INVESTIGATION OF CORROSION AND WEAR PROPERTIES OF DIFFERENT QUALITY STEEL MATERIALS AFTER LASER HARDENING PROCESS

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“I declare that all the information within this thesis has been gathered and presented in accordance with academic regulations and ethical principles and I have according to the requirements of these regulations and principles cited all those which do not originate in this work as well.”

Osama Albahlol Alshtewe ALBAHLOL

ABSTRACT

M. Sc. Thesis

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In this study, laser surface hardening process was applied at 1200,1250,1300 degrees at 4mm/s and 6mm/s scanning speeds and laser forces adjusted to maximum surface temperature and these samples were encoded from one to six. Subsequently, the images of these samples under the stereo microscope were examined and the hardened depth of field was measured at this temperature and scanning speeds. Changes in the microstructures of samples were examined in SEM and optical microscope and carbon diffusion (decarburization) on the surface was confirmed after laser hardening in the EDX images taken. Vickers hardness test was performed at certain distances (HV1) from the surface under a load of 1kg and the results were compared with microstructure and EDX results. As a result of tribological analyses, wear strengths and abrasion behaviors were examined together with post-wear SEM images and how laser hardening changed the wear mechanism in the material. Samples tested for potentiodnamic corrosion were compared with the main material corrosion resistances and compared with graphs of how corrosion resistances changed.

Key Words : Laser hardening, steel, mechanical property, microstructure, wear, corrosion.

Science Code : 91421

ÖZET

Yüksek Lisans Tezi

FARKLI KALİTEDE ÇELİK MALZEMELERİN LAZER SERTLEŞTİRME İŞLEMİ SONRASI KOROZYON VE AŞINMA ÖZELLİKLERİNİN İNCELENMESİ

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Bu çalışmada, 4mm/s ve 6mm/s tarama hızlarında 1200, 1250 ve 1300 derecelerde lazer yüzey sertleştirme işlemi uygulanmış ve lazer kuvvetleri maksimum yüzey sıcaklığına ayarlanmış ve bu numuneler birden altıya kadar kodlanmıştır. Daha sonra bu örneklerin stereo mikroskop altında görüntüleri incelenmiş ve bu sıcaklık ve tarama hızlarında sertleşen alan derinliği ölçülmüştür. Numunelerin mikroyapılarındaki değişiklikler SEM'de incelenmiş ve alınan EDX görüntülerinde lazerle sertleştirme sonrası optik mikroskopta ve yüzeyde karbon difüzyonu (dekarburizasyon) doğrulanmıştır. Vickers sertlik testi 1 kg yük altında yüzeyden belirli mesafelerde (HV1) gerçekleştirilmiş ve sonuçlar mikroyapı ve EDX sonuçları ile karşılaştırılmıştır. Tribolojik analizler sonucunda aşınma sonrası SEM görüntüleri ile birlikte aşınma dayanımları ve aşınma davranışları incelenmiş ve lazer sertleştirmenin malzemedeki aşınma mekanizmasını nasıl değiştirdiği incelenmiştir. Potansiyodinamik korozyon için test edilen numuneler, ana malzeme korozyon dirençleri ile ve korozyon dirençlerinin nasıl değiştiğine dair grafiklerle karşılaştırıldı.

Anahtar Kelimeler : Lazer yüzey sertleştirme, çelik, mekanik özellik, mikroyapı, aşınma, korozyon.

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ABBREVITIONS

AISI : American Iron and Steel Institute
ASTM : American Society for Testing and Materials
DIN : Deutsches Institut für Normung
HV : Vickers Hardness
SEM : Scanning Electron Microscope
LSH : Laser Surface Hardening

PART 1

INTRODUCTION

Steel is the most common material for building infrastructure and in industries around the world. It is used to manufacture all materials, from needle to petroleum tankers, and the world's production of it in 2013 reached about 1.6 billion tons, while the amount of aluminum metal, which is the second most important engineering mineral, reached 47 million tons after it [1]. This indicates its importance [2]. The reason for the popularity of steel is the relatively low cost of manufacturing, forming, and processing, its distinctive mechanical properties and the abundance of its raw materials [3]. The oldest piece of steel dates back to 2000 BC and was extracted One of the archaeological sites in Anatolia [2].

