THE EFFECT OF HEAT TREATMENT ON MECHANICAL PROPERTIES OF SPRING STEEL

by

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ABSTRACT

THE EFFECT OF HEAT TREATMENT ON MECHANICAL PROPERTIES OF SPRING STEEL

Springs are mechanical elements that exert forces or torques and absorb energy. The absorbed energy is usually stored and later released. Steel springs are made in many types, shapes, and sizes, ranging from delicate hair-springs for instrument meters to massive barrel springs for railroad equipment. In the automotive industry springs are used in many applications. DIN 50CrV4 or AISI 6150 spring steel is widely used as a spring material in this industry. It is a high-carbon chromium-vanadium alloy steel which has been used for numerous applications including premium quality springs. Also, microalloying is applied to 50CrV4 to improve its mechanical properties. In present study, the effect of heat treatment on mechanical properties of spring steel was investigated. Two different 50CrV4 alloys, one is microalloyed with Ti, were austenitized at 910 °C, then oil quenched. Finally, they were tempered at two different tempering temperatures, 410 °C and 440 °C. Their microstructures, and mechanical properties such as hardness, tensile, impact, and fatigue properties were determined and compared. From the specimens, fully tempered-martensitic microstructures were obtained having hardness values range from 460 to 497 HB. Their tensile strengths range from 1585 to 1696 MPa while their fatigue limits range from 870 to 950 MPa. Fatigue tests were performed on a specially set rotating bending fatigue test machine. As a result of the impact test, it was found out that all the specimens were very brittle. Moreover, when we examined the fracture appearance of the impact test specimens, the increase in cleavage area in both two steel alloys could be observed by the decrease in tempering temperature.

ÖZET

ISIL İŞLEMİN YAY ÇELİĞİNİN MEKANİK ÖZELLİKLERİ ÜZERİNDEKİ ETKİLERİ

Yaylar, kuvvet ve tork uygulayan, enerjiyi soğuran mekanik elemanlardır. Absorve edilen enerji genellikle depolanır ve daha sonra salıverilir. İncecik bir saç yayından yapılan gösterge sayacından, demiryolu ekipmanında kullanılan dev varil yaylara kadar uzanan bir yelpazede çelik yaylar, çeşitli tip, şekil ve boyutlarda imal edilirler. Yaylar otomotiv endüstrisinde de birçok uygulamada kullanılmaktadır. 50CrV4 yüksek karbonlu krom-vanadyum alaşımı olup bu alanda sıkça kullanılan bir yay çeliğidir. Aynı zamanda, bu çeliğin mekanik özelliklerini arttırmak için çeliğe mikroalaşımlama uygulanmaktadır. Bu çalışmada, ısıl işlemin yay çeliğinin mekanik özellikleri üzerindeki etkileri araştırıldı. Bir tanesi Ti mikroalaşımlı olmak üzere iki farklı 50CrV4 alaşımı 910 °C de östenitlenip yağda soğutulduktan sonra 410 °C ve 440 °C de olmak üzere iki farklı sıcaklıkta temperlendi. Isıl işlem sonrası, numunelerin mikroyapıları ve sertlik, çekme, darbe, yorulma dayanımları gibi mekanik özellikleri incelendi. Numunelerde tamamen temperlenmiş martenzitik mikroyapı elde edilirken sertlik değerleri 460 ile 497 HB arasında bulundu. Numunelerin çekme dayanımları 1585 ile 1696 MPa arasında bulunurken yorulma dayanımları da 870 ile 950 MPa arasında tespit edildi. Yorulma testleri özel olarak imal edilen dönel eğmeli yorulma testi makinasında gerçekleştirildi. Darbe testleri neticesinde, malzemelerin çok gevrek oldukları ve darbe testi numunelerinin kırık yüzeylerinden de temperleme sıcaklığının düşmesiyle parlak bölgenin arttığı gözlemlendi.

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b	Fatigue strength exponent
d	Diameter
E	Young’s modulus
F	Force
M_{max}	Maximum bending moment
M_s	Martensite start temperature
M_f	Martensite finish temperature
N	Number of cycles
R	Stress ratio
S_{a}	Stress amplitude
S'_f	Fatigue strength coefficient
S_{m}	Mean stress
S_{r}	Range of stress
t	Thickness
W_v	Elastic energy stored per unit volume
σ_f	Strength
δ	Deflection
θ	Angular deflection
ρ	Density
BHN	Brinell hardness number
CFRP	Carbon fiber reinforced polymer
GFRP	Glass fiber reinforced plastic
HSLA	High-strength, low alloy
VSQ	Valve-spring quality

1. INTRODUCTION

Springs serve to absorb and store energy and then to release it. During this cycle the stress in the spring must not exceed a certain maximum in order to avoid settling or premature failure. This consideration limits the amount of energy which can be stored in any spring [1]. Springs come in many shapes and have many purposes: one thinks of axial springs (a rubber band, for example), leaf springs, helical springs, spiral springs, torsion bars. Regardless of their shape or use, the best material for a spring of minimum volume is that with the greatest value of σ^2_f / E, and for minimum weight it is that with the greatest value of $\sigma^2_f / E\rho$ [2].

Springs are made of metal. For light loads the metal can be replaced by plastics. Some applications that require minimum spring mass use structural composite materials. Blocks of rubber can be used as springs, in bumpers and vibration isolation mountings of electric or combustion motors.

High-strength steel (spring steel, in fact) is the traditional choice for spring material. Its easily formed and heat treated. Steel springs are made in many types, shapes, and sizes, ranging from delicate hair-springs for instrument meters to massive barrel springs for railroad equipment. In the automotive industry springs are used in many applications like leaf springs. During the last two decades, considerable efforts have been made in the development of high performance spring steels to meet the needs for weight and cost savings in the automotive industry [3–5].

The basic requirement of a leaf spring steel is that the selected grade of steel must have sufficient hardenability for the size involved to ensure a fully martensitic structure throughout the entire section. Nonmartensitic transformation products detract from the fatigue properties [6].

The present study aims to analyze the influence of tempering temperature on the mechanical properties of two different 50CrV4 alloys frequently used in leaf spring applications.

2. SPRINGS

2.1. The Theory of Spring

A rigid element is a mechanical element that does not bend, deflect, or twist when an external action is exerted on it. Conversely, a flexible element is a mechanical element that changes its geometry when an external force, moment, or torque is applied. Therefore, rigidity and flexibility are terms that apply to particular situations. Deflection analysis is frequently performed in the design of, for example, transmissions, springs, or automotive suspensions. [7].

The property of a material that enables it to regain its original geometry after having been deformed is called elasticity. Springs, effectively using elasticity of materials with high elastic strain, are used to absorb abruptly applied stress, to store absorbed stress in elastic energy, or to alleviate applied impact [8].

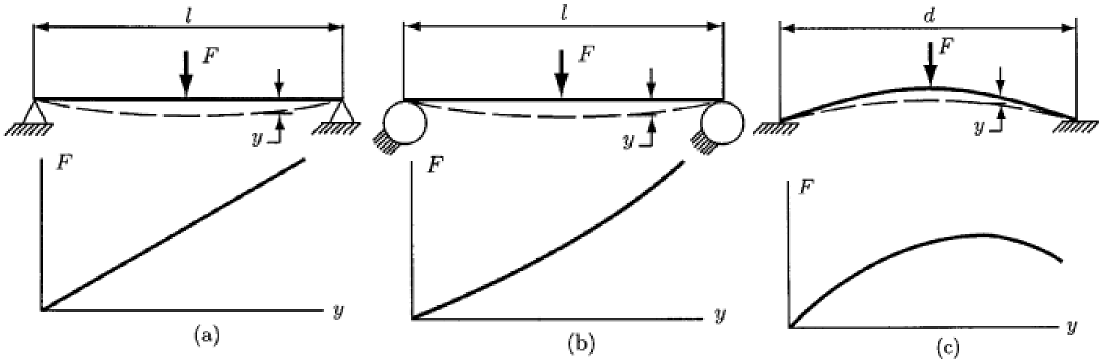


Figure 2.1. Springs. (a) Linear spring; (b) stiffening spring; (c) softening spring [7]

It is assumed that the springs are in no case stressed beyond the elastic limit (i.e., that they are perfectly elastic) and that they are subject to Hooke's law [9]. When a slender member is subjected to transverse loading, we say it acts as a beam. We can find many examples of beam action in our immediate environment. The leaf springs of an automobile suspension transfer the body weight to the axle through beam action [10]. Let us consider a straight beam of length l which is simply supported at the ends and loaded by the transversal force F (Figure 2.1a). If the elastic limit of the material is not exceeded (as indicated by the graph), the deflection y of the beam is linearly related to the force, and, therefore, the beam can be described as a linear spring.

The case of a straight beam supported by two cylinders is illustrated in Figure 2.1b. As the force F is applied to the beam, the length between the supports decreases and, therefore, a larger force is needed to deflect a short beam than that required for a long one. Hence, the more this beam is deflected, the stiffer it becomes. The force is not linearly related to the deflection, and, therefore, the beam can be described as a nonlinear stiffening spring.

A dish-shaped round disk acted upon by the load F is shown in Figure 2.1c. To flatten the disk, a larger force is needed, so the force increases first. Then, the force decreases as the disk approaches a flat configuration. A mechanical element having this behavior is called a nonlinear softening spring. [7].

2.2. Types of Springs

Springs, effectively using elasticity of materials with high elastic strain, are used to absorb abruptly applied stress, to store absorbed stress in elastic energy, or to alleviate applied impact [8].

Springs appear in many shapes, and have many purposes. For example, springs are crucial suspension elements on cars, necessary to minimize the vertical vibrations, impacts and bumps due to road irregularities and create a comfortable ride. [11]. According to their purposes, springs are designed as helical springs, torsion springs, leaf springs, and belleville springs.

2.2.1. Helical Springs

Helical springs are most commonly made of round material and the resilient properties of the steel from which they are made are achieved above all by cold working such as drawing of the material. . For vehicles the wheels of which are subject to low loads these helical springs are well suited [12].

Helical extension springs (Figure 2.2) are used for maintaining the torsional stress in the wire. The initial tension is the external force, F, applies to the spring.

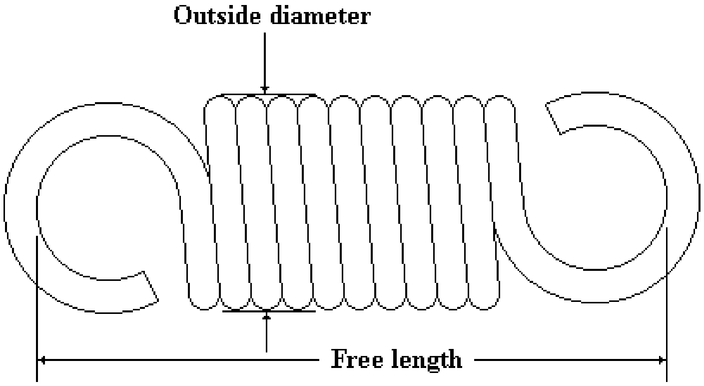


Figure 2.2. Helical Extension Spring [13]

The helical compression springs are usually made of circular cross-section wire or rod (Figure 2.3). These springs are subjected to a torsional shear stress and to a transverse shear stress. There is also an additional stress effect due to the curvature of the helix.

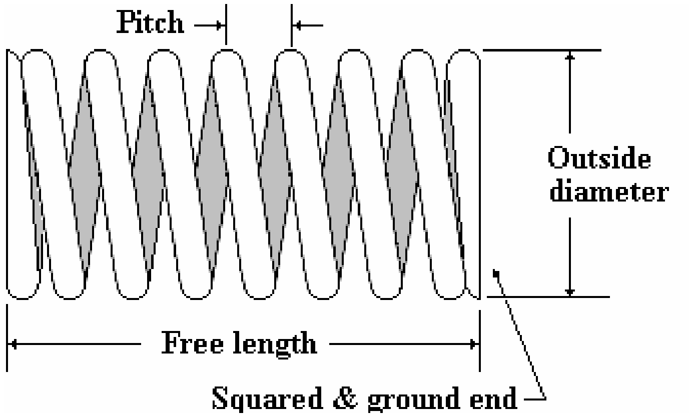
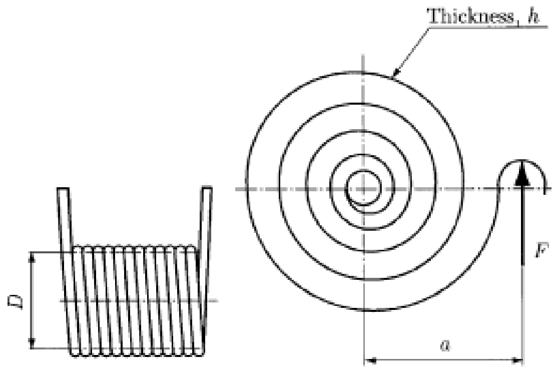


Figure 2.3. Helical Compression Spring [13]

2.2.2. Torsion Spring

Helical torsion springs are used in door hinges, in automobile starters, and for any application where torque is required. Torsion springs are of two general types: helical (Figure 2.4a) and spiral (Figure 2.4b). The primary stress in torsion springs is bending.



(a) (b)

Figure 2.4. Torsion springs a)helical, and b)spiral [14]

2.2.3. Torsion Bar Springs

Cylindrical torsion bars made of round steel are used to spring the body and as anti-roll bars. To transfer the springing movement, both ends have warm-upset heads, which carry a toothed profile or a square [15]. The torsion bar spring, shown in Figure 2.5, is used in automotive suspension.

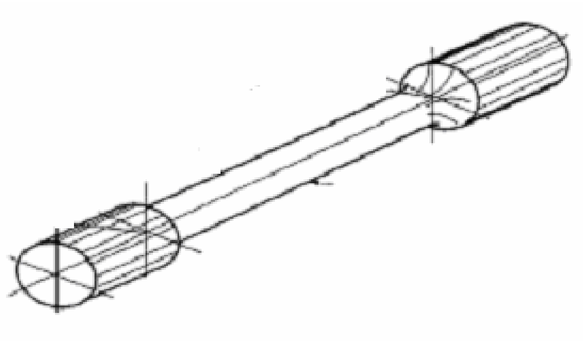


Figure 2.5. The torsion bar spring [14]

2.2.4. Leaf Springs

Leaf springs are subdivided into longitudinal and transverse leaf springs. Longitudinal leaf springs are used only on rigid axles, more commonly on commercial vehicles and trailers. The longitudinal type, is a reliable and persistent element in automotive suspension systems [11]. Transverse leaf springs, by contrast, can provide the springing on both sides of the axle; they were previously used in independent wheel suspensions of passenger cars [15].

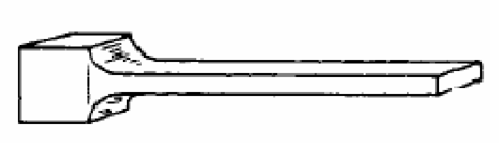


Figure 2.6. Leaf Spring [2]

The term “multi-leaf” has generally applied to springs of constant width and with stepped leaves, each of constant thickness except where leaf ends may be tapered in thickness. More recently, the term has been extended to include an assembly of stacked “single” leaves, each of which is characterized by tapering either in width or in thickness, or by a combination of both [16]. The multi-leaf spring can be a simple cantilever (Figure 2.7a) or a semielliptic leaf (Figure 2.7b). The design of multileaf springs is based on force F, length L, deflection, and stress relationships.

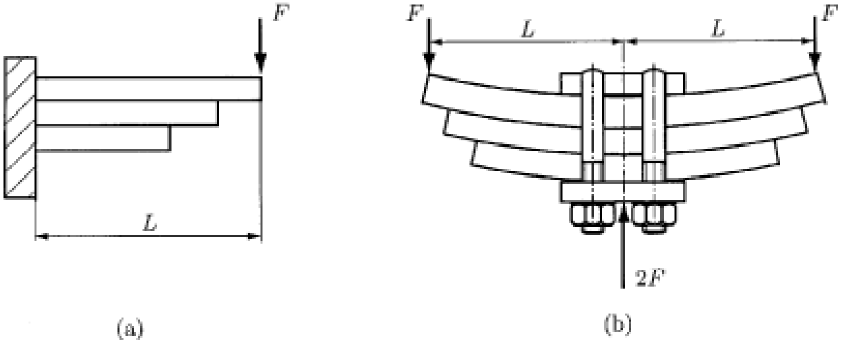


Figure 2.7. Multi-leaf springs a) simple cantilever, b) semielliptic leaf [14]

Leaf springs are most frequently used in suspensions. The mechanical properties defining a vehicle suspension system, particularly the spring rate and static deflection of the leaf spring, directly influence the smoothness of the vehicle's ride [17].

The rate of a spring is the change of load per unit of deflection (N/mm). This is not the same amount at all positions of the spring, and is different for the spring as installed.

The static deflection of a spring equals the static load divided by the rate at static load; it determines the stiffness of the suspension and the ride frequency of the vehicle [1].

2.2.5. Belleville Springs

Belleville springs are made from tapered washers (Figure 2.8a) stacked in series, parallel, or a combination of paralel-series, as shown in Figure 2.8b.

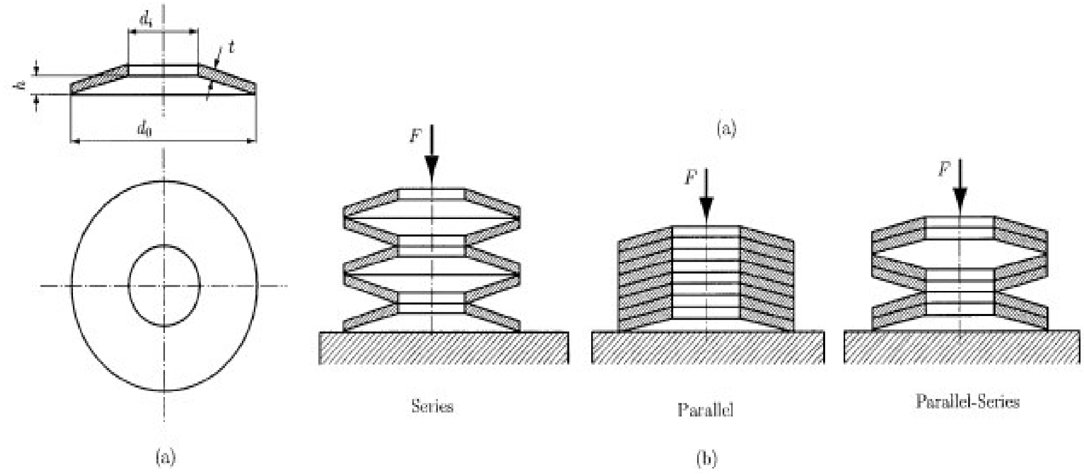


Figure 2.8. a) Belleville spring b) Application types of belleville spring [14]

2.3. Materials For Spring

Springs are mechanical elements that exert forces or torques and absorb energy. The absorbed energy is usually stored and later released. Springs are made of metal. For light loads the metal can be replaced by plastics. Some applications that require minimum spring mass use structural composite materials. Blocks of rubber can be used as springs, in bumpers and vibration isolation mountings of electric or combustion motors.

The hot and cold working processes are used for spring manufacturing. Plain carbon steels, alloy steels, corrosion-resisting steels, or nonferrous materials can be used for spring manufacturing. Spring materials are compared by an examination of their tensile strengths, which requires the wire size to be known. The material and its processing also have an effect on tensile strength [14] .

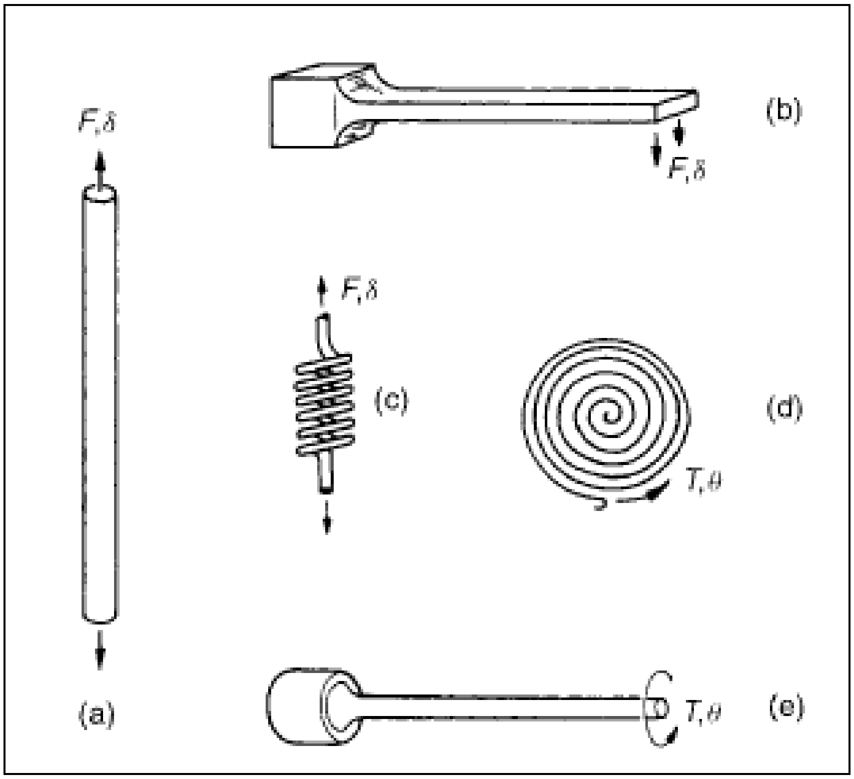


Figure 2.9. Springs store energy. The best material for any spring, regardless of its shape or the way in which it is loaded, is that with the highest value of σ^2_f / E, or, if weight is important, $\sigma^2_f / E\rho$ [2]

Springs come in many shapes (Figure 2.9) and have many purposes: one thinks of axial springs (a rubber band, for example), leaf springs, helical springs, spiral springs, torsion bars. Regardless of their shape or use, the best material for a spring of minimum volume is that with the greatest value of σ^2_f / E, and for minimum weight it is that with the greatest value of $\sigma^2_f / E\rho$ (derived below). We use them as a way of introducing two of the most useful of the charts: Young's modulus E plotted against strength σ_f (Figure 2.10), and specific modulus, E / ρ, plotted against specific strength σ_f / ρ (Figure 2.11).

2.3.1. The Model for Springs

The primary function of a spring is that of storing elastic energy and - when required – releasing it again (Table 2.1). The elastic energy stored per unit volume in a block of material stressed uniformly to a stress σ is

$$W_v = \frac{1}{2}\frac{\sigma^2}{E} \tag{2.1}$$

where E is Young's modulus [11]. It is this W_v that we wish to maximize. The spring will be damaged if the stress σ exceeds the yield stress or failure stress σ_f ; the constraint is $\sigma \le \sigma_f$. So the maximum energy density is

$$W_v = \frac{1}{2}\frac{\sigma_f^2}{E} \tag{2.2}$$

Torsion bars and leaf springs are less efficient than axial springs because much of the material is not fully loaded: the material at the neutral axis, for instance, is not loaded at all. For torsion bars

$$W_v = \frac{1}{3}\frac{\sigma_f^2}{E} \tag{2.3}$$

and for leaf springs

$$W_v = \frac{1}{4}\frac{\sigma_f^2}{E} \tag{2.4}$$

But - as these results show - this has no influence on the choice of material. The best material for springs is that with the biggest value of

$$M_1 = \frac{\sigma_f^2}{E} \tag{2.5}$$

If weight, rather than volume, matters, we must divide this by the density ρ (giving energy stored per unit weight), and seek materials with high values of

$$M_2 = \frac{\sigma_f^2}{\rho E} \tag{2.6}$$

Table 2.1. Design requirements for springs [2]

Function	Elastic spring
Objectives	Maximum stored elastic energy per unit volume Maximum stored elastic energy per unit mass
Constraints	No failure by yield, fracture or fatigue (whichever is the most restrictive), meaning $\sigma < \sigma_f$ everywhere in the spring Adequate toughness: $G_c > 1$ kJ/m^2

2.3.2. The selection of the Spring Material

The choice of materials for springs of minimum volume is shown in Figure 2.10. A family lines of slope 1/2 link materials with equal values of $M_1 = \sigma^2_f / E;$ those with the highest values of M_1 lie towards the bottom right. The heavy line is one of the family; it is positioned so that a subset of materials is left exposed. The best choices are a high-strength steel ((spring steel, in fact) lying near the top end of the line, and, at the other end, rubber. But certain other materials are suggested too: *GFRP* (now used for truck springs), *titanium alloys* (good but expensive), *glass* (used in galvanometers) and *nylon* (children's toys often have nylon springs). Note how the procedure has identified a candidate from almost every class of material: metals, glasses, polymers, elastomers and composites. They are listed, with commentary, in Table 2.2.

