail : tistr@tistr.or.th Website : www.tistr.or.th

# CURRICULUM VITAE

**NAME** : Mr. Dan Tong-in

**BIRTH DATE** : January 22, 1956

**BIRTH PLACE** : Bangkok, Thailand

**EDUCATION** :

| YEAR | INSTITUTE | DEGREE/DIPLOMA |
|---|---|---|
| 1978 | King Mongkut's of Technology North | B.S. (Mechanical Engineering) |
| 1988 | King Mongkut's of Technology North | M.S. (Mechanical Engineering) |

**POSITION/TITLE** : Plant Manager
**WORK PLACE** : Thai Wire Products Public Company Limited
**POSITION/TITLE** : President
**WORK PLACE** : Mahamitr Engineering Company Limited
**PRESENTATIONS** : The effect of stress relieving treatment condition on the quality of pressed concrete wire International Conference. 2009 Finland.
: Oral presentation “Using DOE to reduce costs and improve the quality of pre-stressed concrete wire in the manufacturing process” 2007. Republic of Slovenia.