According to the World Steel Association, there are more than 3,500 steel grades, including distinctive and unique environmental, chemical and physical properties; the amount of carbon, the level of impurities and the elements added to the alloy affect the properties of each of these classes. Commercial steels are classified into four main types according to the content of the metal alloy and its uses [4], Carbon Steels, Manganese, Silicon, Nickel and Chromium [4].

The average life of steel is approximately forty years. On average, newly produced steel contains about 37% of recycled steel. The amount of steel that was used in the world in 2017 reached about 1,587 million tons, and its uses were mainly distributed as follows: 51% in buildings and infrastructure, and 12% in cars and vehicles Transportation, 11% in metallurgy, 15% in mechanical equipment, and other industries. Stainless steel is ideal for use in medical equipment; Because of its inactivity, ease of cleaning, disinfection, corrosion and scratch resistance.

Abrasion is the phenomenon of deterioration of material tolerances and failure of parts to perform their functions as a result of the separation of micro particles from the contacting surfaces due to mechanical effects. Wear event usually; It is seen in shafts, sliding and rolling bearings, brake linings, engine pistons and cylinders, gears and turbine blades used as motion transmission elements. Wear intensity, wear surface roughness and wear particle shape give us information about possible wear.

The physical metallurgical phenomena in laser beam hardening are generally similar to those in conventional martensitic texture hardening, but the suitability of a material for laser hardening is largely determined by the material's texture. The material must have a fine-grained texture so that the carbon can dissolve in a very short time and traverse the necessary diffusion path of a few µm. Therefore, steels with high ferrite content are not suitable for laser hardening [4]. Laser hardening can be applied to cast irons and steels containing at least 0.3% carbon or more.

Since laser hardening is suitable for processing in the desired direction and in a limited area, that is, it is suitable for hardening of the selected area, no structure and hardness changes are observed in the areas where hardening is not desired. The power density value required for laser hardening is in the range of 103 – 104 W/cm^2. The power density is determined by the mode of the laser beam. The shape and dimensions of the hardened section formed by the heating and subsequent cooling of the irradiated surface vary depending on the process parameter [6].

The effective parameters in laser surface hardening are laser power, processing speed, beam shape, power density, duration of action, degree of absorption, energy absorption and temperature distribution. The laser power and the shape of the beam affect the degree of absorption and duration of action. The degree of absorption and the duration of action affect the temperature distribution. Processing speed varies depending on wavelength and laser type [7].

The degree of absorption varies according to the material surface. An undesirable surface roughness reflects the beam undesirably. Materials that reflect light, such as aluminum, copper and silver, have a mirror effect. In addition, the angle of the laser beam falling on the surface should not be less than 28o. Otherwise, absorption does not occur. The degree of absorption can be increased by coating the surface with a non-metallic layer. However, the degree of absorption also depends on the wavelength, material and surface temperature [8].

PART 2

LITERATURE REVIEW

Iron cannot be used in pure form for technical use, so it is mainly used only for some special purpose. In contrast, steel has significantly better mechanical properties and a wide range of applications in industry and daily life [5].

2.1. DEFINITION OF STEEL

There are several definitions of steel in the literature. European standards define steel as an iron material suitable for hot processing. Also, steel can be defined as an alloy (alloy) of iron and carbon (<2%) with or without the addition of other alloying elements. The importance of steel in the development of civilization is evidenced by the fact that the current annual amount of steel produced in the world is about ten times greater than the total amount produced from all other metals and alloys. More than 1 billion tons of steel are produced annually in the world [6].