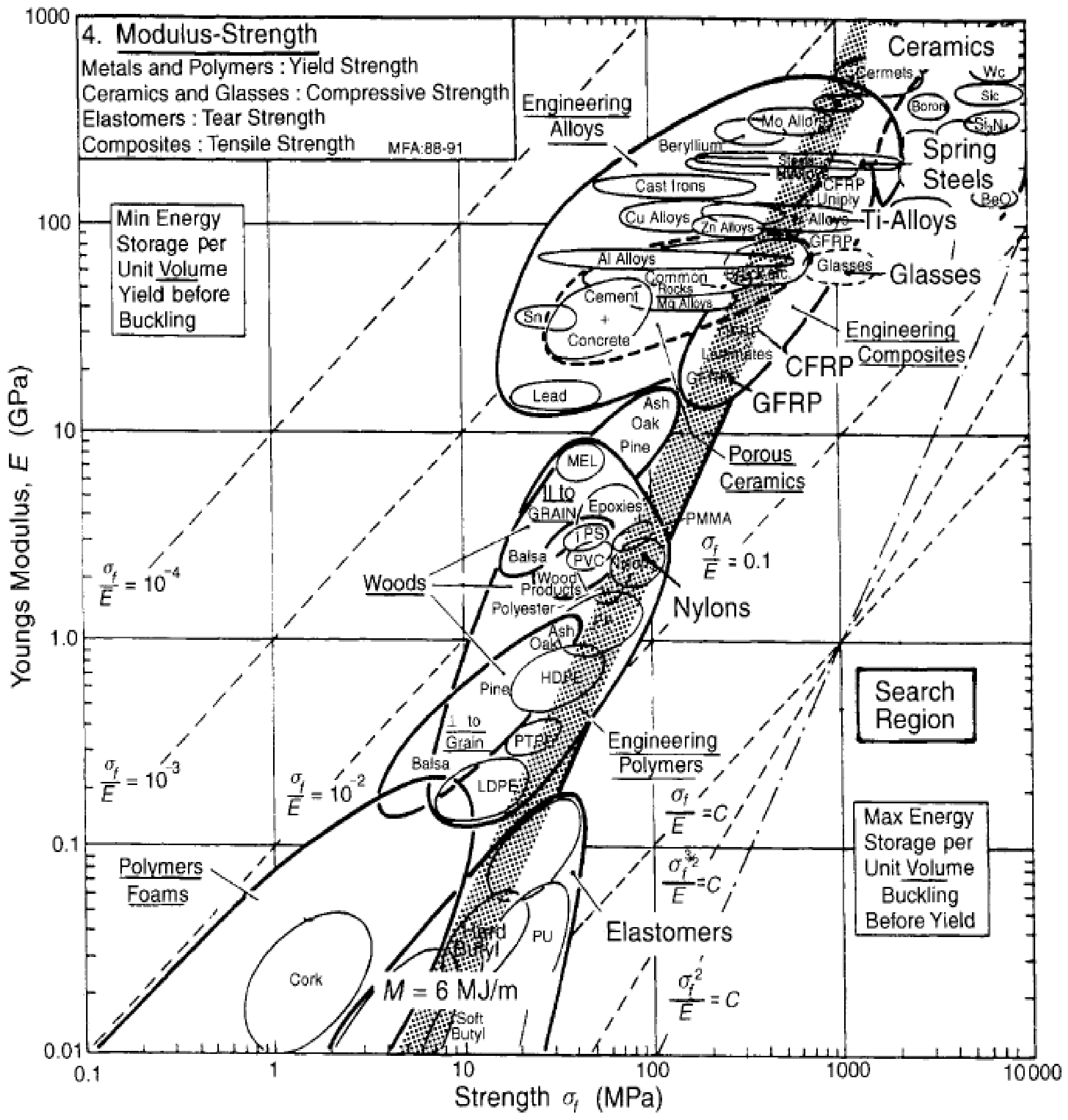


Figure 2.10. Young modulus vs. strength diagram for the choice of materials for springs of minimum volume [2]

Materials selection for light materials with equal values of springs is shown in Figure 2.11. A family of lines of slope 2 link materials with equal values of

$$M_2 = \left(\frac{\sigma_f}{\rho}\right)^2 \Big/ \left(\frac{E}{\rho}\right) = \frac{\sigma_f^2}{E\rho} \qquad (2.7)$$

One is shown at the value M_2 = 2 kJ/kg. Metals, because of their high density, are less good than composites, and much less good than elastomers. (You can store roughly eight times more elastic energy, per unit weight, in a rubber band than in the best spring steel.) Candidates are listed in Table 2.3. Wood, the traditional material for archery bows, now appears.

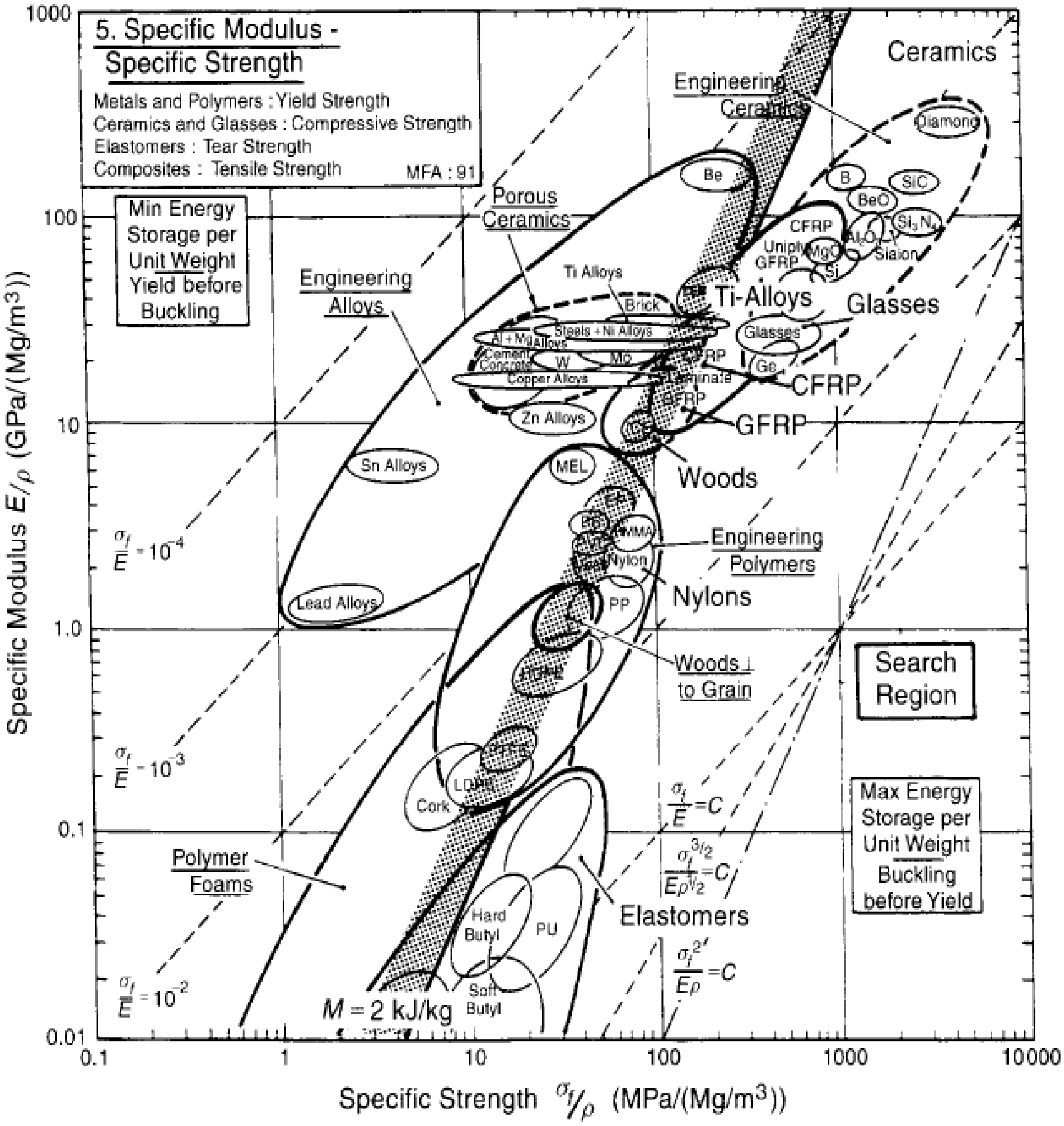


Figure 2.11. Specific modulus vs. specific strength diagram for the choice of materials for springs of minimum weight [2]

Table 2.2. Materials for efficient small springs [2]

Material	$M_1 = \frac{\sigma_f^2}{E} (MJ/m^3)$	Comment
Ceramics	(10–100)	Brittle in tension; good only in compression.
Spring steel	15–25	The traditional choice: easily formed and heat treated.
Ti alloys	15–20	Expensive, corrosion resistant.
CFRP	15–20	Comparable in performance with steel; expensive
GFRP	10–12	Almost as good as CFRP and much cheaper
Glass (fibres)	30–60	Brittle in tension, but excellent if protected against damage; very low loss factor.
Nylon	1.5–2.5	The least good; but cheap and easily shaped, but high loss factor.
Rubber	20–50	Beter than spring steel; but high loss factor.

Table 2.3. Materials for efficient light springs [2]

Material	$M_2 = \frac{\sigma_f^2}{E\rho} (kJ/kg)$	Comment
Ceramics	(5–40)	Brittle in tension; good only in compression.
Spring steel	2–3	Poor, because of high density.
Ti alloys	2–3	Better than steel; corrosion resistant; expensive
CFRP	4–8	Better than steel; expensive
GFRP	3–5	Beter than steel; less expensive than CFRP
Glass (fibres)	10–30	Brittle in tension, but excellent if protected.
Wood	1–2	On a weight basis, wood makes good springs.
Nylon	1.5–2	As good as steel, but with a high loss factor.
Rubber	20–50	Outstanding; 10 times beter than steel, but with high loss factor.

2.3.3. Additional Considerations

Many additional considerations enter the choice of a material for a spring. Springs for vehicle suspensions must resist fatigue and corrosion; Automotive diaphragm springs are exposed to repeated fatigue cycles (over 10^6 cycles) under high stress (40%~50% of tensile strength), and thus require steels with excellent fatigue properties [8]. IC valve springs must cope with elevated temperatures. Polymers have a relatively high loss factor and dissipate energy when they vibrate; metals, if strongly hardened, do not. Polymers, because they creep, are unsuitable for springs which carry a steady load, though they are still perfectly good for catches and locating-springs which spend most of their time unstressed. The reliability of many mechanical and electrical devices is closely connected with the quality of springs used in their construction. Due to operational safety, springs have to meet increasing performance requirements, which concern mechanical properties, fatigue strength as well as the resistance to work in corroding media [18].

3. STEEL FOR SPRINGS

3.1. Steel

Steel which is primarily alloy of iron and carbon is the most important engineering and constructural material [19]. Steel was first produced in China and Japan in about 600–800 a.d. The steelmaking process is essentially one of refining the pig iron by the reduction of the percentage of manganese, silicon, carbon, and other elements, and of controlling the composition of the output by the addition of various elements. The molten metal from the blast furnace is transported into one of three types of furnace: open-hearth, electric, or basic oxygen [20].

Steel generally contains between 0.05 % and 2.0 % C. We shall distinguish whether or not a significant amount of alloying elements other than carbon is used. A composition of 5% total noncarbon additions will serve as an arbitrary boundary between low-alloy and high-alloy steels [21].

3.1.1. Carbon and Low-Alloy Steels

The majority of ferrous alloys are carbon and low-alloy steels. The reasons for this are straightforward. Such alloys are moderately priced due to the absence of large amounts of alloying elements, and they are sufficiently ductile to be readily formed. The final product is strong and durable. These eminently practical materials find applications from ball bearings to metal sheet formed into automobile bodies [21].

Low-carbon steel, also called mind steel, has less than 0.30 % carbon. Medium-carbon steel has 0.30 % to 0.60 % carbon. High-carbon steel has more than 0.60 % carbon. Carbon steels containing sulfur and phosphorus are also available; they are known as resulfurized carbon steels, and rephosphorized and resulfurized carbon steels.

In order to improvve the strength-to-weight ration of steels, a number of high-strength, low alloy (HSLA) steels have been developed. These steels have alow carbon content (usually less than 0.30 %). They are characterized by a microstructure consisting of fine-grain ferrite as one phase and a hard second phase of martensite and austenite [22].

Applications of HSLA steels include oil and gas pipelines, heavy-duty highway and off-road vehicles, construction and farm machinery, industrial equipment, storage tanks, mine and railroad cars, barges and dredges, snowmobiles, lawn mowers, and passenger car components. Bridges, offshore structures, power transmission towers, light poles, and building beams and panels are additional uses of these steels [23].

3.1.2. High-Alloy Steels

Alloy addition must be made with care and justification bacause they are expensive. We shall look at three cases in which engineering design requirements justify high-alloy compositions. Stainless steels require alloy additions to prevent damage from a corrosive atmosphere. They are called “stainless” because in the presence of oxygen (air) they develop a thin, hard adherent film of chromium oxide that protects the metal from corrosion [22]. Tool steels require alloy additions to obtain sufficient hardness for machining applications. So-called superalloys require alloy additions to provide stability in high-temperature applications such as turbine blades [21].

3.1.3. Effects of Various Elements in Steel

Various elements are added to steels, in order to impart the properties of hardenability, strength, hardness, toughness, wear resistance, workability, weldability, and machicability. These elements are listed below in alphabetic order, with summaries of their benefical and detrimental effects.

Generally, the higher the percentages of these elements in steels, the greater are the particular properties that they impart; for example, the higher the carbon content, the greater the hardenability of the steel and the greater its strength, hardness, and wear resistance. On the other hand, ductility, weldability, and toughness are reduced with increasing carbon content [22].

Aluminium is an element which is a deoxidizer for steel and is required in order to control the size of austenite crystal grains. When the Al content is lower than 0.005 %, the crystal grains cannot be made fine. On the other hand, when it exceeds 0.100 %, the castability of molten steel at the time of solidification thereof is liable to lower [24].

Boron in small amounts has a very beneficial effect in particular on the hardenability and hence of course also on the elastic limit, without loss of (or even with some improvement in) machinability and formability. The content of C may, if boron is added, be kept lower than with a conventional spring steel. This of course makes the steel cheaper, and at the same time it becomes less liable to surface decarbonisation which would cause the fatigue limit to be reduced [12].

Calcium deoxidizes steels, improves toughness, and may improve formability and machinability.

Carbon presence in iron is necessary to make steel. Carbon is essential to the formation of cementite (as well as other carbides), and to the formation of pearlite, spheroidite, bainite, and iron-carbon martensite [25]. It improves hardenability, strength, hardness, and wear resistance; it reduces ductility, weldability, and toughness.

Cerium controls the shape of inclusions and improves toughness in high-strength, low-alloy steels; it deoxidizes steels.

Chromium improves toughness, hardenability, wear and corrosion resistance, and high-temperature strength; it decreases the depth of hardness penetration resulting from heat treatment, by promoting carburization. When added in large amounts, Cr shows a tendency of increasing a relaxation value of steel materials which have been quenched and tempered. In addition, Cr serves to slightly deteriorate the toughness of steel materials which have been quenched and tempered. On the other hand, Cr serves to impart toughness to hot rolled steels and ensures the stability and reliability of a wire-drawing process, after the hot rolling, without involving any heat treatment [26].

Cobalt improves strength and hardness at elevated temperatures.

Copper improves resistance to atmospheric corrosion and, to a lesser extent, increases strength, with little loss in ductility; it adversely affects hot-working characteristics and surface quality.

Lead improves machinability; it causes liquid-metal embrittlement.

Manganese improves hardenability, strength, abrasion resistance, and machinability; it deoxidizes the molten steel and reduces hot shortness; and it decreases weldability [27].

Molybdenum improves hardenability, wear resistance, toughness, elevated-temperature strength, creep resistance, and hardness; it minimizes temper embrittlement [22, 28].

Nickel improves strength, toughness, and corrosion resistance; it improves hardenability. If the amount is less than 0.2 %, the effect of improving the hardenability and toughness is not fully attained, and if the amount exceeds 2.0 %, there is a possibility of forming a large amount of retained austenite in the quenching operation [29].

Niobium (columbium) imparts fineness of grain size and improves strength and impact toughness; it lowers transition temperature; and it may decrease hardenability.

Phosphorus improves strength, hardenability, corrosion resistance, and machinability; it severely reduces ductility and toughness.

Silicon improves strength, hardness, corrosion resistance, and electrical conductivity; it decreases magnetic hysteresis loss, machinability, and cold formability. Si is an element which is inexpensive and which is effective in improving the resistance to permanent set of coil springs obtained by quenching and tempering and/or oil tempering treatments [26].

Sulfur improves machinability when combined with manganese; it lowers impact strength and ductility; it impairs surface quality and weldability.

Titanium improves hardenability; it deoxidizes steels. Ti precipitate in a steel in the forms of nitrides, carbides, and carbonitrides. Thus when it is added, the precipitates form and temper softening resistance is obtained, which fact makes it possible to secure a high strength without softening even when a steel is subjected to a heat treatment such as stress relief annealing in a high temperature tempering process or nitriding. Ti often takes the form of precipitates already in molten steel because the precipitation temperature of Ti nitrides is high [30].

Tungsten has the same effect as cobalt. Used in small amounts, tungsten combines with the free carbides in steel during heat treatment, to produce high wear resistance with little or no loss of toughness [25].

Vanadium improves strength, toughness, abrasion resistance, and hardness at elevated temperatures; it inhibits grain growth during heat treatment. It is useful in preventing the decarburization similarly to Cr. Vanadium is added to steel materials in order that crystal grains are refined to impart toughness to the material and improve the resistance to delayed fracture, thus improving the reliability of performance [26].

3.1.4. Effects of Various Elements on Martensite Transformation

As in carbon steels, the martensite transformation in alloy steels takes place under rapid cooling from temperatures higher than the equilibrium temperature of the $\gamma \rightarrow \alpha$ transformation. At the martensite transformation temperature both the diffusion movement of metal atoms of iron and alloying elements and that of metalloid atoms of carbon and nitrogen are suppressed. For this reason the martensite transformation in steels proceeds by a diffusionless mechanism.

The martensite transformation can take place in carbon-containing alloy steels, non-carbon-containing alloy steels, and binary iron-alloying element alloys. The martensite transformation usually leads to formation of a supersaturated α-iron-based solid solution. In carbon-containing steels the solid solution is supersaturated mainly with carbon, and in non-carbon-containing alloy steels, with alloying elements. The content of carbon and alloying elements in martensite is the same as that in the initial austenite.

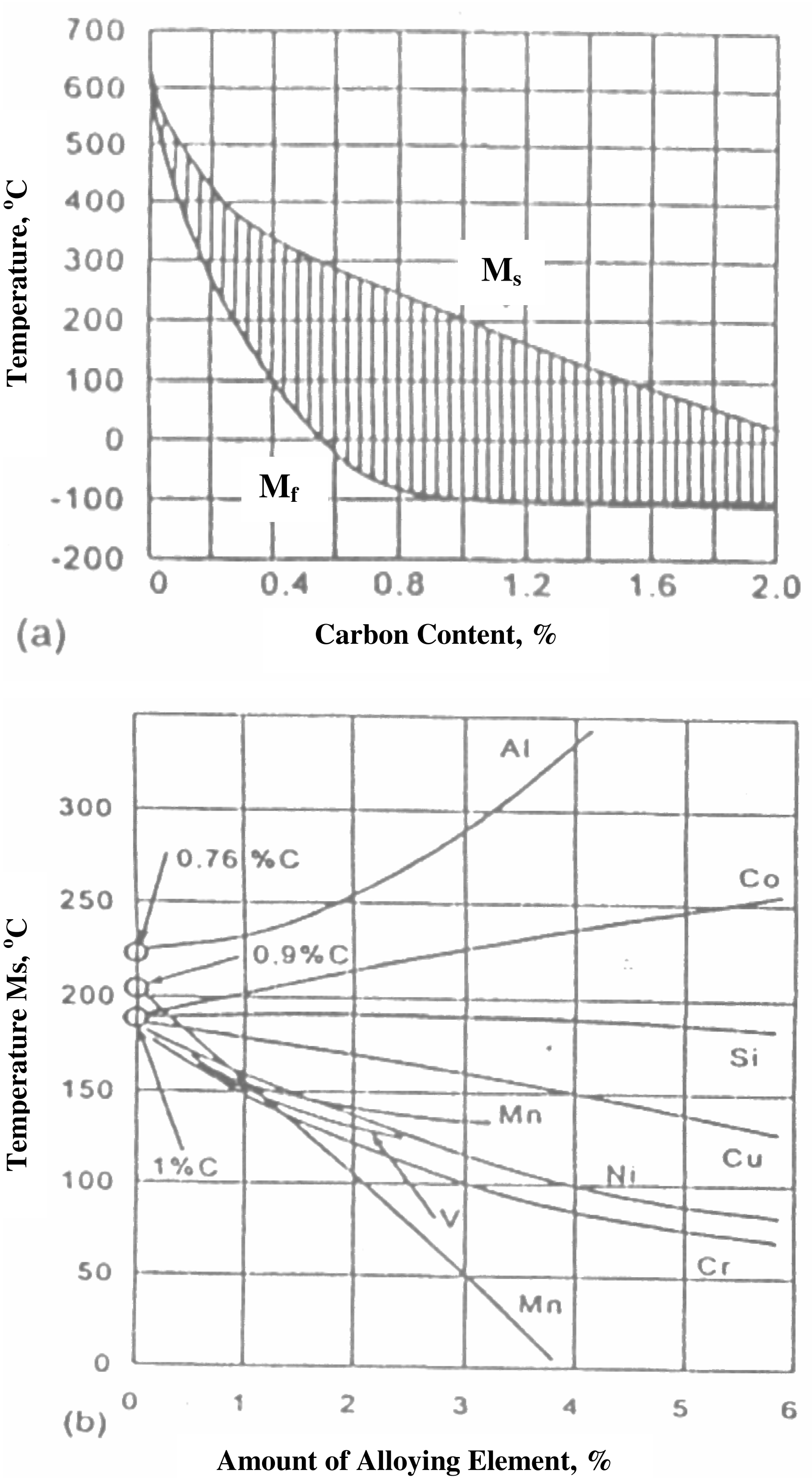


Figure 3.1. The influence of the content of (a) carbon and (b) alloying elements at 1% C on the martensite point position [31].

The transformation of austenite into martensite during cooling starts at a certain temperature called M_s. This temperature is independent of the cooling rate over a very wide range of cooling rates.