Steel is a deformable iron alloy that, in addition to carbon, contains certain impurities that can be either beneficial or harmful. Useful impurities in steel are for example chromium, nickel, molybdenum, etc., while phosphorous and sulfur are mainly harmful. In addition to the elements listed above, steel can also contain trace elements (copper, tin, arsenic, etc.) and gases (oxygen, nitrogen, and hydrogen), which usually exacerbate the properties of the final product [7].

The multiple use of steel mainly arises from its beneficial properties, that is, the ability to achieve a good combination of strength, hardness, elongation, formability and changes in composition by alloying, heat treatment, etc. The basic properties of steel depend on the chemical composition, microstructure, condition, shape and dimensions of the final product. Due to the economical method of production (compared to other metallic materials) and preferred properties, steel can be used in a wide variety of applications. Steel is used as a material in all branches of industry, transportation, construction, agriculture, crafts and all other industries [8].

Due to the degree of progress in the development of new types of steels and in the field of metallurgy production and heat treatment, most of the different types (not the total mass) of the steel produced in the world belong to the group of special (special) steels. Thus, the range of special steels includes all types of stainless steels and the vast majority of high-quality steels [9].

2.2. THE IMPORTANCE OF STEEL

Steel is one of the most important building and engineering materials, because nearly 80% of all metals produced are compatible with steel. Steel is of great importance due to its combination of strength, ease of manufacture, and a wide range of properties at low cost [10].

Some steels are relatively soft and ductile and can be quickly shaped into various shapes such as automobile bodies, and others can be hardened enough to act as steel cutting tools. Others can be manufactured to possess strength and durability for use on automobile hubs, containers or container containers. A tacky example is the razor blade, which is very stiff [11].

From these examples, the word steel appears to be an umbrella term with many sub-classifications; In fact, there are several thousand different types of steels, based on the various formulations that are produced commercially [12].

2.3. IRON

Basically, all steels are basically iron, or more appropriately, an alloy of iron and carbon. So-called simple carbon steels are those that generally contain, apart from carbon, small amounts or percentages of Mn, Si, S, and P. An example of this is 1045 steels containing 0.45% carbon, 0.75% manganese, 0.40 % Phosphorous, 0.50% sulfur, 0.22% silicone [13].

2.4. STEEL ALLOY

They are those that contain specific amounts or percentages of other elements in the chemical composition. The most common elements mixed with this steels are nickel, chromium, molybdenum, vanadium and tungsten. Manganese also falls into this category if specified within a percentage greater than 1%. One or more of these alloying elements may be required to provide steels with special properties or properties for engineering applications [14].

2.5. STEEL COMPONENTS

Carbon is the main component in steel, and the amount of carbon present in simple carbon steels has a clear effect on the properties of the steel and on the choice of heat treatment applied to some desirable properties due to the importance of the carbon content. A method for classifying simple carbon steels depends on their content. When only a small amount of carbon is in a particular steel it is called low [15].

2.6. CARBON STEEL

Low carbon steels generally contain less than 0.30% C by weight. When steel contains 0.30 to 0.60% C the steel is classified as a medium carbon steel. Steels with a percentage greater than 0.60% carbon are classified as high carbon steels and those with a percentage greater than 77% carbon may be called tool steels [11].

The carbon content is rarely in the range of 1.3 to 2%. The upper limit of carbon in steel is 2%, when more than this carbon content is present, iron and carbon alloys are considered cast iron. The carbon content of cast iron is in the range of 2.3 to 4% carbon [11].

In short, steel is a ferrous carbon alloy where the carbon content is generally in the range of 0.05 to 1% and sometimes it is in the range from I to 2%. Simple carbon steels consist only of iron, except for 0.40% of both P and S, and a few tenths of a percentage of chromium. A tenth of a percent of some unspecified elements found in carbon steels such as nickel (Cr) or vanadium (Ni) are known as the remaining elements. The percentage of these non-specific elements becomes important for choosing heat treatment in specific applications. If these specified levels are exceeded, medium alloy steels are more than just simple carbon steel [11].