The martensite transformation kinetics of most carbon and structural and tool alloy steels is athermal in character. The athermal martensite transformation is characterized by a smooth increase in the amount of martensite as the temperature is lowered continuously in the martensite interval M_s-M_f. where M_f is the martensite finish temperature. As a rule, this transformation takes place in steels with the martensite point M_s higher than room temperature.

A version of a thermal martensite transformation is explosive martensite transformation, where a certain quantity of martensite is formed instantly at or a little below the temperature M_s. This transformation is observed in alloys with the martensite point below room temperature.

The position of the martensite point also determines the microstructure and substructure of the martensitic quenched steel. At temperatures M_s below room temperature, lamellar (plate) martensite is formed in quenched iron-carbon and alloy steels. Crystals of this martensite are shaped as fine lenticular plates. In steels with the martensite point M_s higher than room temperature, lath martensite is formed during quenching. Crystals of this martensite have the form of approximately equally oriented thin plates, which are combined into more or less equiaxial packets. The substructures of needle and lath martensite are qualitatively different.

From what has been said above it might be assumed that the martensite transformation kinetics, the morphological type of martensite, the substructure of martensitic quenched steels, and other phenomena are connected to a great extent with the martensite start temperature M_s. Thus the influence of the elements on martensite transformation is determined primarily by their influence on the position of the martensite point M_s.Of practical importance is also the martensite finish temperature M_f.

Table 3.1. The quantitative influence of alloying elements (per 1% of the alloying element) [31]

Element	Mn	Cr	Ni	V	Si	Mo	Cu	Co	Al	
Shift of point M_s	-45	-35	-26	-30	0	-25	-7	+12	+18	°C
	-81	-63	-47	-54	0	-45	-13	+22	+32	°C

Experiments concerned with the influence of alloying elements on the position of the martensite point show that Co and Al elevate the martensite start temperature, Si has little if any effect, and all the other elements decrease M_s (Figure 3.1).

The quantitative influence of alloying elements is approximately given in Table 3.1 (per 1 w % of the alloying element).

These data are given for carbon steels containing 0.9-1.0 % C. For a wider range of C content, the quantitative influence of the elements can be different. In particular, it was established that the smaller the C content, the weaker is the influence of the alloying elements on the position of point M_s. The martensite start temperature of medium-carbon alloy steels can be estimated using empirical formula

$$M_s(°C) = 520 - 320(\%C) - 50(\%Mn) - 30(\%Cr) - 20[\%(Ni + Mo)] - 5[\%(Cu + Si)] \quad (3.1)$$

where %C, %Mn, etc. are the contents of the corresponding elements in weight percent.

The results of calculations by this formula for steels containing 0.2-0.8% C are in good agreement with the experimental data. However, for multialloy steels this formula does not always yield reliable data because if a steel contains several alloying elements it is impossible to determine their combined effect on the martensite point by simple summation. Thus, for example, Mn lowers the point M_f, to a greater extent than Ni, but in a steel with a high Cr content its effect is weaker than that of Ni.

The martensite point M_s is affected most by C dissolved in austenite (Figure 3.1). The transformation finish temperature M_f intensively decreases, too, as the C content is increased up to 1% (to 100 °C) and remains constant at higher amounts of carbon.

The reason carbon and alloying elements influence the position of the martensite point is mainly a change in the relative thermodynamic stability of γ and α phases of iron, because the martensite transformation itself is the $\gamma \rightarrow \alpha$ transformation considering the conditions it takes place in [31].

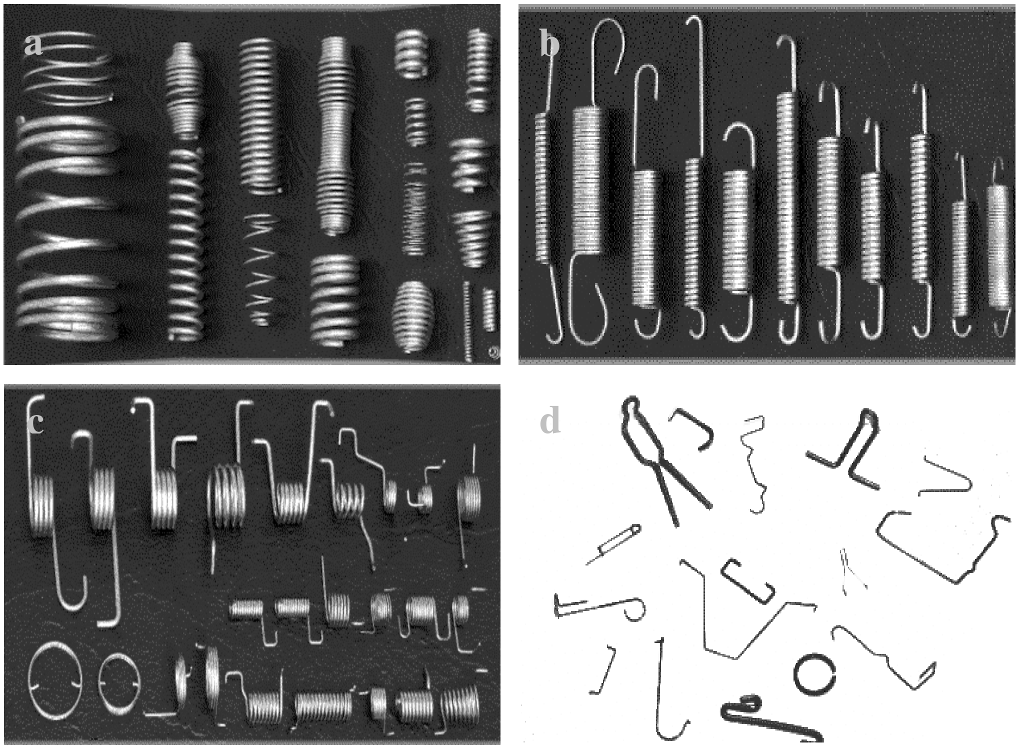


Figure 3.2. Wire springs a) compression b) extension c) torsion d) wire forms [33]

3.2. Steel for Springs

Steel springs are made in many types, shapes, and sizes, ranging from delicate hair-springs for instrument meters to massive barrel springs for railroad equipment. In the automotive industry springs are used in many applications. During the last two decades, considerable efforts have been made in the development of high performance spring steels to meet the needs for weight and cost savings in the automotive industry. [3–5]. Relatively small steel springs are usually cold wound from wire. Relatively large, hot-wound springs are quite different from cold-wound springs and treated in a seperate section. Flat and leaf springs are also treated seperately to the extent that they differ from wire springs in material and fabrication.

Wire springs are of four types: compression springs (including die springs), extension springs, torsion springs and wire forms. Compression springs are open wound with varying space between coils and are provided with plain, plain and ground, squared, or squared and ground ends. The spring can be cylindrical, conical, barrel, or hourglass shaped. Compression springs can be found in ballpoint pens, pogo sticks, and the valve assemblies of gasoline engines. Extension springs are normally close wound, usually with specified initial tension, and, because they are used to resist pulling forces, are provided with hook or loop ends to fit the specific application. Ends may be integral parts of the spring or specially inserted forms. Extension springs are found in garage door assemblies, vise-grip pliers, and carburetors. Torsion springs are usually designed to work over an arbor and to resist a force that causes the spring to wind. They can be found on clipboards, underneath swing-down tailgates, and, again, in car engines. Wire forms are made in a wide variety of shapes and sizes [13, 32].

Flat springs are usually made by stamping and forming of strip material into shapes such as spring washers. However, there are other types, including motor springs (clock type), constant-force springs, and volute springs, that are wound from strip or flat wire.

Chemical composition, mechanical properties, surface quality, availability, and cost are the principal facors to be considered in selecting steel for springs. Both carbon and alloy steels are used extensively. Where special properties are required, spring wire or strip made of stainless steel, a heat-resistant alloy, or a nonferrous alloy can be substituted for the carbon or alloy steel.

3.3. Cold-Wound Springs

3.3.1. Mechanical Properties

Steels of the same chemical composition may perform differently because of different mechanical and metallurgical characteristics. These properties are developed by the steel producer through cold work and heat treatment or by the spring manufacturer through heat treatment.

Rockwell hardness and tensile strength for any grade of spring steel strip depend on thickness. The same properties in different thicknesses can be obtained by specifying different carbon contents. The relationship between thickness of spring steel strip containing 0.50 to 0.95% C and Rockwell hardness is shown in Figure 3.3. The optimal hardness of a spring steel increases gradually with decreasing thickness.

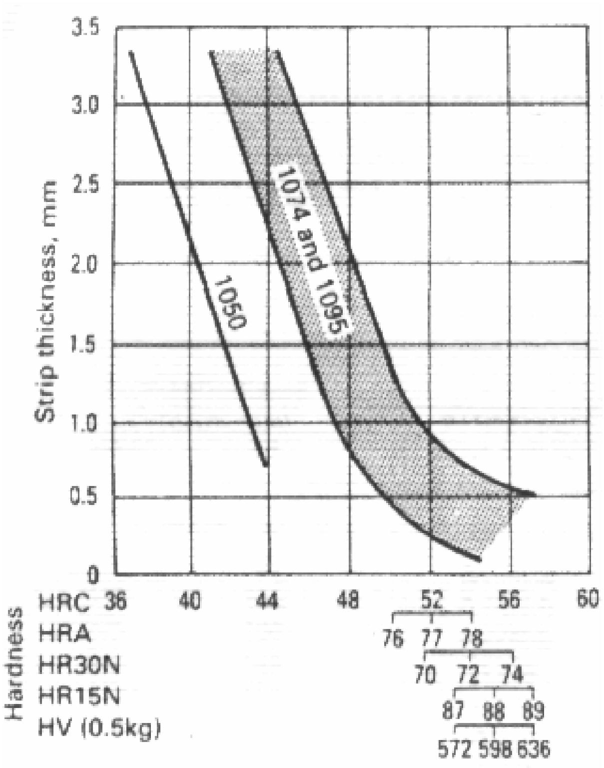


Figure 3.3. Effect of strip thickness on the optimal hardness of spring steel strip for high-stress use [32]

Fatigue strength is another important mechanical property of steel spring. However, this property is affected by many factors, and because of this complexity, fatigue is discussed in a seperate section.

3.3.2. Characteristics of Spring Steel for General Use

The several types of steel wire used for mechanical springs are produced in a variety of chemical compositions, the primary consideration is that the wire have the specific properties necessary for the application. The required properties vary with the intended use of the spring and with the problems involved in its fabrication. The factors governing the selection of spring wire include :

- The load range through which the spring must operate
- The corresponding stress range for the wire
- Weight and space limitations
- Expected life of the spring
- Temperatures and other environmental conditions to be encountered in service
- Severity of deformation to be encountered during fabrication

As stress on the wire increases, wire with higher strength is required. Because the surface of the wire is the most highly stressed part of a spring and because spring motion gives rise to torsion effects, freedom from surface imperfections becomes increasingly important as maximum stress or required stress or required service life increased.

The three types of wire, hard-drawn spring wire, oil-tempered wire, and music wire, used in the greatest number of applications of cold-formed springs.

Amoung the grades of steel wire used for cold-formed springs (Table 3.2), hard-drawn spring wire is the least costly, and its surface quality is comparatively low. This wire is used in applications involving low stresses or static conditions. Oil-tempered wire is a general-purpose wire. Its spring properties are obtained by heat treatment. It is slightly more expensive but is significantly superior in surface smoothness. Most cold-wound automotive springs are made of oil-tempered wire. Music wire is the carbon steel wire used for small springs. It is comparable to valve-spring wire in surface quality. Guitar and piano strings are made from this material, as are most small springs.

Chromium-silicon and chromium-vanadium steel spring wire and strip are suitable for moderately elevated temperature service. The chromium-silicon steel spring wire can be used at temperatures as high as 230 ^{o}C. High-tensile hard-drawn wire fills the gap where high strength is needed, but where the quality of music wire is not required.

Table 3.2. Common wire and strip steels used for cold-formed springs [32]

Material Type	Grade and Specification	Nominal Composition, %	Minimum Tensile Strength(a), MPa
Cold-drawn wire			
High-carbon steel	Music wire, ASTM A228	0.70-1.00 C, 0.20-0.60 Mn	1590-2750
	Hard-drawn, ASTM A227	0.45-0.85 C, 0.30-1.30 Mn	1010-1950
	High-tensile hard-drawn, ASTM A679	0.65-1.00 C 0.20-1.30 Mn	1180-2230
	Oil tempered, ASTM A229	0.55-0.85 C 0.30- 1.20 Mn	1140-2020
	Carbon VSQ(b), ASTM A230	0.60-0.75 C 0.60-0.90 Mn	1320-2330
Alloy steel	Chromium vanadium, ASTM A231, A232(b)	0.48-0.53 C 0.80-1.10 Cr 0.15 min V	1310-2070
	Modified chromium vanadium(b), ASTM A878	0.60-0.75 C 0.35-0.60 Cr 0.10-0.25 V	1410-2000
	Chromium silicon, ASTM A877(b), A401	0.51-0.59 C 0.60-0.80 Cr 1.20-1.60 Si	1620-2070
Colled-rolled strip			
Carbon Steel	Medium carbon (1050), ASTM A682	0.47-0.55 C 0.60-0.90 Mn	Tempered 1100-1930
	Regular carbon (1074), ASTM A682	0.69-0.80 C 0.50-0.80 Mn	Tempered 1100-2210
	High carbon (1095), ASTM A682	0.90-1.04 C 0.30-0.50 Mn	Tempered 1240-2340
Alloy steel	Chromium vanadium, AMS 6455	0.48-0.53 C 0.80-1.10 Cr 0.15 min V	1380-1720
	Chromium silicon, AISI 9254	0.51-0.59 C 0.60-0.80 Cr 1.20-1.60 Si	1720-2240
(a) Minimum tensile strength varies within the given range according to wire diameter. (b) Valve-spring quality.			

3.3.3. Characteristics of Valve-Spring Quality Wire

All valve-spring quality (VSQ) wires have the highest surface quality attainable in commercial production. Most VSQ wire producers remove the surface of the wire rod before drawing to final size. This practice improves the surface quality and eliminates decarburization.

Carbon steel spring wire is the least costly of the VSQ wires. Chromium-vanadium steel VSQ wire is superior to the same quality of carbon steel wire for service at 120 ^{o}C and above. Chromium-silicon steel VSQ wire can be used at temperatures as high as 230 ^{o}C. These are higher quality, higher strength versions of oil tempered wire, used in high-temperature applications such as automotive valve springs [13, 32].

3.3.4. Wire Quality

In dynamic applications, in which fatique strength is an important factor, the performance differences of spring material depends on surface quality when materials are of similar composition and tensile strength. Because the initiation and growth of fatigue cracks is strongly affected by surface quality, seams and surface decarburization are important factors in dynamic applications of spring quality wire and especially valve-spring quality wire. Freedom from surface imperfections is of paramount importance in some applications of springs that are highly stressed from shock and fatigue loading.

3.3.5. Residual Stresses

Residual stresses can increase or decrease the strength of a spring material, depending on their direction. For example, residual stresses induced by bending strengthen wire for deflection in the same diretion yet weaken it for deflection in the opposite direction. In practice, residual stresses are either removed by stress relieving or induced to the proper direction by cold setting and shot peening.

3.3.6. Plating of Springs

Steel springs are often electroplated with zinc or cadmium to protect them from corrosion and abrasion. In general, zinc has been found to give the best protection in atmospheric environments, but cadmium is better in marine and similar environments involving strong electrolytes.

If stress relieving has been attended to, and the springs are truly clean before plating, then the usual baking treatment of around 200 °C for 4 h should lessen the small amount of hydrogen absorbed and redistribute it to give blister-free springs, which will not fail.

Another tecnique that solves the hydrogen problem is mechanical plating, which involves cold welding particles of zinc or other soft-metal powder to an immersion copper flash plate on the spring.

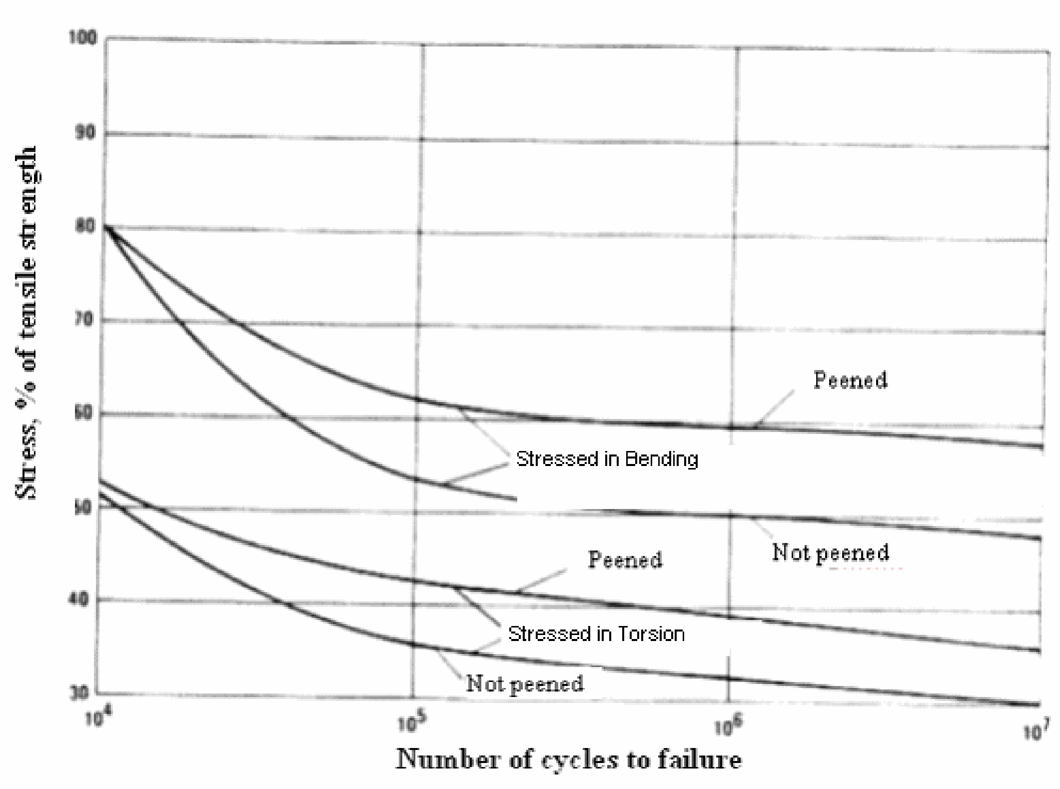


Figure 3.4. Fatigue curves for peened and unpeened steel spring wires [32]

3.3.7. Fatigue

For those springs that are dynamically loaded, it is common practice to obtain basic mechanical data from *S-N* fatigue curves. Shot peening of springs improves fatigue strength by prestressing the surface in compression. The extent of improvement in fatigue strength to be gained by shot peening is shown in Figure 3.4.

Table 3.3. Recommended Steels for Hot-Wound Helical Springs [32]

Corrected maximum solid stres	Diameter of spring wire (hot rolled)		
MPa	9.5-25.4 mm	25.4-50.8 mm	50.8-76.2 mm
Static load			
825	1070 1095	1095	1095
965	1070 1095	51B60H 4161	4161
1100	5150H 5160H	51B60H 4161	4161
1240	5150H 5160H 50B60H	51B60H 4161	4161
Variable load, designed for minimum life of 50,000 cycles			
690	1095	1095	1095
825	1095	51B60H 4161	4161
965	5150H 5160H 50B60H	51B60H 4161	4161
1100	5150H 5160H	51B60H 4161	4161
1240	5150H 5160H 50B60H	51B60H 4161	4161
Variable load, designed for minimum life of 2 million cycles			
690	1095	1095	1095
825	1095	51B60H 4161	4161

3.4. Hot-Wound Springs

Although some hot-wound springs are made of steels that are also used for cold-wound springs, hot-wound springs are usually much larger, which results in significant metallurgical differences.

3.4.1. Hardenability Requirements

Steels for hot-wound springs are selected mainly on the basis of hardenability. Carbon steels with about 0.70 to 1.00 % C are suitable and widely used for statically and dynamically loaded springs in the smaller sizes. Carbon steels are also used for larger springs in the lower stress range, where some hardenability can be sacrificed safely. In most cases, alloy steeels are usually required for the larger sizes because of the need for hardenability. Most specifications for hot-wound alloy steel springs require 0.50 to 0.65% C and a minimum hardness of 50 HRC at the center after oil quenching from about 815 ^{o}C and before tempering (The austenitizing temperature will vary, depending on the specific steel.)

Recommended steels for hot-wound helical springs are given in Table 3.3, covering variations in stress range, type of loading, and wire size. In the table, where more than one steel is recommended for a specific set of conditions, they are arranged in the order of increasing hardenability. Hardenability requirements increase as required strength and/or wire diameter increases.

3.4.2. Surface Quality

Hot-wound springs fabricated from bars of large diameter will normally show much deeper surface decarburization, in the range from 0.13 to 0.38 mm, unless special material preparation and processing techniques are used. The detrimental effects of decarburization are less noticable on hot-wound springs because other weaknesses, such as the surface imperfections and irregularities typical of a hot-rolled surface, create additional focal points for fatigue cracks [32].

3.5. Leaf Springs

3.5.1. Material

Metal leaf springs are incorporated into a variety of different vehicle suspensions including, automobiles, light to heavy trucks, trailers, construction equipment, locomotives, and railroad cars. They are also employed in recreational vehicles, such as bicycles, snowmobiles, and ATVs (All Terrain Vehicles). The leaf spring improve the quality or smoothness of the vehicle's ride [17].

The basic requirement of a leaf spring steel is that the selected grade of steel must have sufficient hardenability for the size involved to ensure a fully martensitic structure throughout the entire section. Nonmartensitic transformation products detract from the fatigue properties.

Automotive chassis leaf springs have been made from various fine grained alloy steels such as grades 9260, 4048, 4161, 6150, 8660, 5160, and 51B60 [6, 34].

Table 3.4. Measurements of typical mechanical properties of leaf spring steel [6]

Hardness :	Bhn 388-461, Rockwell C 42-49
Tensile Strength :	1300 – 1700 MPa
Yield Strength (0.2 % offset) :	1170 – 1550 MPa
Reduction of Area :	25 % min
Elongation :	7 % min

In the United States almost all leaf springs are currently made of chromium steels such as 5160, 51B60, or their H equivalents. For example, with 5160, the chemistry is specified as an independent variable (while the hardenability of the steel is a dependent variable which will vary with the chemistry). 5160H is essentially the same steel except that the hardenability is specified as an independent variable (while chemistry is a dependent variable which will may be adjusted to meet the hardenability band requirement.

In general terms, higher alloy content is necessary to insure adequate hardenability when the thicker leaf sections are used. When considering the grade of steel to be used, it is recommended either that the hardenability be calculated from the chemistry (for example, 5160), or that the hardenability band charts (for example, 5160H) for the various H steels.

3.5.2. Mechanical Properties

Steels of the same hardness in the tempered martensitic condition have approximately the same yield and tensile strengths. The ductility, as measured by elongation and reduction of area, is inversely proportinal to the hardness. Based upon experience, the optimum mechanical properties for leaf spring applications are obtained within the range of Brinell hardness numbers 388–461. A specification for leaf springs usually consists of a range of Bhn 415–461 for thin section sizes.

3.5.3. Surface Decarburization

Surface decarburization may reduce the fatigue durability of the springs; therefore, it is important that surface decarburization be at a minimum.

Hot rolled steel bars, as received from the mills, have some decarb, at least of the minimum Type 3, where more than 50 % of the base carbon content remains at the surface.

If decarb is of Type 2, where 50 % or less of the base carbon content remains at the surface, the decarb normally does not exceed a depth of 0.25 mm for steels of thicknesses 5.00 through 12.50 mm.

3.5.4. Mechanical Prestressing

Presetting, shot peening, and/or strees peening at ambient temperatures produces large increases in fatigue durabilitywithout increasing the size of the spring. These prestressing methods are more effective in increasing the fatigue properties of a spring than are changes in material.

When a load is applied to a leaf spring, the surface layers are subject to the maximum bending stress. One surface of each leaf will be in tension and the opposite surface will be in compression. Fatigue failures of the leaves usually start at or near the surface on the tension side. Since residual stresses are algebraically additive to load stresses, the introduction of residual compression stresses in the tension surface by prestressing reduces the operating stress level, thereby increasing the fatigue life.

Presetting (synonymous terms are : cold setting, bulldozing, setting-down, scragging) produces residual compressive stresses in the tension surface and residual tensile stresses in the compression surface by forcing the leaves to yield or take a permanent set in the direction of subsequent service loading. While this operation is beneficial to fatigue life, its primary effect is the reduction of “settling” (load loss) in service. Presetting is usually done on the spring assembly.

Shot Peening introduces compressive residual stresses by subjecting the tension side of the individual leaves to a stream of high-velocity shot.

Stress Peening (strain peening) is a means of introducing higher residual compressive stresses than is possible with shot peening with the leaf in free (unloaded) position. Stress peening is done by shot peening the leaf while it is loaded (under stress) in the direction of subsequent sevice loading.

4. HEAT TREATMENT FOR SPRING STEEL

4.1. Oil Quenching Process

All modern quenching oils are based on mineral oil, usually paraffin based, and do not contain fatty oils. Usage of oils opens up a number of options for the heat treater :

- Normal-speed oil for treating steels high in hardenability
- Medium-speed oils for medium hardenability steels
- High-speed oils for treating low hardenability steels and for other applications
- Hot oil quenching (also called marquenching or martempering) provides another option
- Water-washable quenching oils: for removing oils on treated parts with plain water

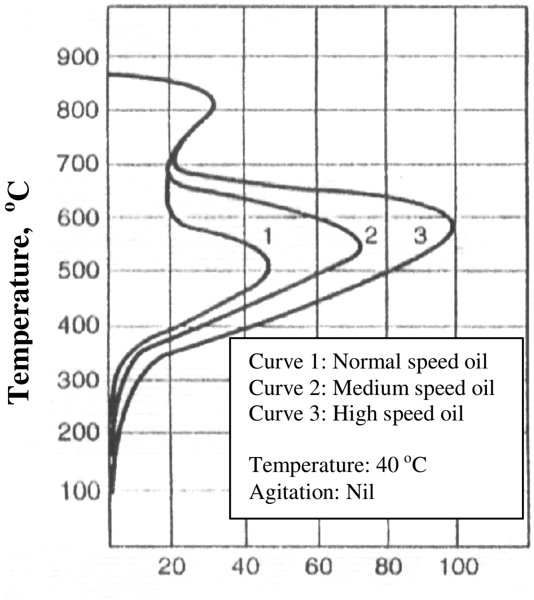


Figure 4.1. Cooling rate curves for quenching oils [35]

4.1.1. Characteristics of Process

Oils are characterized in various ways, depending upon operating requirements. Quenching speed and operating temperature are amoung these considerations.

The importance of quenching speed is that it influences hardness and depth of hardening. Cooling rate curves for normal-, medium-, and high-speed quenching oils are shown in Figure 4.1. Cooling curves for different quenchants are given in Figure 4.2.

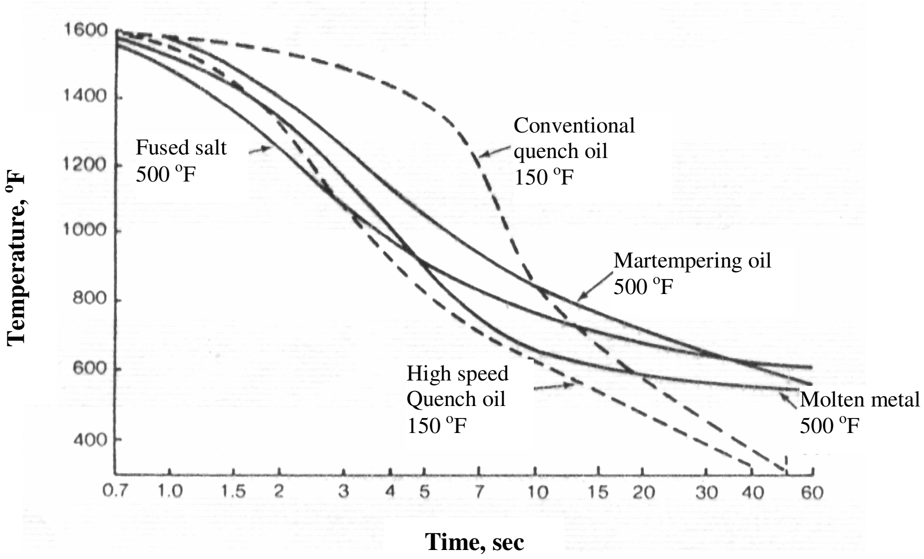


Figure 4.2. Cooling rates for different quenchants [35]

Almost all quenching oils produce lower quenching rates than water or brine solutions, but they remove heat from workpieces more uniformly than water normally does, meaning less likelihood of distortion and cracking.

Temperature of operation is important because it influences oil life, quenching speed, viscosity of oil, distortion of workpieces. Effect of temperature on quenching speed for a hot quenching oil is shown in Figure 4.3.

Changing in viscosity can indicate oxidation and thermal degradation, or the presence of contaminants. In general, viscosity goes up as an oil degrades and can result in changes in quenching speed.

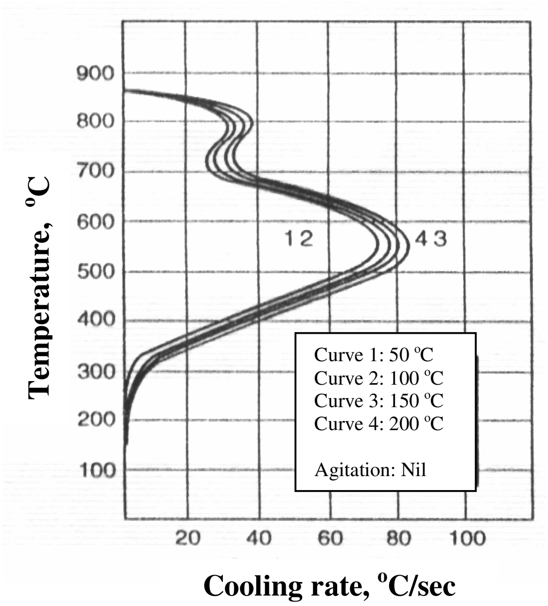


Figure 4.3. Effect of temperature on quenching speed of hot oil [35]

Flash point, another consideration, is the lowest temperature at which oil vapors ignite in the presence of and ignition source; it is important because it is related to the maximum safe operating temperature – usually 40 to 50 °C below the open cup flash point for oil.

4.1.2. Operating Information

Data on the use temperatures for conventional, accelerated, and marquenching oils are given in Table 4.1.

Table 4.1. Characteristics of Quenching Oils [35]

Type of oil	Bath temperature °C	Flash point °C	Typical viscosity at 40 °C, SUS
Conventional	<65	170	105
Accelerated	<120	180	94
Marquenching	<200	300	700

Applications based on oil speed are as follows:

Normal-speed oils : used for where the hardenability of a steel is high enough to provide specified mechanical properties with slow cooling. Typical appllications are highly alloyed steels and tool steels

Medium-speed oil : typical applications are medium- to high-hardenability steels

High-speed quenching oils : for low hardenability allloys, carburized and carbonitrided parts. And medium hardenability steel parts large in cross-section that require very high rates of cooling to get maximum mechanical properties

Hot oil quenching is for applications where it is desirable to keep distortion and cracking to a minimum. It is a two-step operation. Operating temperature of the oil is generally 100 to 200 ^{o}C. Operating temperature is held until the temperature throughout the workpiece is uniform. Then, workpieces are air cooled to ambient temperature.

4.2. Tempering Processes/Technology

Tempering is a process in which previously hardened or normalized steel is usually heated to a temperature below the lower critical temperature and cooled at a suitable rate, primarily to increase ductility and toughness, but also to increase grain size of the matrix. Steels are tempered by reheating after hardening to obtain specific values of mechanical properties and also to relieve quenching stresses and to ensure dimensional stability. Tempering usually follows quenching from above the upper critical temperature; however, tempering is also used to relieve the stresses and reduce the hardness developed during welding and to relieve stresses induced by forming and machining.

4.2.1. Principal Variables

Variables that affect the microstructure and the mechanical properties of a tempered steel include tempering temperature, time at temperature, cooling rate from the tempering temperature, composition of the steel, including carbon content, alloy content, and residual elements.

Table 4.2. Typical Hardnesses of Various Carbon and Alloy Steels after Tempering [36]

	Carbon Content	Hardness, HRC, after tempering for 2 h at (°C)							
Grade	%	205	260	315	370	425	480	540	Heat treatment
Carbon steels, water hardening									
1030	0,30	50	45	43	39	31	28	25	Normalized at 900 °C, water quenched from 830-845 °C, average dew point, 16 °C
1040	0,40	51	48	46	42	37	30	27	
1050	0,50	52	50	46	44	40	37	31	
1060	0,60	56	55	50	42	38	37	35	Normalized at 885 °C, water quenched from 800-815 °C, average dew point, 7 °C
1080	0,80	57	55	50	43	41	40	39	
1095	0,95	58	57	52	47	43	42	41	
Alloy steels, water hardening									
1330	0,30	47	44	42	38	35	32	26	Normalized at 900 °C, water quenched from 800-815 °C, average dew point, 16 °C
2330	0,30	47	44	42	38	35	32	26	
3130	0,30	47	44	42	38	35	32	26	
4130	0,30	47	45	43	42	38	34	32	Normalized at 885 °C, water quenched from 800-855 °C, average dew point, 16 °C
5130	0,30	47	45	43	42	38	34	32	
8630	0,30	47	45	43	42	38	34	32	
Alloy steels, oil hardening									
1340	0,40	57	53	50	46	44	41	38	Normalized at 870 °C, oil quenched from 830-845 °C, average dew point, 16 °C
3140	0,40	55	52	49	47	41	37	33	
4140	0,40	57	53	50	47	45	41	36	
4340	0,40	55	52	50	48	45	42	39	Normalized at 870 °C, oil quenched from 830-845 °C, average dew point, 13 °C
4640	0,40	52	51	50	47	42	40	37	
8740	0,40	57	53	50	47	44	41	38	
4150	0,50	56	55	53	51	47	46	43	Normalized at 870 °C, oil quenched from 830-870 °C, average dew point, 13 °C
5150	0,50	57	55	52	49	45	39	34	
6150	0,50	58	57	53	50	46	42	40	
Data were obtained on 25 mm bars adequately quenched to develop full hardness.									

In a steel quenched to a microstructure consisting essentially of martensite, the iron lattice is strained by the carbon atoms, producing the high hardness of quenched steels.

Under certain conditions, hardness may remain unaffected by tempering or may even be increased as a result of it. For example, tempering a hardened steel at very low tempering temperatures may cause no change in hardness but may achieve a desired increase in yield strength. Also, those alloy steels that contain one or more of the carbide-forming elements (chromium, molybdenum, vanadium, and tungsten) are capable of secondary hardening; that is, they may become somewhat harder as a result of tempering.

The tempered hardness values for several quenched steels are presented in Table 4.2. Temperature and time are interdependent variables in the tempering process. Within limits, lowering temperature and increasing time can usually produce the same result as raising temperature and decreasing time. However, minor temperature changes have a far greater effect than minor time changes in typical tempering operations. With few exceptions, tempering is done at temperatures between 175 and 705 ^{o}C and for times from 30 min to 4 h.

4.2.2. Structural Changes

Based on x-ray, dilatometric, and microstructural studies, there are there distinct stages of tempering, even though the temperature ranges overlap :

Stage I : The formation of transition carbides and lowering of the carbon content of the martensite to 0.25 % (100 to 250 ^{o}C).

Stage II : The transformation of retained austenite to ferrite and cementite (200 to 300 ^{o}C).

Stage III : The replacement of transition carbides and low-temperature martensite by cementite and ferrite.

4.2.3. Dimensional Changes

Martensite transformation is associated with an increase in volume. During tempering, martensite decomposes into a mixture of ferrite and cementite with a resultant decrease in volume as tempering temperature increases. Because a 100% martensitic structure after quenching cannot always be assumed, volume may not continuously decrease with increasing tempering temperature.

The retained austenite in plain carbon steels and low-alloy steels transforms to bainite with an increase in volume, in stage II of tempering. When certain alloy steels are tempered, a precipitation of finely distributed alloy carbides occurs, along with an increase in hardness, called secondary hardness, and an increase in volume. With the precipitation of alloy carbides, the M_S temperature (temperature at which martensite starts to form from austenite upon cooling) of the retained austenite will increase and transform to martensite during cooling from the tempering temperature.

4.2.4. Tempering Temperature

Several empirical relationships have been made between the tensile strength and hardness of tempered steels. The measurement of hardness commonly is used to evaluate the response of a steel to tempering. Figure 4.4 shows the effect of tempering temperature on hardness, tensile and yield strengths, elongation, and reduction in area of a plain carbon steel (AISI 1050) held at temperature for 1 h. It can he seen that both room-temperature hardness and strength decrease as the tempering temperature is increased. Ductility at ambient temperatures, measured by either elongation or reduction in area, increases with tempering temperature.

Most medium-alloy steels exhibit a response to tempering similar to that of carbon steels. There is no decrease in ductility in the temperature range of tempered martensite embrittlement, or TME (also known as 260 °C embrittlement or one-step temper embrittlement) because the tensile tests are performed on smooth, round specimens at relatively low strain rates. However, in impact loading, catastrophic failure may result when alloy steel is tempered in the tempered martensite embrittlement range (260 to 370 °C).

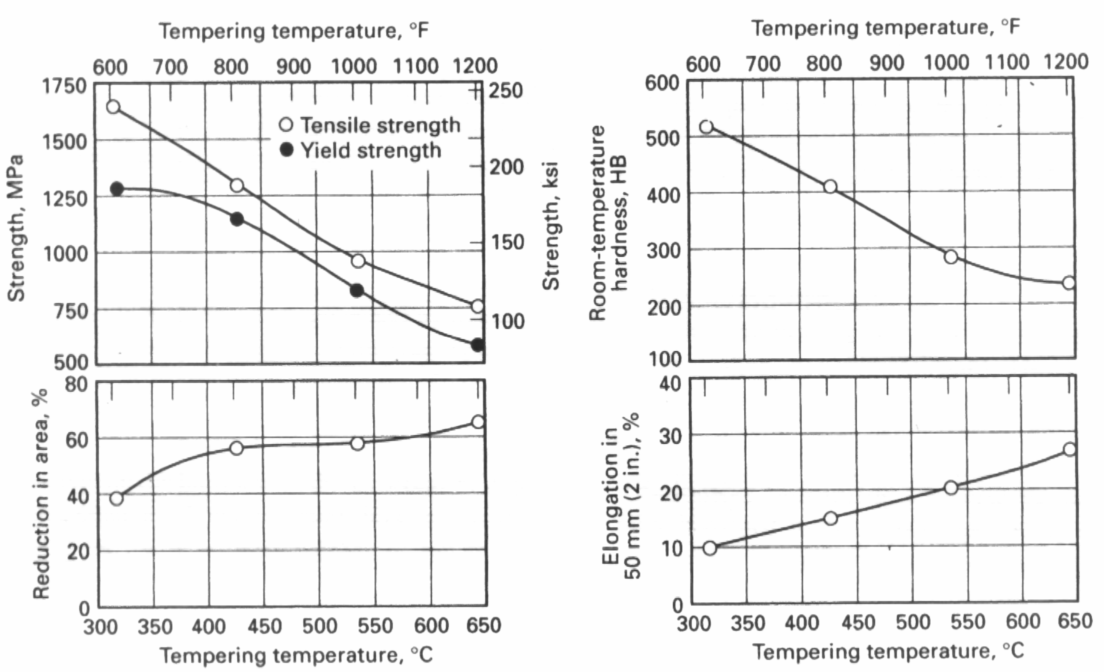


Figure 4.4. Effect of tempering temperature on room-temperature mechanical properties of 1050 steel [36]

Whereas elongation and reduction in area increase continuously with tempering temperature, toughness, as measured by a notched-bar impact test, varies with tempering temperature for most steels.

4.2.5. Tempering Time

The diffusion of carbon and alloying elements necessary for the formation of carbides is temperature and time dependent. The effect of tempering time on the hardness of a 0.82 % C steel tempered at various temperatures is shown in Figure 4.5. Changes in hardness are approximately linear over a large portion of the time range when the time is presented on a logarithmic scale. Rapid changes in room temperature hardness occur at the start of tempering in limes less than 10 s. Less rapid, but still large, changes in hardness occur in limes from 1 to 10 min, and smaller changes occur in times from 1 to 2 h. For consistency and less dependency on variations in time, components generally are tempered for 1 to 2 h. The levels of hardness produced by very short tempering cycles, such as in induction tempering, would be quite sensitive to both the temperature achieved and the time at temperature.

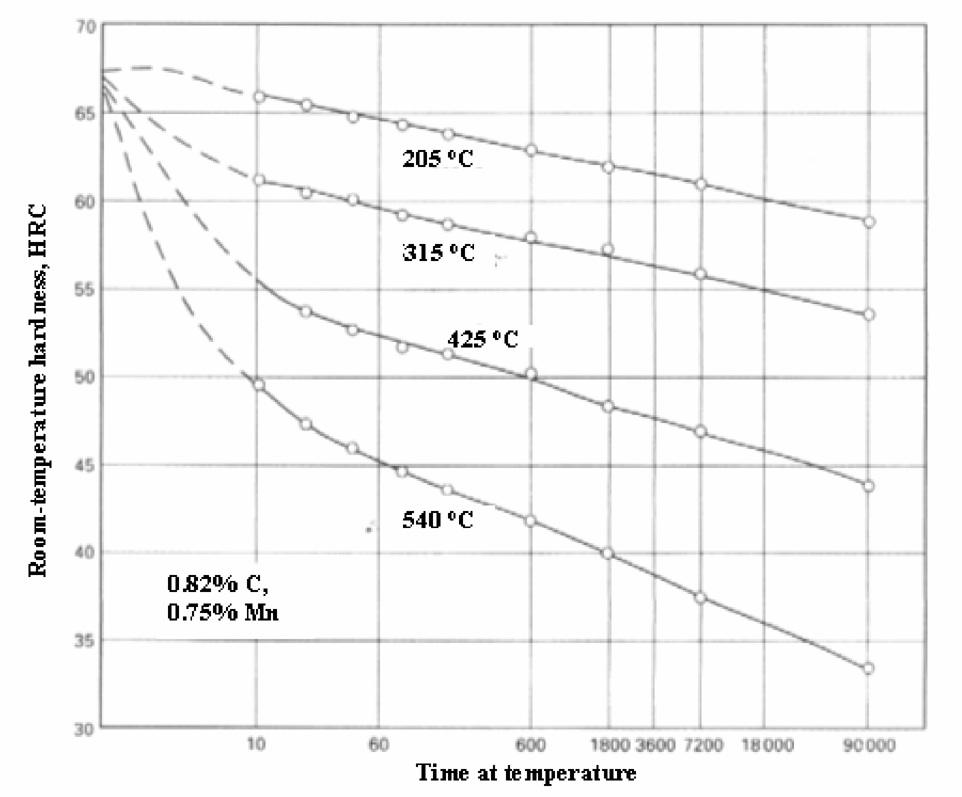


Figure 4.5. Effect of time at four tempering temperatures on room-temperature hardness of quenched 0.82 % C steel. [36]

4.2.6. Carbon Content

The principal effect of carbon content is on as-quenched hardness. The relative difference in hardness compared with as-quenched hardness is retained after tempering.

4.2.7. Alloy Content

The main purpose of adding alloying elements to steel is to increase hardenability (capability to form martensite upon quenching from above its critical temperature). The general effect of alloying elements on tempering is a retardation of the rate of softening, especially at the higher tempering temperatures. Thus, to reach a given hardness in a given period of time, alloy steels require higher tempering temperatures than do carbon steels.

Alloying elements can be characterized as carbide forming or non-carbide forming. Elements such as nickel, silicon, aluminum, and manganese, which have little or no tendency to occur in the carbide phase, remain essentially in solution in the ferrite and have only a minor effect on tempered hardness. The carbide forming elements (chromium, molybdenum, tungsten, vanadium, tantalum, niobium, and titanium) retard the softening process by the formation of alloy carbides.

Strong carbide-forming elements such as chromium, molybdenum, and vanadium are most effective in increasing hardness at higher temperatures above 205 °C. Silicon was found to be most effective in increasing hardness at 315 °C. The increase in hardness caused by phosphorus, nickel, and silicon can be attributed to solid-solution strengthening. Manganese is more effective in increasing hardness at higher tempering temperatures. The carbide-forming elements retard coalescence of cementite during tempering and form numerous small carbide particles. Under certain conditions, such as with highly alloyed steels, hardness may actually increase. This effect, mentioned previously, is known as secondary hardening.

In addition to ease of hardening and secondary hardening, alloying elements produce a number of other effects. The higher tempering temperatures used for alloy steels presumably permit greater relaxation of residual stresses and improve properties. Furthermore, the hardenability of alloy steels requires use of a less drastic quench so that quench cracking is minimized. However, higher hardenability steels are prone to quench cracking if the quenching rate is too severe. The higher hardenability of alloy steels may also permit the use of lower carbon content to achieve a given strength level but with improved ductility and toughness [36, 37].

5. EXPERIMENTAL STUDY

5.1. Materials Used in the Experiments

As mentioned before, during the last two decades, considerable efforts have been made in the development of high performance spring steels to meet the needs for weight and cost savings in the automotive industry. DIN 50CrV4 or AISI 6150 spring steel is widely used as a spring material in this industry. It is a medium high-carbon chromium-vanadium alloy steel which has been used for numerous applications including premium quality springs. Its as-quenched hardness is generally 55 to 60 HRC, depending on the precise carbon content. Hardenability is relatively high, approximately the same as for 4140H. The chromium content is mainly responsible for the hardenability. The vanadium serves as a grain refiner and has no significant effect on hardenabilily. Is forgeable, but is not recommended for welding [38].

The chemical composition of 6150 steel alloy is 0.48 to 0.53 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.80 to 1.10 Cr, 0.15 V min. The chemical composition of 50CrV4 steel alloy is 0.47 to 0.55 C, 0.70 to 1.00 Mn, 0.035 P max, 0.035 S max, 0.15 to 0.40 Si, 0.90 to 1.20 Cr, 0.15 V min. 6150 and 50CrV4 steels are in the same category of spring steel designated by AISI and DIN, respectively [39,40].

Table 5.1. Chemical composition of A steel alloy used in the study (as per cent).

C	Si	S	P	Mn	Ni	Cr	Mo	V	Cu	Ti	Al
0.52	0.31	0.006	0.010	0.99	0.14	1.11	0.02	0.13	0.18	0.00	0.024

Table 5.2. Chemical composition of B steel alloy used in the study (as per cent).

C	Si	S	P	Mn	Ni	Cr	Mo	V	Cu	Ti	Al
0.55	0.31	0.006	0.008	1.08	0.14	1.28	0.02	0.13	0.22	0.01	0.030

In this experiment, two different 50CrV4 alloys are investigated. For convenience, 50CrV4 steel alloy not microalloyed with Ti will be referred to as A steel alloy hereinafter, while 50CrV4 steel alloy microalloyed with Ti as B steel alloy. A and B steel alloy are obtained from “Uzel Otomotiv Sistemleri A.Ş.”. Their chemical compositions are given in Table 5.1 and Table 5.2, respectively.