2.7. STEEL CLASSIFICATION

Due to the wide variety of steels present and manufacturers, this has given rise to a large number of standards and regulations that differ from country to country [13].

However, there are other regulatory standards for steel, with great international application, such as American AISI (American Iron and Steel Institute) and ASTM (American Society for Testing and Materials), German DIN standards, or ISO 3506 [13].

- low carbon steel (% C <0.25)
- Medium carbon steel (0.25 <% C <0.55)
- High carbon steel (2>% C> 0.55)

Table 2.1 Classification of steel according to its carbon content [13].

Name of Steel	**Carbon Content in Steel**
Very Low carbon steel (dead steel)	< 0.1%
Mild steel	Up to 0.25%
Medium carbon steel	0.25-0.7%
High carbon steel (hard steel)	0.7-1.5%

It is those in which the content of any of the other alloying elements, except for carbon, as the alloying elements added are manganese (Mn), chromium (Cr), nickel (Ni), vanadium (V) or titanium (Ti). On the other hand, based on the carbon content present in the steel, there are the following groups as Table 2.1 [12].

Steel is an alloy of iron and carbon in a percentage of this last element that varies between 0.08% and 2% by mass of its composition. The branch of metallurgy that specializes in producing steel is called the iron and steel industry. The steel produced before the detonation of the first atomic bombs is low-background steel, not contaminated by radionuclides [17].

Steel should not be confused with iron, which is a relatively ductile hard metal with an atomic diameter (dA) of 2.48 Å, a melting temperature of 1535 ° C and a boiling point of 2740 ° C [18]. For its part, carbon is a nonmetal with a smaller diameter (dA = 1.54 Å), soft and brittle in most of its allotropic forms (except in the diamond shape). The diffusion of this element in the crystalline structure of the previous one is achieved thanks to the difference in atomic diameters, forming an interstitial compound. The main difference between iron and steel is in the percentage of carbon: steel is iron with a percentage of carbon between 0.03% and 1.075%; from this percentage other alloys with iron are considered [18].

It should be noted that steel has different constituents according to its temperature, specifically, from higher to lower hardness, pearlite, cementite and ferrite; in addition to austenite (for more information consult the article Iron-carbon diagram) [18].

Steel preserves the metallic characteristics of iron in its pure state, but the addition of carbon and other elements, both metallic and non-metallic, improves its physico-chemical properties. However, if the alloy has a carbon concentration greater than 1.8%, castings are produced, 1 which are much more brittle than steel and cannot be forged, but rather have to be cast [19].

There are many types of steel depending on the alloying element or elements that are present. The definition in percentage of carbon corresponds to carbon steels, in which this non-metal is the only alloying agent, or there are others but in lower concentrations [20]. Other specific compositions receive particular names based on multiple variables such as the elements that predominate in their composition (silicon steels), their susceptibility to certain treatments (carburizing steels), some enhanced characteristic (stainless steels) and even in function of its use (structural steels). Usually these iron alloys are included under the generic name of special steels, which is why the definition of common or "carbon" has been adopted here, which in addition to being the first manufactured and the most used, served as the basis for the others. This wide variety of steels led Siemens to define steel as a compound of iron and another substance that increases its strength [21].

2.8. MECHANICAL PROPERTIES AND CHEMICAL PHYSICS OF STEEL

Although it is difficult to establish the physical and mechanical properties of steel because these vary with the adjustments in its composition and the various thermal, chemical or mechanical treatments, with which steels with combinations of characteristics suitable for countless applications can be achieved [22].