5.2. Heat Treatment

Recommended heat treatment practice for 50CrV4 steel alloy is for normalizing, heat to 900 °C, then, cool in air.

For annealing, in order to obtain a predominantly pearlitic structure, heat to 830°C, cool rapidly to 760 °C, then cool to 675 °C. at a rate not to exceed 8 °C per h; or heat to 830 °C, cool rapidly to 675 °C, and hold for 6 h. To obtain a predominantly spheroidized structure, heat to 760 °C, and cool to 675 °C at a rate not to exceed 6 °C per h; or heat to 760 °C, cool rapidly to 650 °C, and hold for 10 h.

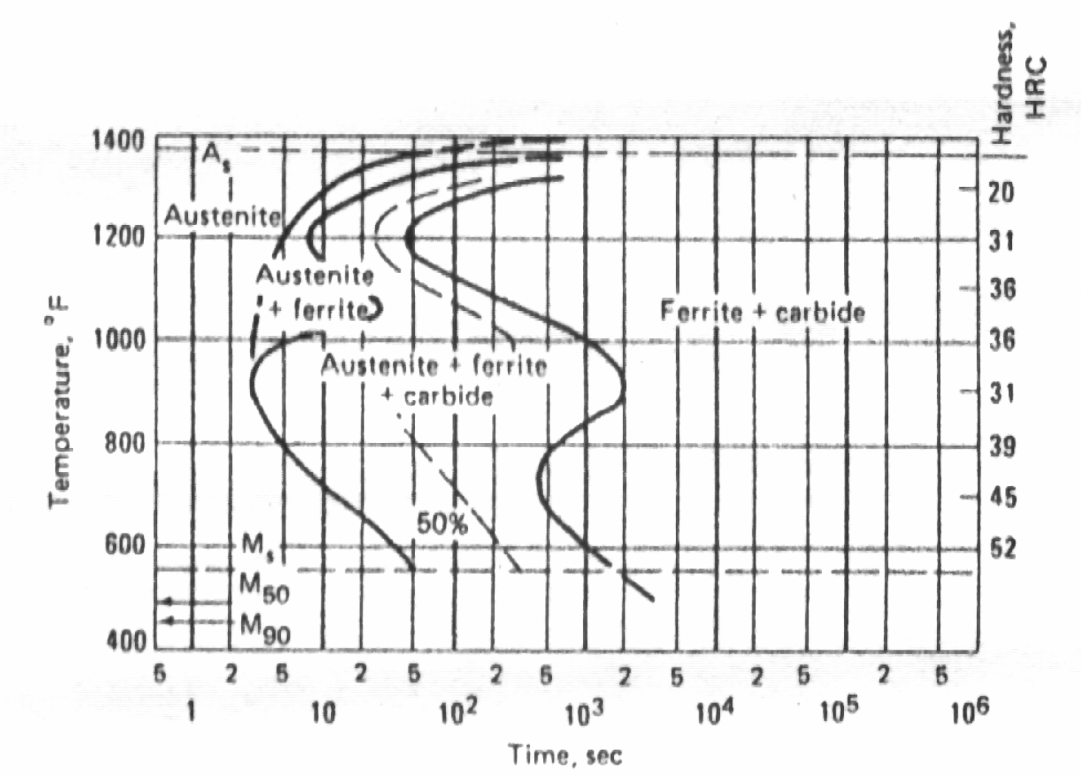


Figure 5.1. 6150: Isotermal Transformation Diagram. [38]

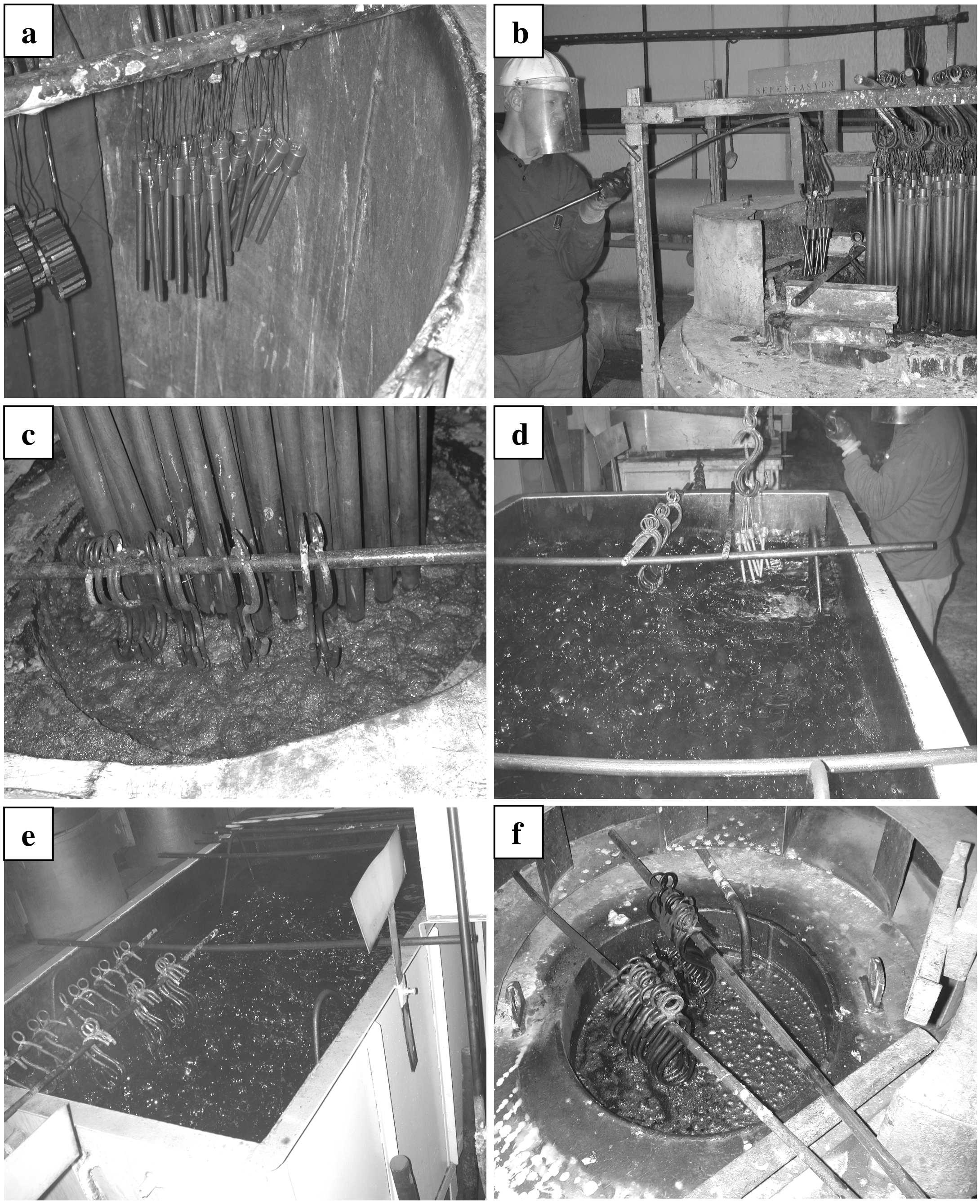


Figure 5.2. The process of heat treatment : a) preheating, b) inserting into austenitization bath, c) austenitization, d) inserting into oil quenching media, e) oil quenching, f) tempering

For hardening, heat to 870 °C, and quench in oil. Then for tempering, reheat immediately after quenching (preferably before the temperature of the parts drops below the range of 38 to 50 °C) to the temperature required to obtain the desire combination of mechanical properties.

For austempering. in many spring applications, this steel is austempered by austenitizing at 870 °C, quenching in an agitated molten salt bath at 315 °C, holding for 1 h, and air cooling. No tempering is required. Hardness after this treatment generally ranges from approximately 46 to 51 HRC [38].

In this experiment, the heat treatments were performed at Uzel Heat Treatment Department. Specimens were heat treated by preheating to 300–400 °C, then austenitizing at 910 °C for 10 minutes, then oil quenching. And ultimately, in order to observe the effect of tempering temperature on mechanical properties of A and B steel alloys, the specimens were tempered at two different temperature, 410 °C and 440 °C, and hold for 1 hour at these temperatures. For convenience, A steel alloy tempered at 410 °C will be referred to as AD steel alloy hereinafter, while A steel alloy tempered at 440 °C as AX steel alloy. And likewise, B steel alloy tempered at 410 °C will be referred to as BD steel alloy hereinafter, while B steel alloy tempered at 440 °C as BX steel alloy. The heat treatments applied in this study are tabulated in Table 5.3. So, there are four groups of steel alloys investigated for mechanical properties.

Table 5.3. The heat treatment schedule.

Steel	Austenitization	Tempering
AD	910 °C, 10 min. → Oil quenching	410 °C, 1 h
AX	910 °C, 10 min. → Oil quenching	440 °C, 1 h
BD	910 °C, 10 min. → Oil quenching	410 °C, 1 h
BX	910 °C, 10 min. → Oil quenching	440 °C, 1 h

The austenitizing and tempering were performed in neutral salt bath with a temperature control of ±1 °C. During austenitizing, all specimens of each combination of steel was inserted into the bath all together in order to attain same mechanical properties in every individual specimen of each group. Then, the specimens were quenched in agitated oil at 25 °C. The process of heat treatment is illustrated in Figure 5.2.

5.3. Mechanical Testing

5.3.1. Tensile Testing

The room temperature longitudinal tensile properties were determined according to ASTM E-8M [41] using a 9 mm in diameter and 45 mm in gage length round specimens as shown in Figure 5.3. Specimens were machined oversized from the bars, and after the heat treatments, were ground to the final dimensions. Triple tests were performed for each conditions means 12 tensile testing specimens were prepared for four group. Tensile tests were performed using "Zwick Tensile Testing Machine" shown in Figure 5.4 in Uzel laboratory.

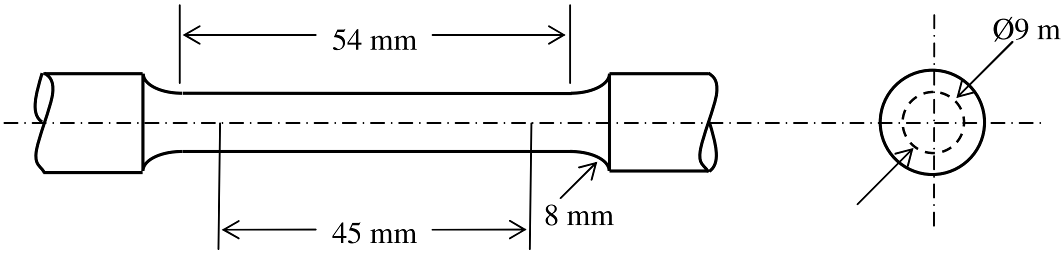


Figure 5.3. Tensile test specimens.

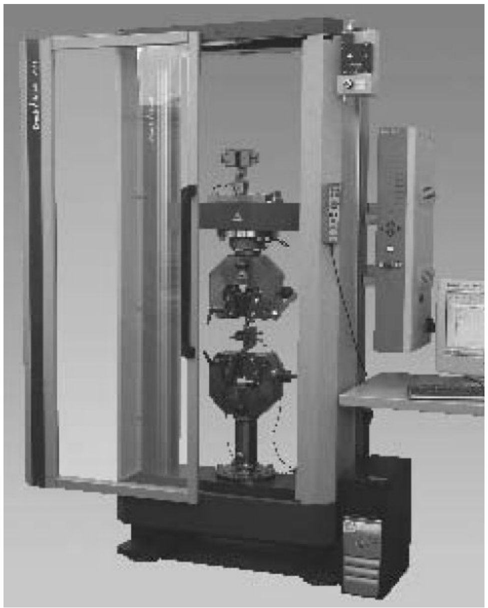


Figure 5.4. Zwick Tensile Testing Machine

5.3.2. Hardness Testing

Hardness tests were carried out from the fatigue and tensile tests specimens, individually. Two points, center and surface, were measured for each specimen for Brinell micro-hardness testing according to ASTM E-10 [42]. In Brinell test, a specified load is applied to a flat surface of the specimen to be tested, through a hard ball of specified diameter. The average diameter of the indentation is used as a basis for calculation of the Brinell hardness number.

For the test specimen, Brinell hardness tests are made on prepared areas and sufficient metal must be removed from the surface to eliminate decarburized metal and other surface irregulaties. The thickness of the piece tested must be such that no bulge or other marking showing the effect of the load appears on the side of the piece opposite the indentation. The tests were applied on “Emcotest M4U 025 Hardness Machine”.

Figure 5.5. Hardness testing machine

5.3.3. Impact Testing

A Charpy V-notch impact test is a dynamic test in which a notched specimen is struck and broken by a single blow in a specially designed testing machine. The measured test values may be the energy absorbed, the percentage shear fracture, the lateral expansion opposite the notch, or a combination thereof.

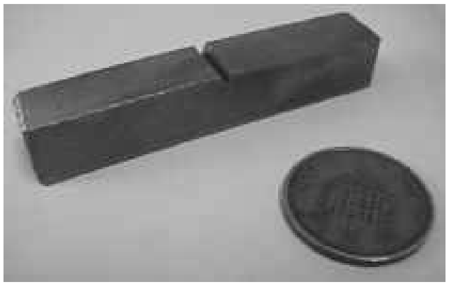


Figure 5.6. Charpy V-notch specimen

A Charpy impact machine is one in which a notched specimen is broken by a single blow of a freely swinging pendulum. The pendulum is released from a fixed height. Since the height to which the pendulum is raised prior to its swing, and the mass of the pendulum are known, the energy of the blow is predetermined. A means is provided to indicate the energy absorbed in breaking the specimen.

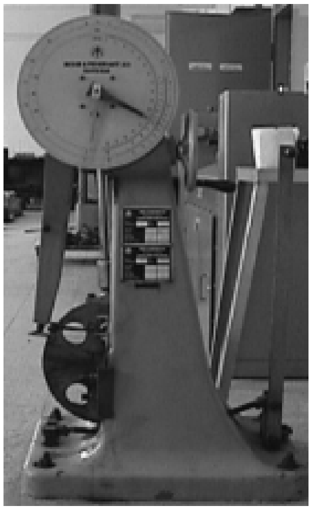


Figure 5.7. Impact testing machine

The room temperature longitudinal impact properties were determined using Charpy V-notch specimens as shown in Figure 5.6. While testing, ASTM A 370-05 standard is used [42]. Three specimens were prepared for each of 4 groups. Testing is done on “Mohr&Federhaff Ag. Charpy Testing Machine” shown in Figure 5.7.

5.3.4. Fatigue Testing

Fatigue is the progressive, localized, and permanent structural change that occurs in a material subjected to repeated or fluctuating strains at nominal stresses that have maximum values less than (and often much less than) the static yield strength of the material. Fatigue may culminate into cracks and cause fracture after a sufficient number of fluctuations [43].

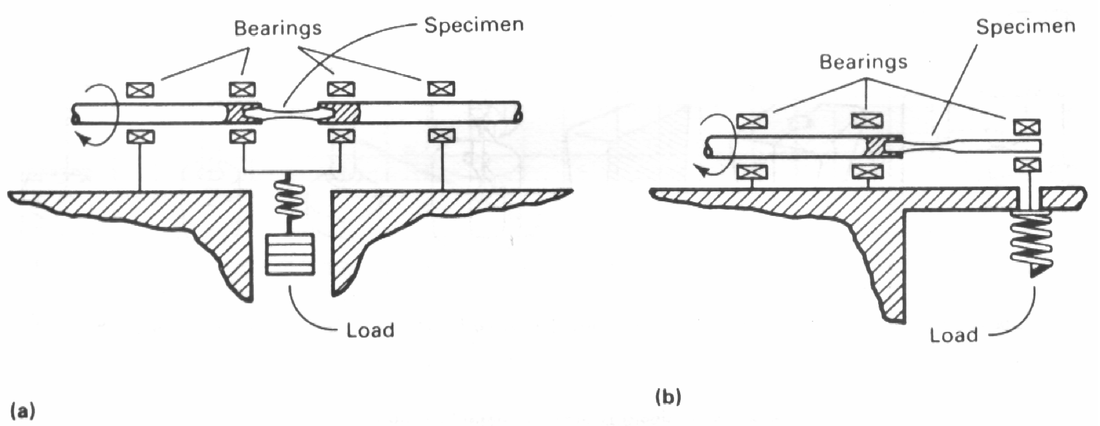


Figure 5.8. Schematic of rotating beam fatigue testing machines a) Four point loading R.R. Moore testing machine, b) Single-end rotating cantilever testing machine [44]

Fatigue test specimens are primarily described by the mode of loading :

- Direct (axial) stress
- Plane bending
- Rotating beam
- Alternating torsion
- Combined stress

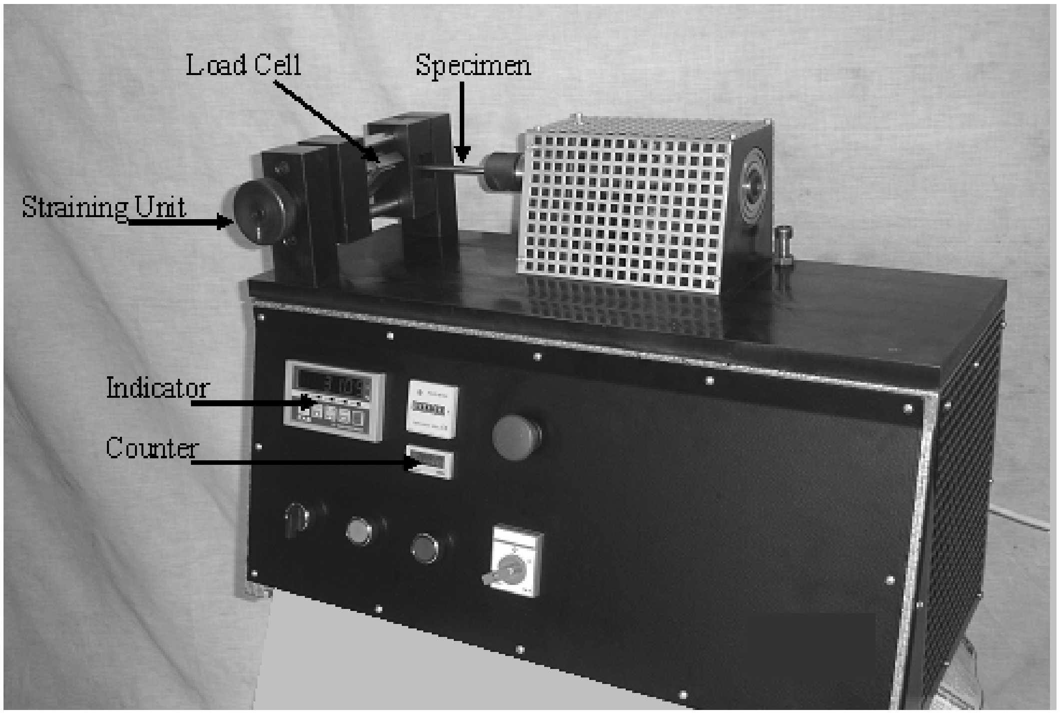


Figure 5.9. Rotating bending fatigue test machine

Testing machines, however, may be universal-type machines that are capable of conducting all of the above modes of loading, depending on the fixtures used.

The most common types of fatigue machines are small bending fatigue machines. In general, these simple, inexpensive systems allow laboratories to conduct extensive test programs with a low equipment investment.

Cantilever beam machines, in which the test specimen has a tapered width, thichness, or diameter, result in a portion of the test area having uniform stress with smaller load requirements than required for uniform bending or axial fatigue of the same section size [44].

Typical rotating beam machine types are shown in Figure 5.8. The R.R. Moore-type machines (Figure 5.8a) can operate up to 10000 rpm. Rotating bending fatigue test is a simple method of determining fatigue properties at zero mean load by applying known bending moments to rotating round specimens [45]. Large amounts of *S-N* data have been historically generated based on fully reserved rotating bending testing machines [46]. In all bending-type tests, only the material near surface is subjected to the maximum stress; therefore, in a small-diameter specimen, only a very small volume of material is under test.

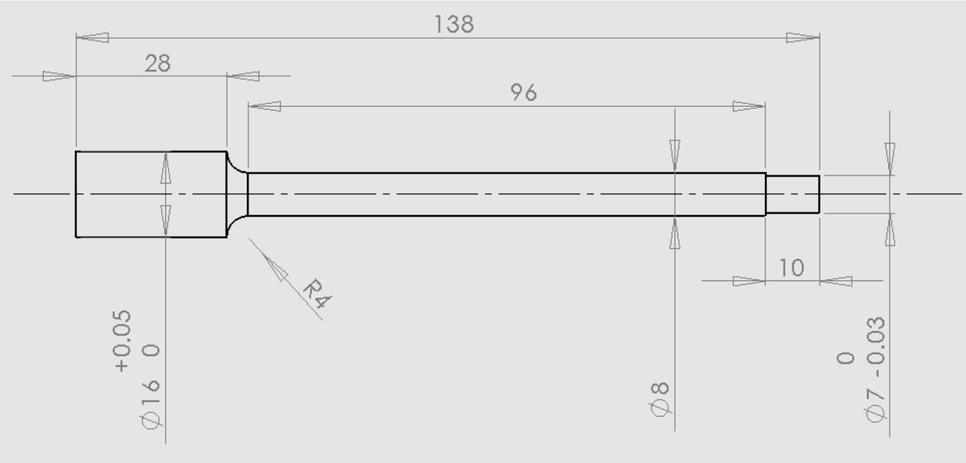


Figure 5.10. Rotating bending fatigue test specimen

A typical fatigue test specimen has three areas: the test section and the two grip ends. The grip ends are designed to transfer load from the test machine grips to the test section. The design and type of specimen used depend on the fatigue testing machine used and the objective of the study [44].

In this study, a rotating bending fatigue test unit was set to the laboratory as shown in Figure 5.9. This unit is a single-end rotating cantilever testing machine as shown in Figure 5.8b.

The working principle of this machine is simple. A 1 HP (0.75 kW) motor with 3000 rpm transmits power to the spindle via V-belt. And, the fatigue specimen shown in Figure 5.10 is mounted to the end of the spindle via clamp while other side of the specimen is assembled to the bearing. The bearing is mounted to the load cell, and the load cell is mounted to the straining screw. Ultimately, straining screw is assembled to the steering wheel.

As the steering wheel is turned, the straining unit pulls the specimen via the bearing mounted on it. Due to this pulling, the specimen is bended. The load cell measures the pulling force, and finally, from the indicator the pulling force is read. Also, a sensor is placed at the end of motor spindle. Its duty is to sense the rotation and to send pulses to the counter so as to count the number of rotation. One rounds corresponds one cycle of the fatigue. The working principle is illustrated in Figure 5.11.

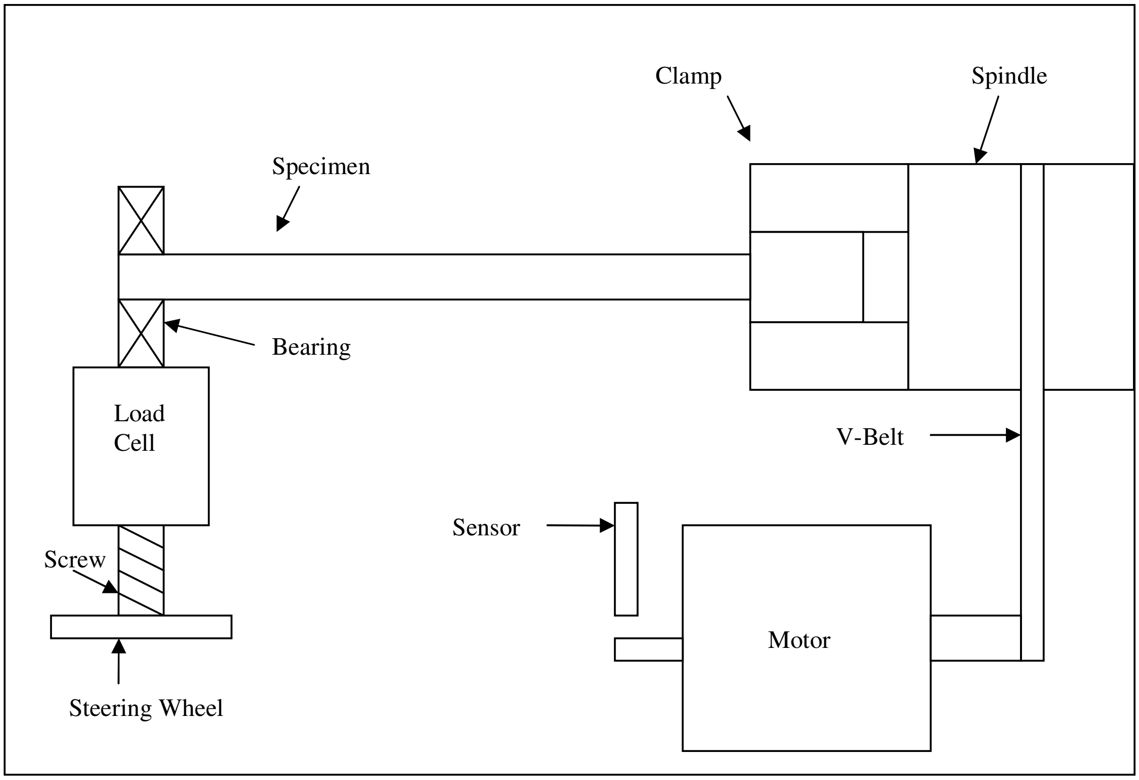


Figure 5.11. Schematic illustration of rotating beam fatigue machine

In this type of rotating bending fatigue test machine the deflection in the specimen cannot be precisely measured. Instead of this, as its mentioned before, the load cell measures the pulling force acting on the specimen (Then, reciprocating stress is calculated with the formula 5.5). In addition to this, as the load cell is mounted to the straining unit, the pulling force is continuously measured during the test. So, at any stage of the test the load applied can be read from the indicator which enhances the reliability of the test..

The other significant point of this machine is that the load indicator can be adjusted to the upper and lower limits to run the machine. This means for instance, the test will be done at some stress value corresponds to the 40 kg of pulling force. If the indicator is adjusted to the upper value of 40 kg, and to the lower value of 39 kg, the motor would only run between the pulling force of 39 and 40 kg. This property gives two advantages to the machine. First, it improves reliability, second, the machine will automatically stops after fracture occurs (If the lower value is adjusted to very low value, for instance 1 kg which means fracture occurs, the machine will stop after the loading reduces under 1 kg).

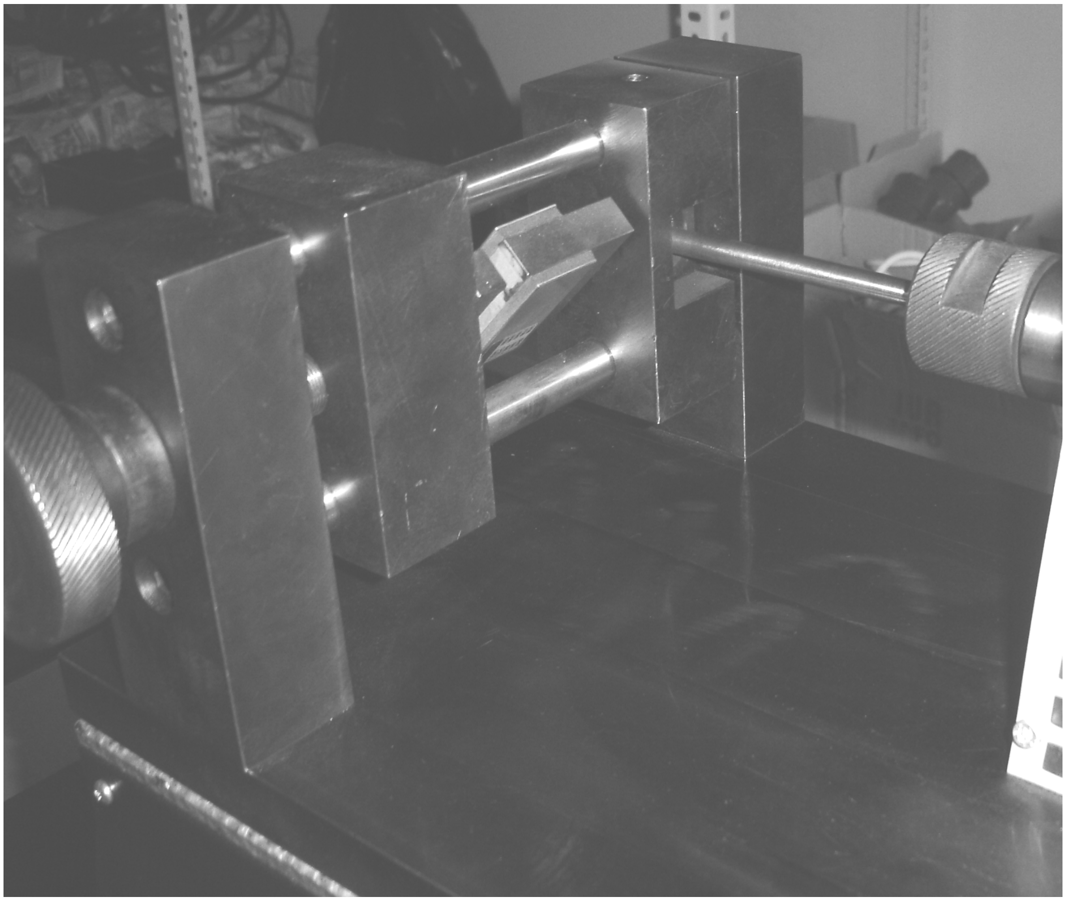


Figure 5.12. Straining mechanism of the rotating bending fatigue machine

Fatigue life (N) is the number of cycles of stress or strain of a specified character that a given specimen sustains before failure of a specified nature occurs [47].

Fatigue limit (or endurance limit) is the value of the stress below which a material can presumably endure an infinite number of stress cycles, that is, the stress at which the *S*-

N diagram becomes and appears to remain horizontal. The existence of a fatigue limit is typical for carbon and low-alloy steels.

Historically, engineers have relied on macroscopic properties such as hardness and tensile strength to estimate fatigue limits. A general relationship between the fatigue limit and the tensile strength of a material has been observed. The value for the ratio of the bending fatigue limit and the tensile strength in the linear range varies from 0.25 to 0.6, depending on the microstructure of the steel (e.g., grain size, inclusions, porosity, and graphite nodules). The bending fatigue limit of steel having highly tempered martensite microstructure is estimated as 55 % of the tensile strength [46].

Fatigue strength, which should not be confused with fatigue limit, is the stress to which the material can be subjected for a specified number of cycles. The term fatigue strength is used for materials, such as most nonferrous metals, that do not exhibit well-defined fatigue limits. It is also used to describe the fatigue behavior of carbon and low-alloy steels at stresses greater than the fatigue limit.

As indicated before, rotation bending fatigue test is used for determining the fatigue properties at zero mean stress. The mean stress, S_m, is the algebraic average of the maximum stress and the minimum stress in one cycle :

$$S_m = \frac{\left(S_{\max} + S_{\min}\right)}{2} \tag{5.1}$$

During fatigue testing, the test specimen is subjected to alternating loads until failure. The loads applied to the specimen are defined by either a constant stress range (S_r) or a constant stress amplitude (S_a). The range of stress, S_r, is defined as the algebraic difference between the maximum stress and the minimum stress in one cycle :

$$S_r = S_{\max} - S_{\min} \tag{5.2}$$

The stress amplitude, S_a, is equal to one-half of the range of stress :

$$S_a = \frac{S_r}{2} = \frac{(S_{\max} - S_{\min})}{2} \tag{5.3}$$

Stress ratio is the algebraic ratio of two specified stress values in a stress cycle. Commonly used stress ratio R is the ratio of the minimum stress to the maximum stress ($R = S_{\min}/S_{\max}$). When stresses are fully reversed as in the rotating bending fatigue test, R = -1.

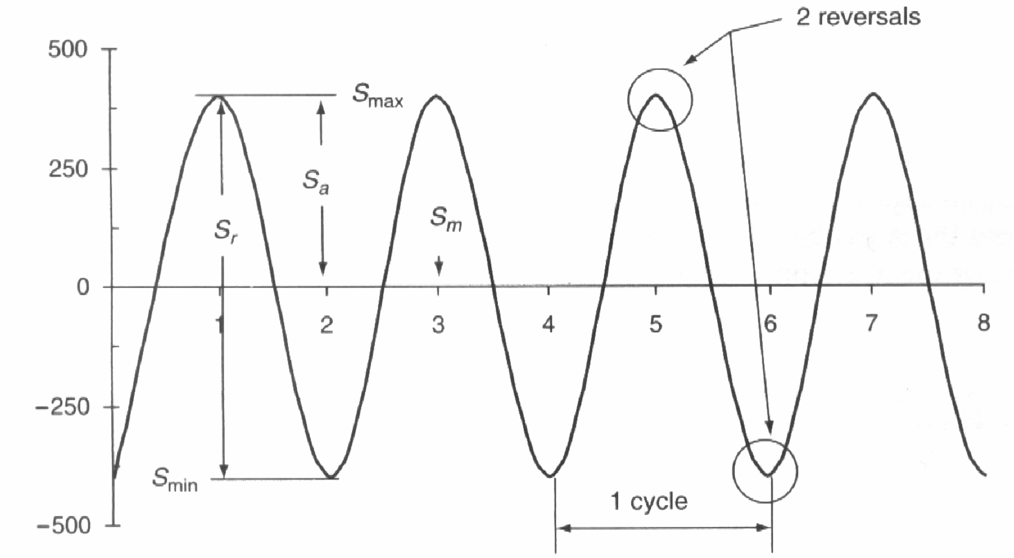


Figure 5.13. Symbols used with cyclic stresses and cycles [46]

Typically, for fatigue analysts, it is a convention to consider tensile stresses positive and compressive stresses negative. The magnitude of the stress range or amplitude is the controlled (independent) variable and the number of cycles to failure is the response (dependent) variable. The number of cycles to failure is the fatigue life (N_f), and each cycle is equal to two reservals ($2N_f$). the symbols of stresses and cycles mentioned previously are illustrated in Figure 5.13.

The results of the fatigue tests are usually plotted as the maximum stress or stress amplitude versus the number of cycles, N_f, to failure, using a logarithmic scale for the number of cycles. Stress may be plotted on either a linear or a logarithmic scale. The resulting curve of data points is called an *S-N* curve. It should be noted that the fully reversed condition, R = -1, is the most severe, with the least fatigue life [43].

The *S-N* curve in fatigue testing is sometimes described by the Basquin equation

$$S_a = S_f^{'}(2N_f)^b \tag{5.4}$$

where S_a is the stress amplitude and both $S_f^{'}$ and *b* represent empirical constants that depend on material properties and testing conditions. $S_f^{'}$ is related to the fatigue strength coefficient (which, to a good approximation, equals the true fracture strength S_f, corrected for neckling, in a monotonic tension test for most metals) of the material and *b* represents the fatigue strength exponent or Basquin exponent which, for most metals, is in the range of -0,05 to -0,12 [48-50].

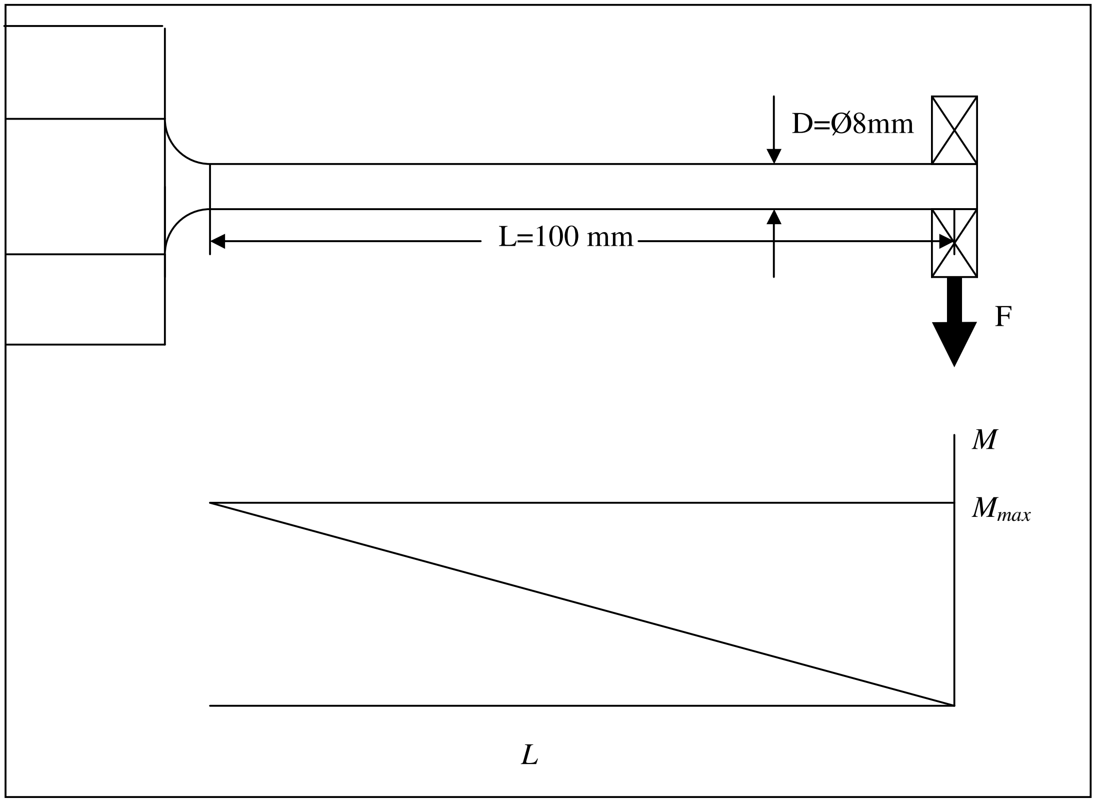


Figure 5.14. Schematic illustration of the loading of the specimen

Since the mid-1800s, a standard method of fatigue analysis and design has been the stress-based approach. This method is also referred to as the stress-life or the *S-N* approach [46].

The design of a machine element that will be subjected to cyclic loading can be approached by adjusting the configuration of the part so that the calculated stresses fall safely below the required line on an *S-N* plot. In a stress-based analysis, the material is assumed to deform in a nominally elastic manner, and local plastic strains are neglected. To extend that these approximations are valid, the stress-based approach is useful. These assumptions imply that all the stresses will essentially be elastic [43].

The rotating bending fatigue test machine set up for this study is working on a principle of the stress-based approach. The loading of the fatigue specimen is illustrated in Figure 5.14. The maximum stress, S_{max}, can be calculated by bending stress formula :

$$S_{\max} = \frac{32M_{\max}}{\Pi D^3} \tag{5.5}$$

Here $M_{\max}$ is the maximum bending moment, D is the diameter of the fatigue specimen. $M_{\max}$ is the multiplication of the force acting on the specimen and the length of the testing region ($M_{\max}$=F.L).

In the rotating bending fatigue test, for each group 20 fatigue specimens were prepared. This means totally 80 fatigue specimens were prepared and heat treated for 4 groups. The specimens were formed from 30 mm diameters bars to their final shapes as shown in Figure 5.10 by turning. Only in testing region (the section having 8 mm diameter) is machined oversized. Then the specimens are heat treated as its mentioned in section 5.2, heat treatment section, by their groups. After the heat treatment process, the surfaces of the specimens were grinded with 120-220-360-600-1200 grinding papers to their final sizes, successively in order to obtain a similar mirror-like polished surface before testing. The tests were carried out in air at room temperature (23 ^{o}C).

The evaluation of the fatigue strength of each group was carried out employing 12 samples, which meets the number of specimens required in *S-N* testing for research and development testing of components and specimens according to the ASTM standard 739 (6-12 samples) [51].

It is well known that the shape of *S-N* curves can depend markedly on the material and test conditions. In this experiment the linearized *S-N* relationship of the following formula is used [51].

$$\log N = A + B(S) \tag{5.6}$$

According to the ASTM E-468 standards, infinite life was specified at a number of $5X10^6$ cycles [52]. The test stress is decreased for each succeeding specimen until one or two specimens do not fail in the specified numbers of cycles. The highest stress at which a runout (nonfailure) is obtained is taken as the fatigue limit [50].

Figure 5.15. Optical microscope and monitoring system

5.4. Metallographic Examination

Sections to be used for metallography were cut from the fatigue and tensile specimens. They were ground on successively 220 and 400 grit abrasive papers under flood to prevent heating and then polished to 9 and 3 μm finish successively using special solutions. All specimens for microstructural study were etched in a 2.5 % nital solution and the microstructures were viewed on “Clemex – Nikon“ optical microscope shown in Figure 5.15.

The specimens were examined for martensitic structure. The spring steel must insure a fully martensitic structure throughout the entire section after the heat treatments. Nonmartensitic transformation products detract from the fatigue properties.

Figure 5.16. Grinding and polishing machine

6. RESULTS AND DISCUSSIONS

As its mentioned before, the specimens are grouped into four according to their alloys and heat treatments. In Table 5.3 the corresponding group names of the specific alloy and heat treatment can be seen.

6.1. Tensile Properties

In tensile testing, the results of 0.2 % yield strength, tensile strength, and elongation are shown in Table 6.1.

Table 6.1. Tensile test results

Group	Trial name	0.2 % Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
AD	AD1	1551	1637	1.48
	AD2	1540	1660	1.60
	AD3	1574	1647	1.51
	AD Average	**1555**	**1648**	**1.53**
BD	BD1	1569	1681	1.52
	BD2	1584	1695	1.66
	BD3	1600	1712	1.62
	BD Average	**1584**	**1696**	**1.60**
AX	AX1	1474	1583	3.48
	AX2	1482	1575	3.41
	AX3	1493	1597	3.55
	AX Average	**1483**	**1585**	**3.48**
BX	BX1	1513	1613	2.56
	BX2	1506	1607	2.64
	BX3	1526	1620	2.75
	BX Average	**1515**	**1613**	**2.65**

As its seen on Figure 6.1, the results for both yield and tensile strengths are higher for tempering temperature of 410 °C than for tempering temperature of 440 °C for both two different 50CrV4 alloys. In addition to this, for both tempering temperature of 410 °C and 440 °C, tensile and yield strength results are slightly higher for B-steel alloy than A-steel alloy.

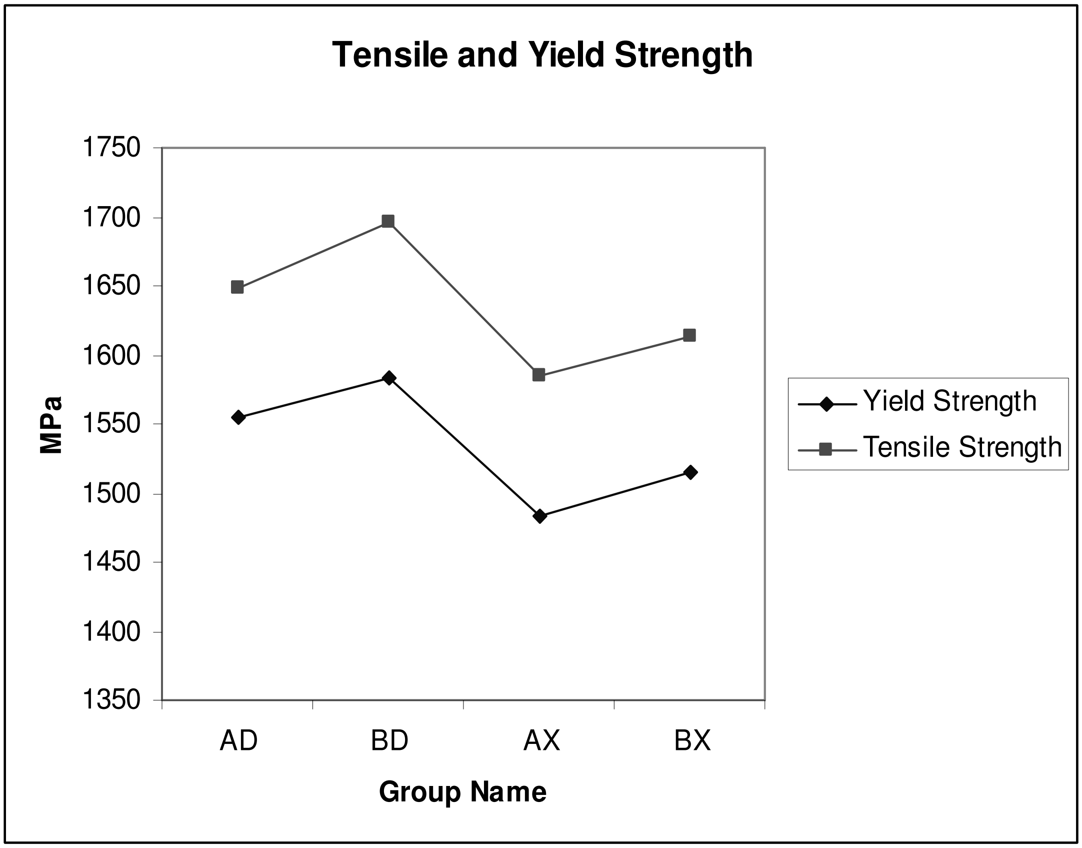


Figure 6.1. Tensile and yield strength comparison of the groups.

About ductility, if we analyse Figure 6.2, when tempering temperature is decreased from 440 °C to 410 °C, elongation is also decreased more than 50 % for A-steel alloy, and about 40 % for B-steel alloy. Another interesting point derived from the figure is that for tempering temperature of 410 °C, elongations of A-steel alloy and B-steel alloy are almost same, elongation of B-steel alloy is slightly higher, while for tempering temperature of 440 °C, elongation of A-steel alloy is much higher than B-steel alloy.

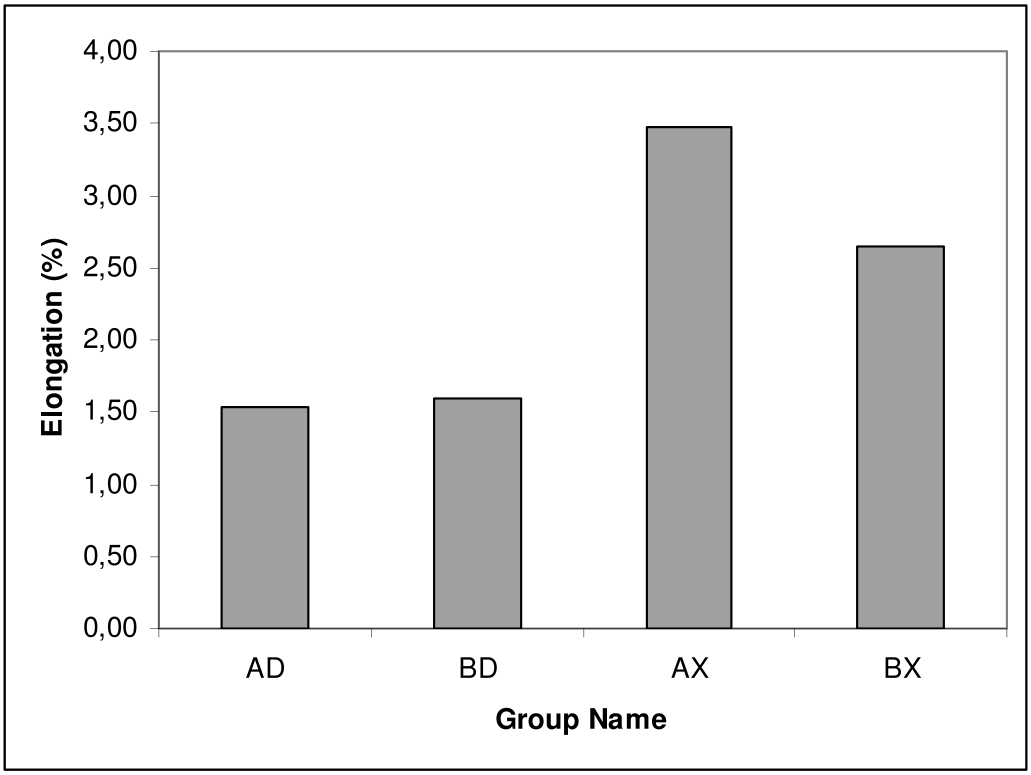


Figure 6.2. Elongation comparison of the groups

6.2. Hardness Properties

In hardness testing, the average of hardness results taken from tensile and fatigue specimens are given in Table 6.2. Here, Brinell test is applied to the specimens.