- Its average density is 7850 kg / m³ [22].
- Depending on the temperature, the steel can contract, expand or melt [23].
- The melting point of steel depends on the type of alloy and the percentages of alloying elements. That of its main component, iron, is around 1510 ° C in its pure state (unalloyed), however steel frequently has melting temperatures of around 1375°C, and in general the temperature necessary for melting increases to as the percentage of carbon and other alloys increases (except eutectic alloys that melt suddenly). On the other hand, high-speed steel melts at 1650 ° C [23].
- Its boiling point is around 3000 ° C [24].
- It is a very tough material, especially in some of the alloys used to make tools [23].
- Relatively ductile. With it are obtained thin threads called wires.

- It is malleable. Thin sheets called tinplate can be obtained. Tinplate is a sheet of steel, between 0.5 and 0.12 mm thick, coated, generally electrolytically, by tin [21].
- It allows a good mechanization in machine tools before receiving a heat treatment [24].
- Some compositions and shapes of steel maintain greater memory, and deform when they exceed their elastic limit [22].
- The hardness of steels varies between that of iron and that which can be achieved by alloying it or other thermal or chemical processes, among which perhaps the best known is the tempering of steel, applicable to steels with a high carbon content, which allows, when it is superficial, keep a tough core in the piece to avoid brittle fractures. Typical steels with a high degree of surface hardness are those used in machining tools, called high-speed steels, which contain significant amounts of chromium, tungsten, molybdenum and vanadium. The technological tests to measure hardness are Brinell hardness test, Vickers and Rockwell, among others [22].
- It can be welded easily [21].
- Corrosion is the greatest disadvantage of steels since iron rusts very easily, increasing its volume and causing superficial cracks that allow oxidation to progress until the part is completely consumed. Steels have traditionally been protected by various surface treatments. Although there are alloys with improved corrosion resistance such as "corten" construction steels suitable for the elements (in certain environments) or stainless steels [23].
- It has a high electrical conductivity. Although it depends on its composition, it is approximately 24 3 · 106 S / m. Aluminum conductors with a steel core are frequently used in high voltage overhead lines, the latter providing the necessary mechanical strength to increase the spans between the towers and optimize the cost of the installation [24].
- It is used for the manufacture of artificial permanent magnets, since a magnetized piece of steel does not lose its magnetization if it is not heated to a certain temperature. Artificial magnetization is done by contact, induction or by electrical procedures. As regards stainless steel, ferritic stainless steel does stick with the magnet, but austenitic stainless steel does not stick with the magnet

since the iron phase known as austenite is not attracted to the magnets. Stainless steels mainly contain nickel and chromium in percentages of the order of 10% in addition to some alloys in a lesser proportion [24].

- An increase in temperature in a steel element causes an increase in its length. This increase in length can be valued by the expression:, being the coefficient of expansion, which for steel is approximately 1.2 · 10−5 (that is). If there is freedom of expansion, no major subsidiary problems arise, but if this expansion is prevented to a greater or lesser degree by the rest of the components of the structure, complementary efforts appear that must be taken into account. Steel expands and contracts according to a coefficient of expansion similar to the coefficient of expansion of concrete, so its simultaneous use in construction is very useful, forming a composite material called reinforced concrete.25 Steel gives a false feeling of security as it is non-combustible, but its fundamental mechanical properties are seriously affected by the high temperatures that the profiles can reach in the course of a fire [24].

2.8.1. 5140 Alloy Steel

Alloy Steel is a high quality specific strength band alloy structural steel. It belongs to the high quality low carbon, low alloy chrome, molybden, nickel endu steel case. The enduendutemply temperate is 28-34 HRc. Also, the delivery of annealed AISI 5140 steel hardens less than 250HB [25].

AISI 5140 Alloy Steel Structural Properties is a specification for nickel chromium molybde alloy steel. Also, AISI 5140 with lower carbon content range, so AISI 5140 alloy steel has good weld ability [26].

2.8.2. Steel 4340 Characteristics

Low alloy steel with Chromium, Nickel, Molybdenum. It has great hardenability, toughness and resistance to fatigue. Supplied with heat treatment of tempering (quenching and tempering). It is used in parts that are subjected to high demands on hardness, mechanical resistance and toughness. Its machinability is regular and it has low weld ability [27].