Table 6.2. Hardness test results

Tempering temperature	Group Name	Brinell hardness of tensile sp. (HB)	Brinell hardness of fatigue sp. (HB)	Average Brinell hardness (HB)
410 °C	AD	486	482	484
	BD	495	499	497
440 °C	AX	455	464	460
	BX	467	470	469

As its seen in Figure 6.3, Brinell hardness number (Bhn) for both steels are higher in tempering temperature of 410 °C than in tempering temperature of 440 °C. Besides, in both tempering temperatures of 410 °C and 440 °C, bhn of B-steel alloy is higher than A-steel alloy.

In order to talk more definitely about hardenability comparison of two alloys, another tempering temperature is applied to the alloys while all other conditions of heat treatments remain same. Here, after oil quenching, one specimen of each alloy is subjected to tempering for 1 hour at 380 °C. At this condition, we come up with the same result of tempering temperature of 410 °C, and 440 °C that hardness of B-steel alloy is higher than of A-steel alloy. In tempering temperature of 380 °C, bhn of B-steel alloy is 511 while bhn of A-steel alloy is 501.

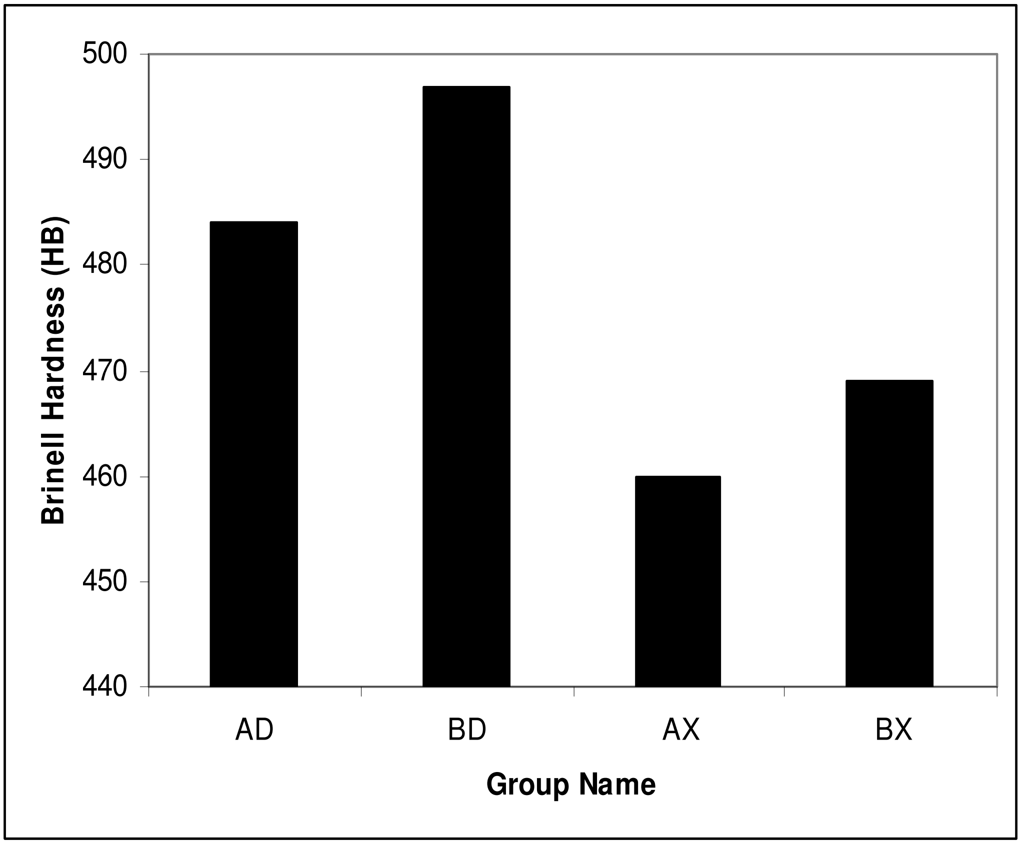


Figure 6.3. Hardness profile of the groups

6.3. Impact Properties

In impact testing, the results of Charpy V-notch impact test are given in Table 6.3. Three specimens were tested per each group and the average of the results are taken into account.

Table 6.3. Charpy impact test results

Group	Trial name	Charpy impact energy (J)
AD	AD1	9
	AD2	6
	AD3	6
	AD Average	**7**
BD	BD1	6
	BD2	6
	BD3	6
	BD Average	**6**
AX	AX1	10
	AX2	10
	AX3	10
	AX Average	**10**
BX	BX1	12
	BX2	12
	BX3	12
	BX Average	**12**

As its represented in Figure 6.4, impact energy of A and B steel alloys are almost same in tempering temperature of 410 °C, impact energy of A steel is slightly higher, while in tempering temperature of 440 °C, impact energy of B-steel alloy is a bit higher but still close to impact energy of A-steel alloy.

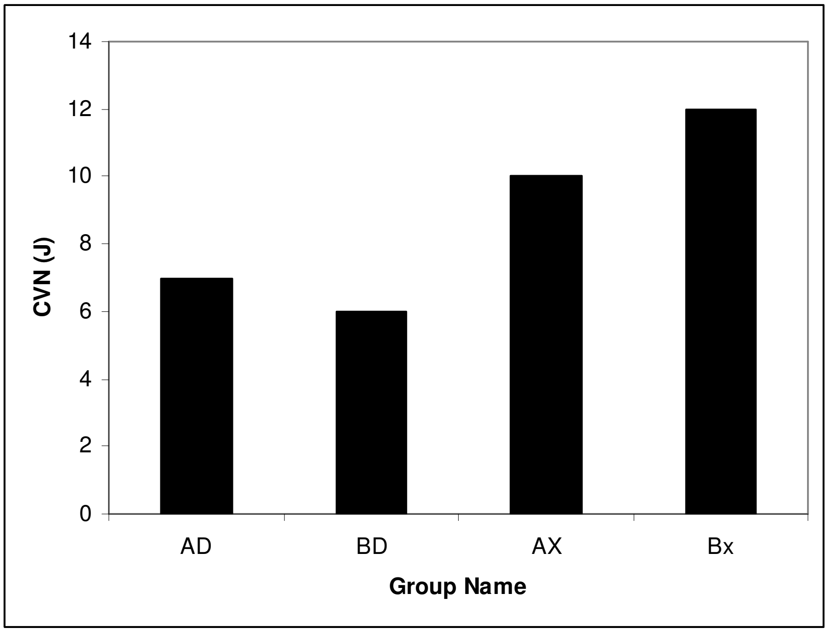


Figure 6.4. Impact test results comparison of the groups

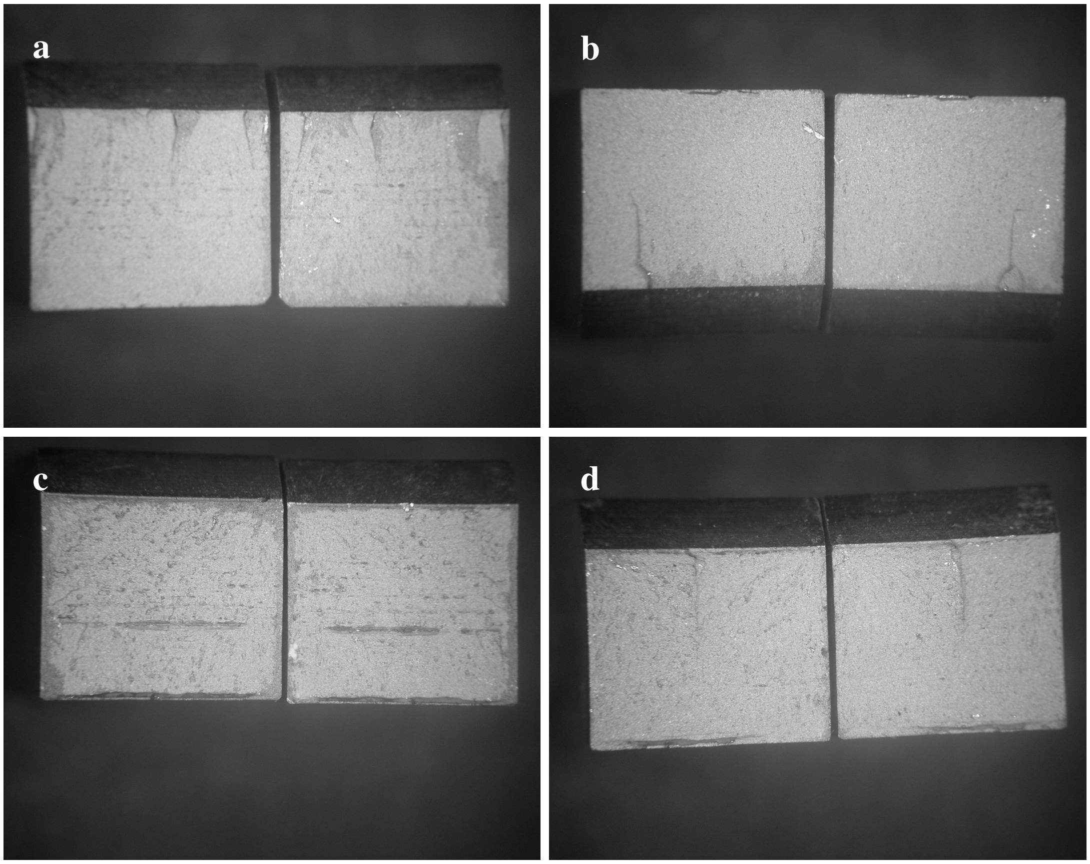


Figure 6.5. Fracture appearance of impact test specimens of a) AD, b) BD, c) AX, d) BX

By increasing the tempering temperature from 410 °C to 440 °C, the impact energy of both A anb B steel alloys dramatically increases, almost become twice of the former.

As its seen from the impact energies, all specimens are very brittle, and by decreasing the tempering temperature, both A and B steel alloys become more brittle. Figure 6.5 shows the fracture appearance of all groups. All photos are taken by stereo microscope. Here, it’s easily observed how brittle the specimens are. Moreover, the increase in cleavage area (shiny) in both A and B steel alloys by the decrease in tempering temperature can be perceived. In tempering temperature of 440 °C, shear areas (dull) can be seen readily. But in tempering temperature of 410 °C, the dull areas are decreased, noticeably. Even there is a very small dull area left in B-steel alloy at this condition.

6.4. Fatigue Properties

The spring steel must insure a fully martensitic structure throughout the entire section after the heat treatments. Nonmartensitic transformation products detract from the fatigue properties. The microstructures of AD, BD, AX, and BX, are given in Figure 6.6. Tempered martensitic microstructures appear in each group. From the microstructural analysis, it can be concluded that tempering is sufficient to obtain the demanded tempered martensite microstructure. In addition to this, the microstructural distribution is very good in each group.

Table 6.4. Estimates of bending fatigue limits

Group Name	Tensile Strength (MPa)	Estimates of Bending Fatigue Limit (MPa)
AD	1648	906
AX	1585	933
BD	1696	872
BX	1613	887

As its mentioned before, the bending fatigue limit of steel having highly tempered martensite microstructure is estimated as 55 % of the tensile strength [46]. The results for estimating the fatigue limit of each group is given in Table 6.4.

The fatigue limits are determined with staircase method with 8 specimens for each group starting with the stress values obtained from Table 6.4, then, applying equal stress increment or decrement of 10 MPa according to the survival or the failure of the event until one or two specimens did not fail in the specified numbers of cycles. The highest stress at which a runout (nonfailure) was obtained is taken as the fatigue limit [50].

Experimental results for determining the fatigue limit of AD, AX, BD, and BX are given in Tables 6.5, 6.6, 6.7, and 6.8, respectively. And, *S-N* curves of them are depicted in Figures 6.7, 6.8, 6.9, and 6.10, respectively.

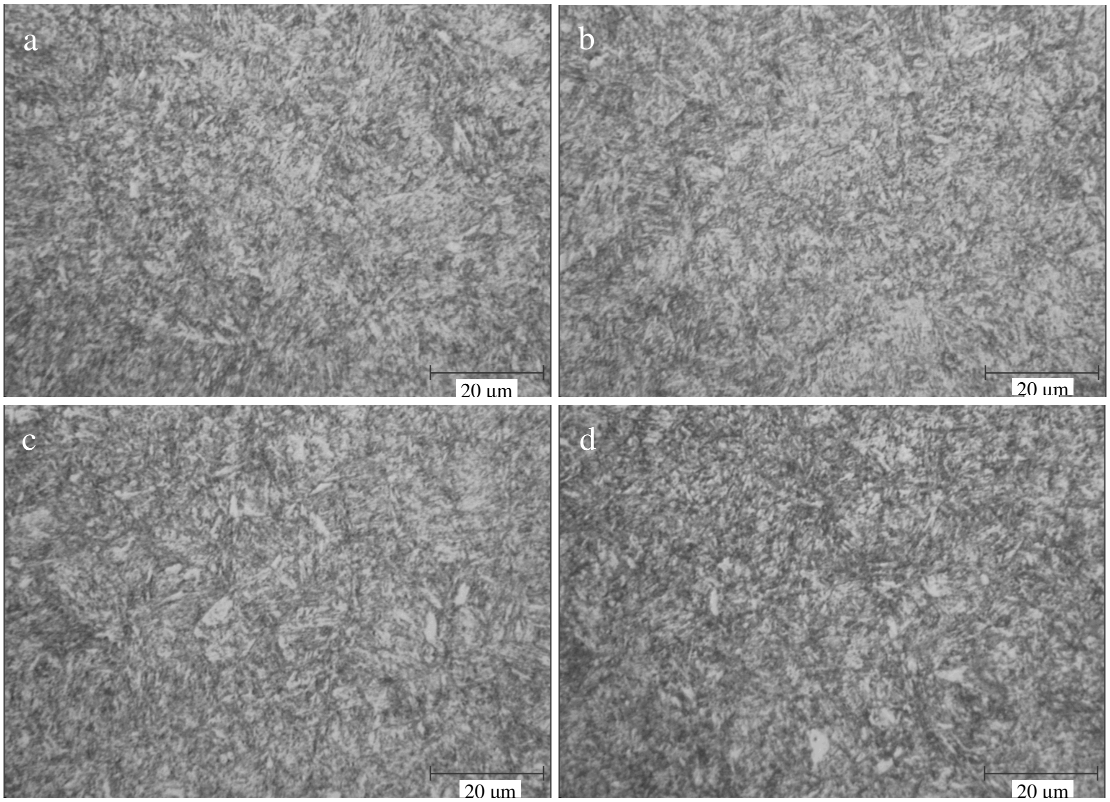


Figure 6.6. Optical micrographs of a) AD, b) BD, c) AX, d) BX

As its shown in Table 6.5, the fatigue limit of AD group is founded as 880 MPa for *R* = -1. In Figure 6.7, *S-N* curve for group AD is illustrated.

Table 6.5. Fatigue test results of group AD

Trail Name	Applied Stress (MPa)	Number of cycles to failure
AD1	910	165.000
AD2	900	224.000
AD3	890	268.000
AD4	880	5.000.000
AD5	890	309.000
AD6	880	930.000
AD7	870	5.000.000
AD8	880	5.000.000
AD9	920	122.000
AD10	920	117.000
AD11	920	151.000
AD12	960	79.000
AD13	960	89.000
AD14	960	58.000
AD15	1000	39.000
AD16	1000	26.000
AD17	1000	24.000

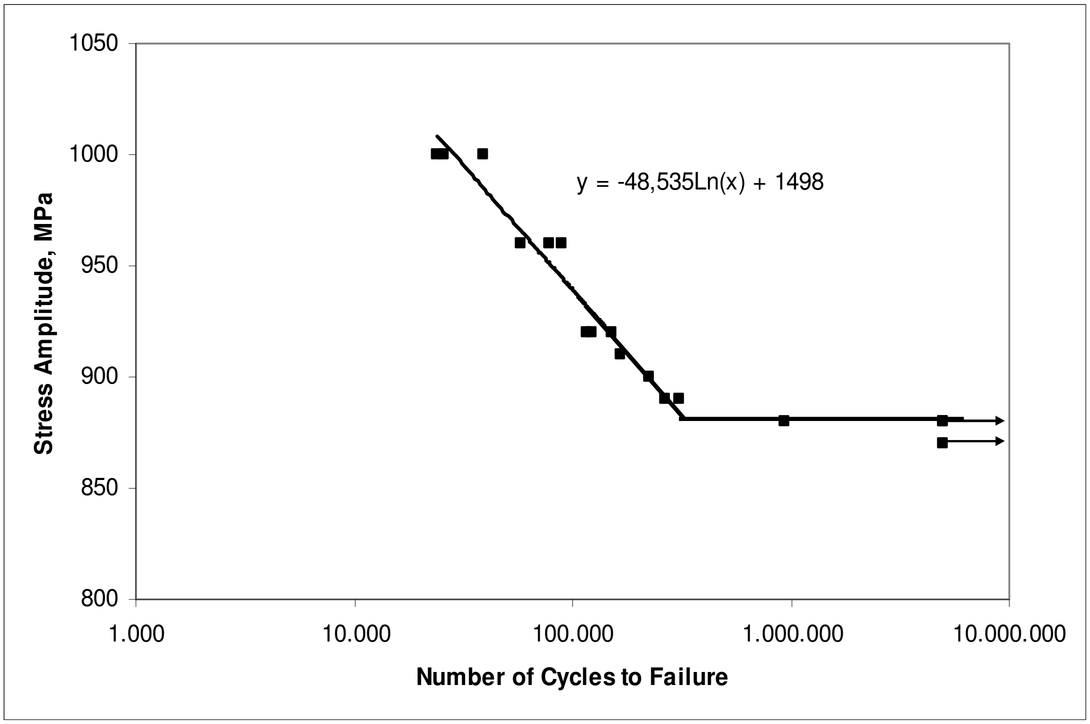


Figure 6.7. *S-N* curve for group AD

Table 6.6. Fatigue test results of group AX

Trail Name	Applied Stress (MPa)	Number of cycles to failure
AX1	870	5.000.000
AX2	880	388.000
AX3	870	5.000.000
AX4	880	273.000
AX5	870	1.624.000
AX6	860	5.000.000
AX7	870	5.000.000
AX8	880	294.000
AX9	910	138.000
AX10	910	109.000
AX11	910	128.000
AX12	950	76.000
AX13	950	81.000
AX14	950	46.000
AX15	990	32.000
AX16	990	29.000
AX17	990	22.000

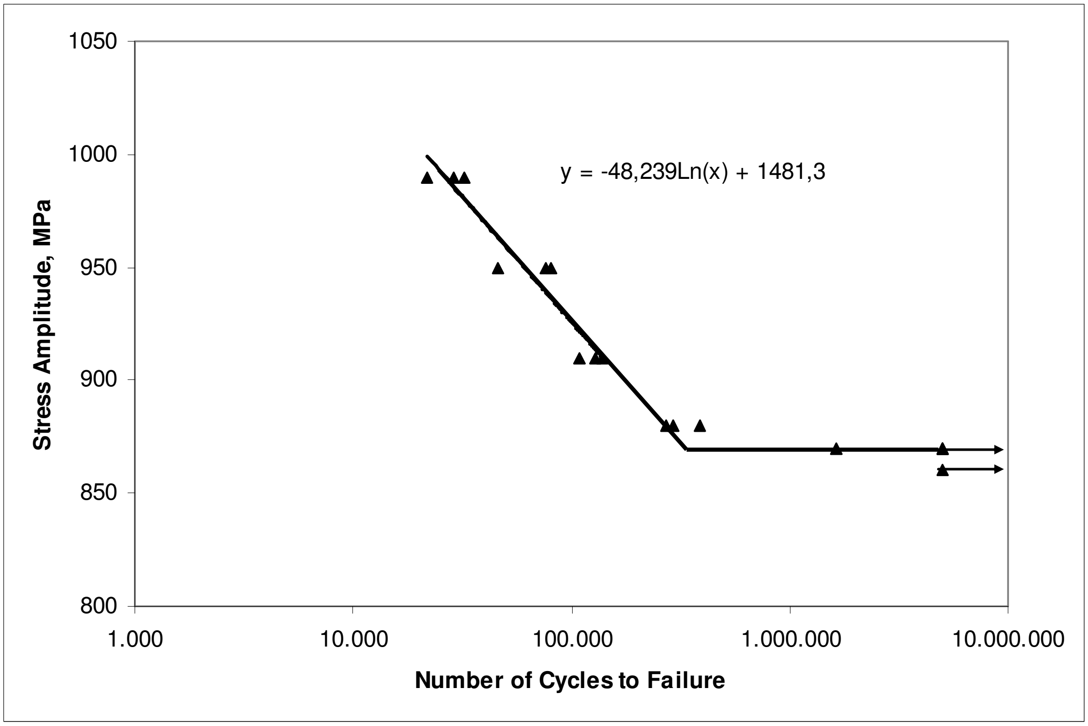


Figure 6.8. *S-N* curve for group AX

Table 6.7. Fatigue test results of group BD

Trail Name	Applied Stress (MPa)	Number of cycles to failure
BD1	930	5.000.000
BD2	940	5.000.000
BD3	950	925.000
BD4	940	5.000.000
BD5	950	519.000
BD6	940	5.000.000
BD7	950	5.000.000
BD8	960	425.000
BD9	990	135.000
BD10	990	194.000
BD11	990	149.000
BD12	1030	78.000
BD13	1030	65.000
BD14	1030	82.000
BD15	1070	41.000
BD16	1070	33.000
BD17	1070	26.000

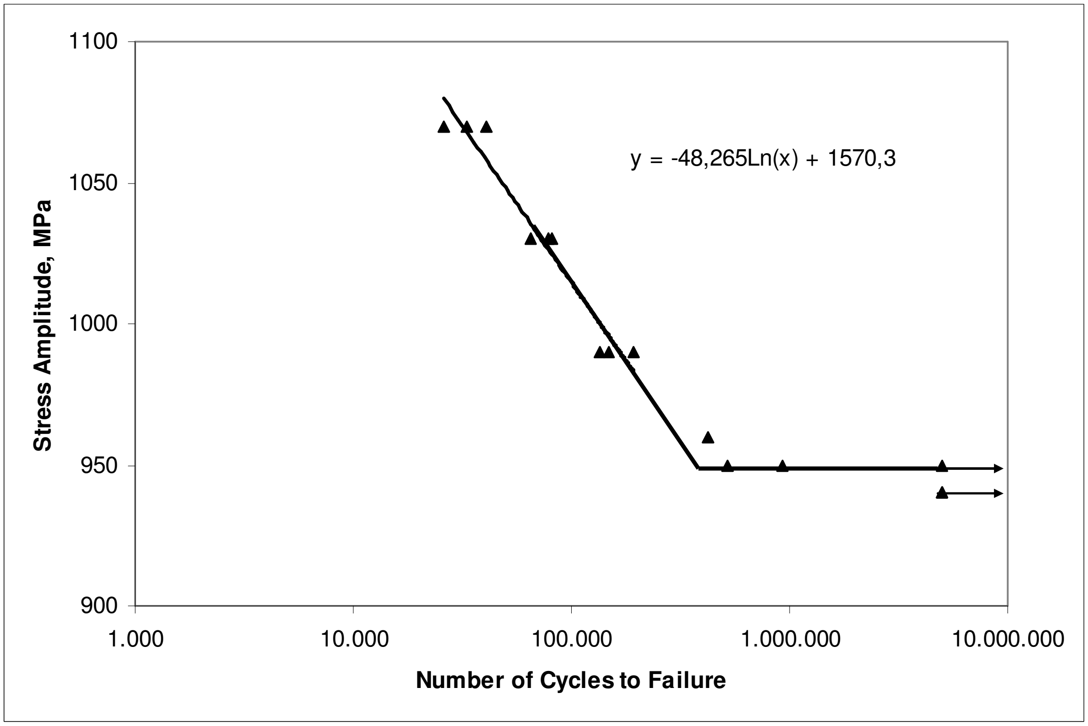


Figure 6.9. *S-N* curve for group BD

Table 6.8. Fatigue test results of group BX

Trail Name	Applied Stress (MPa)	Number of cycles to failure
BX1	890	5.000.000
BX2	900	211.000
BX3	890	1.024.000
BX4	880	5.000.000
BX5	890	507.000
BX6	880	5.000.000
BX7	890	5.000.000
BX8	900	273.000
BX9	930	116.000
BX10	930	92.000
BX11	930	122.000
BX12	970	54.000
BX13	970	79.000
BX14	970	44.000
BX15	1010	20.000
BX16	1010	28.000
BX17	1010	23.000

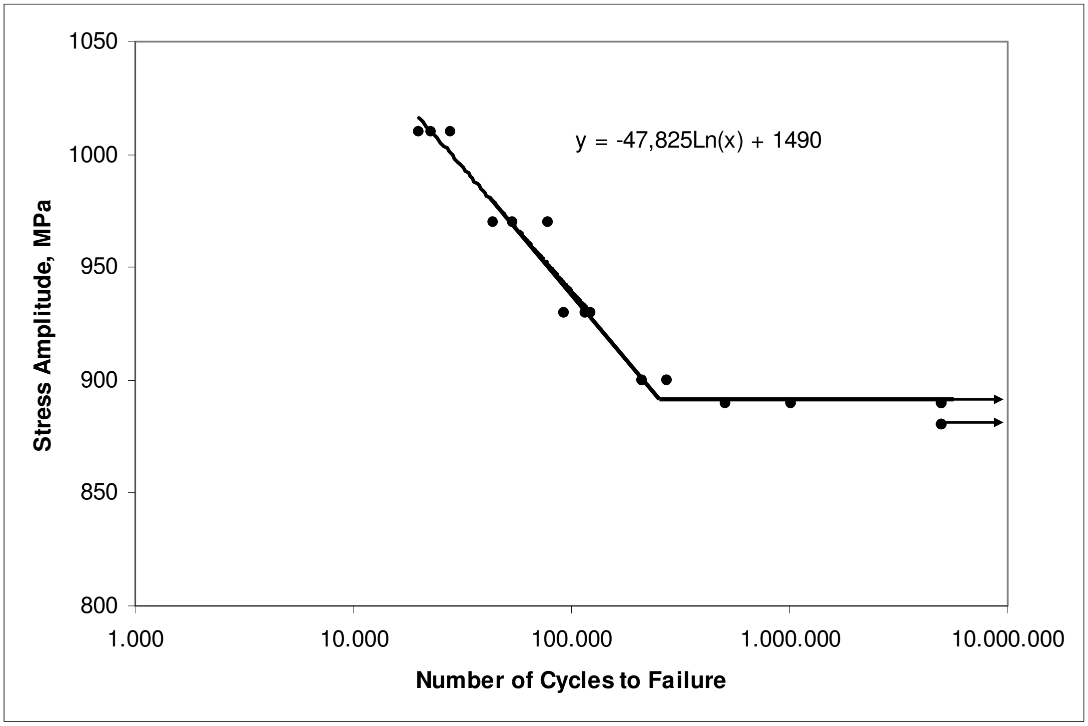


Figure 6.10. *S-N* curve for group BX

In Table 6.6, from the experimental results, the fatigue limit of AX group is determined as 870 MPa for $R = -1$. And, *S*-*N* curve for group AX is constituted in Figure 6.8.

Table 6.9. Experimental results of fatigue limits

Group Name	Fatigue Limit (MPa)	$FatigueLimit \diagup TensileStrength$
AD	880	0.53
AX	870	0.55
BD	950	0.56
BX	890	0.55

The comparison of *S*-*N* curves of groups AD and AX is depicted in Figure 6.11. As its shown in Table 6.9, the fatigue limit of A-steel alloy is almost same in both tempering temperature of 440 °C and 410 °C with 870 MPa and 880 MPa, respectively. Moreover, the values for the ratio of the fatigue limit and the tensile strength of both AD and AX are consistent with the literature.

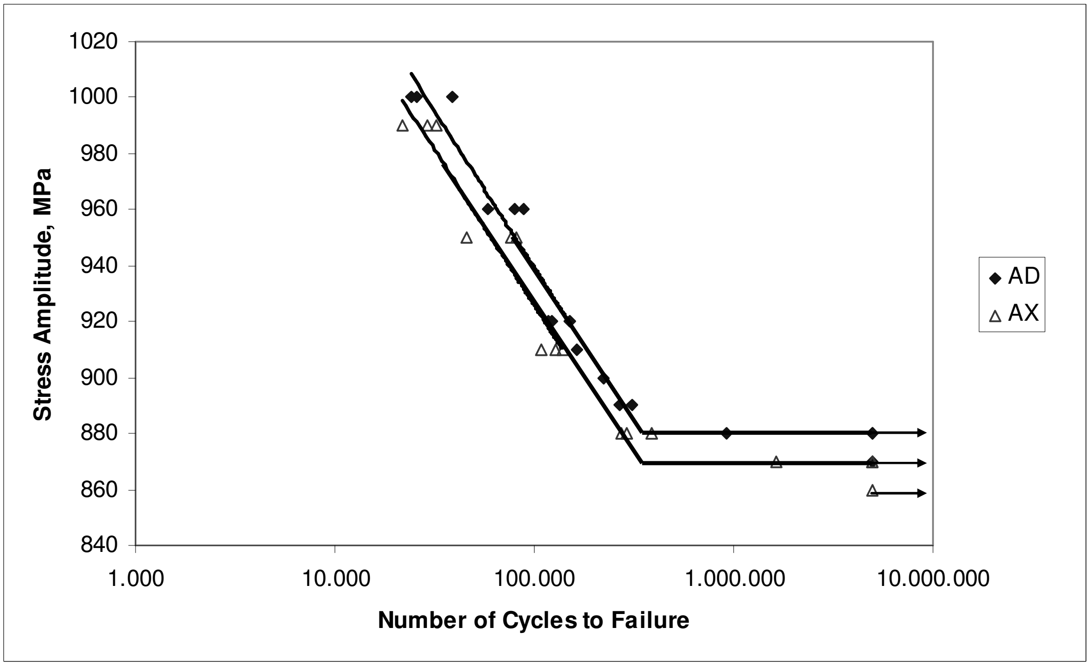


Figure 6.11. *S*-*N* curve for groups AD and AX

From Tables 6.7 and 6.8, the fatigue limits of BD and BX are designated 950 MPa and 890 MPa, respectively. And, in Figures 6.9 and 6.10, the *S-N* curves of them are portrayed. Also, the *S-N* curves of BD and BX are given in Figure 6.12.

The fatigue limit of B-steel alloy increases at tempering temperature of 410 °C. In tempering temperature of 440 °C, the fatigue limit of B-steel alloy is 890 MPa, but it increases to 950 MPa when tempering temperature is reduced to 410 °C. In another words, the fatigue limit of B-steel alloy increases by 6,7 % when the tempering temperature is decreased to 410 °C.

From Table 6.9, the values for the ratio of the fatigue limit and the tensile strength of both BD and BX are again consistent with the literature.

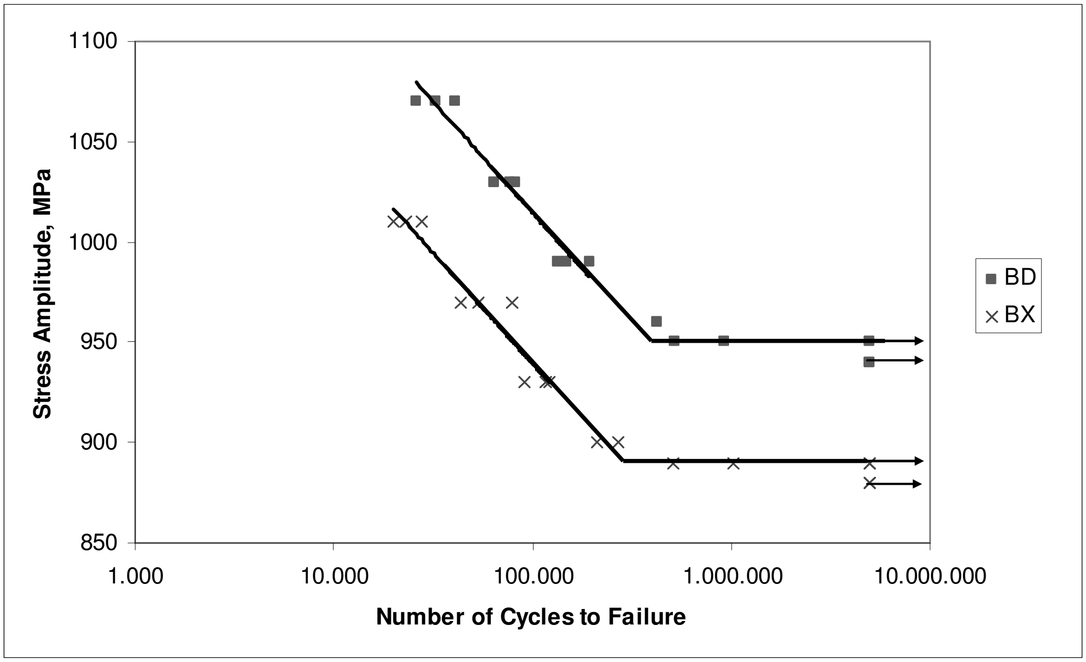


Figure 6.12. *S-N* curve for groups BD and BX

If we compare the fatigue results of A and B steel alloys in tempering temperature of 410 °C, the fatigue limit of B-steel alloy is about 8 % higher than A-steel alloy.

From the comparison of the results of A and B steel alloys tempered at 440 °C, we come up with a different result from the outcome of A and B steel alloys tempered at 410

°C that the fatigue limit of the both steel alloys are nearly same, the fatigue limit of B is slightly higher by 2.3 %.

The Basquin parameters, fatigue strength coefficient, S'_f, and fatigue strength exponent, b, are calculated and presented in Table 6.10.

Table 6.10. Parameters involved in the Basquin relationship for the conditions tested

Group	S'_f	b
AD	1739	-0,0505
AX	1720	-0,0508
BD	1752	-0,0498
BX	1714	-0,0493

Figure 6.13 illustrates the macroscopic fracture surfaces of AD, BD, AX, and BX taken from fatigue specimens by the stereo microscope. As a characteristic of the fatigue fracture, there are two regions in the fractured surface. These are a smooth surface created by crack propagation and a rough surface created by sudden fracture. The fatigue crack propagation regions cover almost half of the cross section.

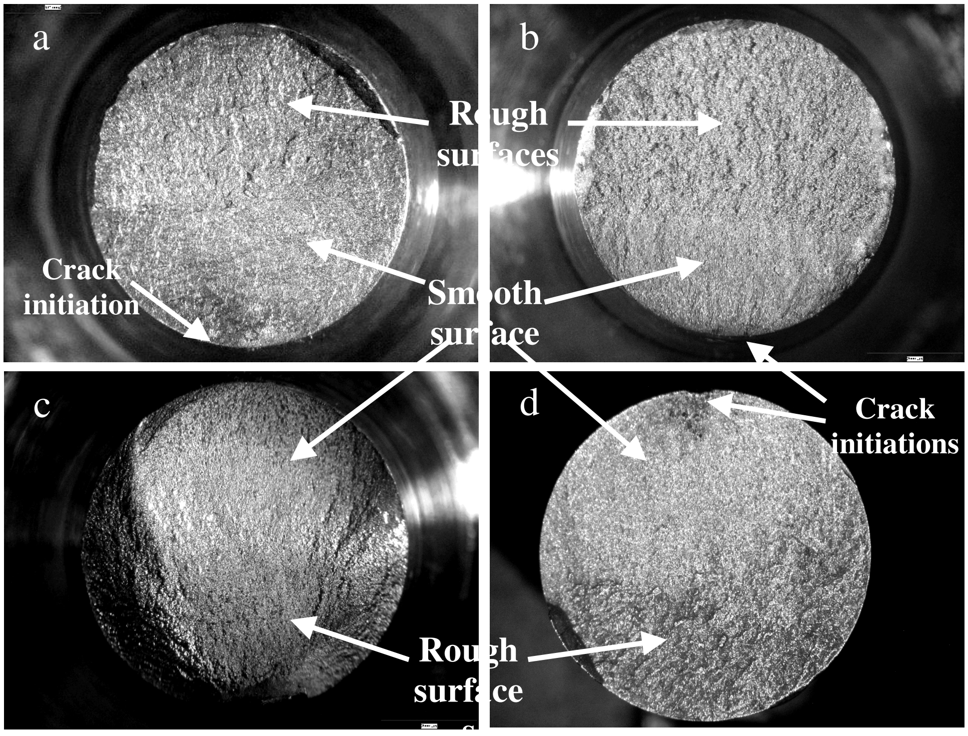


Figure 6.13. Fracture surface of a) AD, b) BD, c) AX, d) BX

7. CONCLUSIONS

Springs are mechanical elements that exert forces or torques and absorb energy. The absorbed energy is usually stored and later released. High-strength steel (spring steel, in fact) is the traditional choice for spring material. Its easily formed and heat treated. 50CrV4 is a medium high-carbon chromium-vanadium alloy steel used for numerous applications including premium quality springs.

In this study, two different 50CrV4 spring steel are heat treated in two different condition and then analysed for mechanical properties. In heat treatment stage, all specimens were austenitized at 910 °C and hold for 10 minutes in natural salt bath at this temperature. Then, they were oil quenched in agitated oil at 25 °C. Eventually, in order to investigate the effect of tempering temperature for two steel alloys, the specimens were tempered at two different temperature, 410 °C and 440 °C, and hold for 1 hour at these temperatures.

0.2 % yield strengths of groups range from 1483 to 1584 MPa, and the tensile strengths of them are among 1585-1696 MPa. Decreasing the tempering temperature increases the yield and tensile strengths of two alloys. However, it decreases the elongation of them. But in all conditions, the elongations of both steels are very low. The tensile properties of B-steel alloy (50CrV4, microalloyed with Ti) are higher than A-steel alloy (50CrV4, not microalloyed with Ti) at both two tempering temperature.

At both two tempering temperature, the hardnesses of two alloys are very high. Increasing the tempering temperature from 410 °C to 440 °C decreases the hardness only about 25 HB. Two steel alloys remain more than 460 HB at tempering temperature of 440 °C, and more than 484 HB at tempering temperature of 410 °C. Furthermore, at both two tempering temperature, the hardness of B-steel alloy is slightly higher than A-steel alloy.

Impact energies of two steels are low like their elongations. In two heat-treatment conditions, both of the alloys are very brittle. Even in tempering temperature of 410 °C, the alloys are more brittle.

Fatigue properties of two alloys are similar in tempering temperature of 440 °C. The fatigue limit of B-steel alloy is 2.3 % higher than A-steel alloy at this condition. In tempering temperature of 410 °C, the fatigue limit of A-steel alloy remains almost same, however, the fatigue limit of B-steel alloy significantly increases by 6.7 %. So, the fatigue limit of B-steel alloy is higher than A-steel alloy by 8 % at this condition.

In microstructural investigation, it's observed that all the heat treatments applied to the specimens were adequate to obtain the desired tempered martensite microstructure homogeneously.

REFERENCES

1. SAE Spring Committee, "General Data", *Manual on Design and Application of Leaf Springs-SAE HS 788*, pp. 1–3, 1982.
2. Ashby, M. F., "Materials for Springs", *Materials Selection in Mechanical Design,* pp. 111–115, 1999.
3. Nam, W. J., C. S., Lee and D. Y., Ban, "Effects of alloy additions and tempering temperature on the sag resistance of Si–Cr spring steels", *Material Science and Engineering*, 2000.
4. Lee, C. S., K. A., Lee, D. M., Li, S. J., Yoo and W. J., Nam, "Microstructural influence on fatigue properties of a high-strength spring steel", *Material Science and Engineering*, 1998.
5. Nam, W. J. and C. S., Lee, "Microstructural influence on sag resistance of Cr containing and Cr free spring steels", *Material Science and Engineering*, 1998.
6. SAE Spring Committee, "Material and Processing", *Manual on Design and Application of Leaf Springs-SAE HS 788*, pp. 97–99, 1982.
7. Marghitu, Dan B., "Deflection and Stiffness", *Mechanical Engineer's Handbook*, pp. 149–172, 2001.
8. Shin, J. C., S., Lee and J. H., Ryu, "Correlation of Microstructure and Fatigue Properties of Two High-Strength Spring Steels*", International Journal of Fatigue*, 1999.
9. Baumeister, T., "Springs", *Standard Handbook for Mechanical Engineers*, pp. 8101–8113, 1967.

10. Crandall, S. H., N. C., Dahl and T. J., Lardner, "Stresses Due to Bending", *An Introduction to the Mechanics of Solids*, pp. 416–511, 1978.

11. Shokreih, M. M. and D., Rezaei, "Analysis and optimization of a composite leaf spring", *Composite Structures,* 2003.

12. Grip et. al., "Spring Steel", U.S. Patent 4,575,912, 1986.

13. Silberstein, D., "How to Make Springs", http://home.earthlink.net/%7Ebazillion/ intro.html, 2003.

14. Marghitu, D. B., "Springs", *Mechanical Engineer's Handbook*, pp. 283–297, 2001.

15. Reimpell, J., H., Stoll and J. W., Betzler, "Spring Types", *The Automotive Chassis : Engineering Principles*, pp. 340–347, 2001.

16. SAE Spring Committee, "Springs", *Leaf Springs for Motor Vehicle Suspension Made to Metric Units-SAE J1123 Nov92*, 1992.

17. Meatto et. al., "Method for Producing A Hybrid Leaf Spring", U.S. Patent 2002/0096249, 2002.

18. Skołyszewski et. al., "Warm forming of acid resistant steel wires used for manufacturing of springs", *Journal of Material Processing Technology,* 2002.

19. Uc, N., "The Effect of High Austenitization Temperatures on the Mechanical Properties and Microstructure of AISI 5140 Steel", *Bogazici University Library,* 1986.

20. Kalpakjian, S. and S. R., Schmid, "Production of Iron and Steel", *Manufacturing Engineering and Technology,* pp. 138–141, 2000.

21. Shackelford, J. F., "Ferrous Alloys", *Introduction to Materials Science for Engineers,* pp. 254–266, 1999.

22. Kalpakjian, S. and S. R., Schmid, “Carbon and Alloy Steels”, *Manufacturing Engineering and Technology,* pp. 144–148, 2000.

23. ASM International, “High-Strength, Low-Alloy Steels”, 2001.

24. Motomura et. al., “Lowly decarburizable Spring Steel”, U.S. Patent 5,951,944, 1999.

25. “Effect of Alloying Elements in Steel”, http://www.primosknives.com/articles/alloys.htm, 2006.

26. Yamada et. al., “Spring Steel for Vehicles”, U.S. Patent 4,409,026, 1983.

27. Gateway Metals, “Effect of Alloying Elements in Steel”, 2006, http://www.gatewaymetals.com/news/alloy.htm

28. Fukuzumi et. al., “High-Strength Spring Steel”, U.S. Patent 6,322,747, 2001.

29. Yamamoto et. al., “Spring Steel Having a Good Sag-Resistance and a Good Hardenability”, U.S. Patent 4,544,406, 1985.

30. Hashimura et. al., “High-Strength Spring Steel and Spring Steel Wire”, U.S. Patent 2003/0201036, 2003.

31. Totten, G. E. and M. A. H., Howes, “Effect of Alloying Elements on Austenite Transformations”, *Steel Heat Treatment Handbook*, pp. 53–61, 1997.

32. ASM International, “Steel for Springs”, *ASM Speciality Handbook : Carbon and Alloy Steels*, pp. 599-615, 1996.

33. “Wire Form Spring”, http://www.multiformspring.com, 1999.

34. Matweb, “Leaf springs”, http://www.matweb.com/search/GetKeyword.asp, 2006.

35. Chandler, H., “Oil Quenching Process”, *Heat Treater's guide : Practices and Procedures for Irons and Steels*, pp. 79–80, 1995.

36. Chandler, H., “Tempering Processes/Technology”, *Heat Treater's Guide : Practices and Procedures for Irons and Steels*, pp. 96–101, 1995.

37. Bain, E. C., “Nature of Tempering Reaction”, *Functions of the Alloying Elements in Steel*, pp. 229-244, 1939.

38. Chandler, H., “6150, 6150H”, *Heat Treater's Guide : Practices and Procedures for Irons and Steels*, pp. 434–436, 1995.

39. Matweb, “AISI 6150 Steel”, http://www.matweb.com/search/ SpecificMaterial.asp?bassnum=M615AB, 2006.

40. Melilli, A. S., “Spring Steels”, *Handbook of Comparative World Steel Standards,* pp. 52–53, 1996.

41. ASTM E-8M-04 Standard, “Standard Test Methods for Tension Testing of Metallic Materials”, 2004.

42. ASTM A-370-05 Standard, “Standard Test Methods and Definitions for Mechanical Testing of Steel Products”, 2005.

43. ASM International, “Fatigue Resistance of Steels”, *ASM Speciality Handbook : Carbon and Alloy Steels*, pp. 245–268, 1996.

44. Boyer, H. E., “Fatigue Testing”, *Atlas of Fatigue Curves*, pp. 1–27, 1986.

45. Sudhakar, K. V., “Fatigue Behaviour of a High Density Powder Metallurgy Steel”, *International Journal of Fatigue*, 2000.

46. Lee, Y., Pan, J., Hathaway, R., Barkey, M., "Stress-Based Fatigue Analysis and Design", *Fatigue Testing and Analysis : Theory and Practice*, pp. 103–180, 2005.

47. ASTM E-206-72 Standard, "Standard Definitions of Terms Relating to Fatigue Testing and The Statistical Analysis of Fatigue Data", 1979.

48. Suresh, S., "Phenomenological Approaches Based on Cyclic Stress and Cyclic Strain", *Fatigue of Materials*, pp. 126–140, 1991.

49. Berrios, J. A., D. G., Teer and E. S., Puchi-Cabrera, "Fatigue Properties of a 316L Stainless Steel Coated With TiN_x Deposits", *Surface & Coatings Technology*, 2001.

50. Dieter, G. E., "Fatigue of Metals", *Mechanical Metallurgy*, pp. 375–431, 1988.

51. ASTM E-739-91 Standard, "Standard Practice for Linear or Linearized Stress Life (S-N) and Strain Life (ϵ-N) Fatigue Data", 2004.

52. ASTM E-468-90 Standard, "Standard Practice for Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials", 2004.