Characterized by high strength and toughness in relatively large sections. Pre hardened and tempered 4340 can be further surface hardened by flame or induction hardening and by nitriding [28].

4340 is used in most industry sectors for applications requiring higher tensile/yield strength than 4140 can provide. Typical applications are: Heavy Duty Shafts, Gears, Axles, Spindles, Couplings, Pins etc. [27].

2.8.3. Steel 8620 Characteristics

AISI 8620 steel has high hardenability without brittleness. It also has good weld ability, little tendency to form cold cracks, and good machinability and cold deformation plasticity. It is used to make gears, shafts, bolts, springs, hand tools, etc. [28].

PART 3

SURFACE HARDENING

3.1. DEFINITION OF SURFACE HARDENING

Surface hardening is the hardening process for the metal surface generating a thin coating of tough metal (called "case"), usually when the part is manufactured and is hardened. Case hardening may offer a fracturing-free part (this can absorb stress without cracking, due to the smooth core), but it can also produce appropriate surface wear resistance. In other words, it is the process of increasing the hardness of the outer surface while the core remains smooth [29].

3.2. STEEL HARDENING PROCESS

At the onset of solidification, if the cooling is fast enough or if there are pearl stabilizers, such as Sn and Sb, the austenite surrounding the graphite will turn into perlite. On the other hand, if the cooling is too slow, the austenite surrounding the graphite will turn into ferrous because the cement (Fe3C) present will have enough time to settle and decompose into graphite and austenite, which in turn will become ferrous [30]. Cast irons can completely contain an iron or perlite matrix, but a mixture of ferrite and pearlite is common. The whole iron matrix is produced by cooling heat treatment, while the pearl matrix is completely produced by normalizing heat treatment (air cooling). In addition to presenting different arrays with different freezing speeds, the differences that characterize gray iron and lumpy iron in transition time from graphite upon passing from a flake or nodule form. The most important thing is that during hardening of nodal iron, graphite begins to precipitate in liquid iron in the form of nodules because it is a more stable phase, causing it to expand to a greater degree and with greater strength than gray iron. The mechanisms of iron hardening and the resulting microscopic dissociation processes are aspects of metallurgy that are not yet fully understood, despite significant research efforts. Specifically, there are three hardening theories that propose mathematical models that allow prediction of grain sizes and distribution in the casting process, two of which are classic models [13].

Most iron foundries have a carbon equivalent composition of less than 4.3%, meaning they are poorly caked. The phase sequence during solidification can be studied using the simplified version of the ternary diagram of iron, carbon and silicon taken at 2% Si, the size of the dendrite is controlled by carbon equivalent; Thus, lower equations produce relatively large dendrites, since the temperature range between Liquids and eutectic lines is greater for these alloys compared to castings with higher carbon equivalent. Rapid cooling promotes accurate dendrite morphology. The carbon content in the liquid increases until the eutectic formula is 4.3%. Once this composition is reached, the liquid turns into two solid substances. The type of solid formed depends on whether solidification after eutectic reaction or melting constant. Iron carbide (Cement, Fe3C) and austenite are formed during the stable reaction and graphite (C) is formed in addition to austenite during the stable reaction [13].

3.3. STIFFNESS

It is a property of a material that can be defined as resistance to deformation, that is, the ratio of force F that causes the same deformation and deformation x. [31].

$$K = \frac{F}{X} \tag{3.1}$$

Where:

k- material stiffness, unit of measurement [N / m]
F- load, force, unit of measure [N]
x-deformation, unit of measure [m]

3.4. THE PURPOSE OF SURFACE HARDENING

In parts of machines operating under dynamic and cyclic loading, fatigue cracks appear in the surface layers under the influence of tensile stresses. If a residual compressive stress is created on the surface, then the tensile stress under load during operation will be lower and the fatigue limit will increase. The second purpose of surface hardening is to create a compressive stress in the surface layers of the parts [33].

3.5. HISTORY

Previously, there were two types of ferrous products, wrought iron with very low carbon content, and the other with high carbon content which is cast iron. The high carbon content makes the metal poorly shock absorbent and more fractured when knocked on. Wrought iron, which contains almost no carbon, is very ductile and has very weak hardness [33].

Surface hardening is to immerse low-carbon iron in a container with a high-carbon material, then heat to give the carbon heat energy that helps it move to the iron's surface. This process forms a thin layer of high-carbon steel on the surface, with the carbon content gradually decreasing as we get closer to the core of the piece. The piece is thus more impact-resistant than low-carbon steel, with a high-carbon steel exterior that is much harder and more wear-resistant [32].

In the past, the process was done by mixing a mixture of bone, charcoal, leather, hooves and urine salt together in an airtight box. This group is then heated to a high temperature below the melting point of the iron for a period of time. The longer the period, the deeper and more diffuse the carbon within the piece [32].

The required depth varies according to the different purposes, for example the need for sharp tools requires a deep surface hardening in order to be grinded and re-sharpened without reaching the core of the soft metal, while machine parts such as gears may only need surface hardening to resist wear [32].

Modern technologies of modern hardening have been able to obtain a homogeneous steel that is regularly graded in carbon content from high to low as we approach the core of the metal. However, heterogeneous surface hardening is sometimes desirable, as it may combine maximum hardness with maximum impact resistance, which is not readily obtainable in homogeneous alloys [33].

3.6. REASONS FOR THE PROCEDURE TO HARDEN THE SURFACE

The reasons for the surface hardening procedure are mentioned below.

- To improve wear resistance
- To improve resistance to high contact pressures
- To improve fracture stiffness
- To improve fatigue resistance [34].

3.7. TYPES OF HARDENING SURFACE HARDENING

In addition to applying wear-resistant coatings to tool surfaces, there are four other groups of surface hardening technologies for cutting tools [35]:

3.7.1. Methods of Mechanical Hardening

The cold hardening of a metal by deformation of the plastic is called working hardening or cold working. At the same time, the structure of the mineral changes: the crystal lattice is deformed and the grains are distorted, that is, they change from homogeneous to unequal. This is accompanied by an increase in stiffness and strength 1.5 - 3 times. Compressive stress in the layer that hardens during work increases fatigue resistance. Surface treatment by plastic deformation increases the reliability of parts, reduces sensitivity to stress concentrates, increases wear resistance and wear resistance, and eliminates traces of previous treatment [35].

It is most often used for hardening tools made of high-speed steel and hard alloys. Surface plastic deformation (SPD) - hardening of the surface layer to a depth of 0.2 -

0.8 mm to create a residual compressive stress in it. During curing, the surface layer is leveled. Elongation of the surface layer is prevented by the force of adhesion to the metal layers lying below it. As a result, biaxial compressive stresses arise in the treatment-cured layer and negligible reactive tensile stresses arise in the thickness of the parent metal. By adding the working tensile stresses, the residual compressive stresses are reduced and compensated at sufficiently large values. Multiple structural deformations arising during hardening in the workplace (grain deformation, local plastic shears) effectively prevent the development of fatigue damage and expand the area of existence of non-expanding cracks, while the increase causes the existence of ultimate stresses [33].

Hardening of work in the stressed state is effective, which is a combination of overload hardening with hardening. In this method, the part is loaded with a load of the same stress as the working one, which causes elastic or elastoplastic deformations of the material. After the load is removed, residual compressive stresses appear in the surface layer. The hardened layer at work is sensitive to heat. At temperatures of 400-500 ° C, the stiffening effect disappears completely due to the recrystallization process that occurs at these temperatures, which eliminates the changes in structure and crystal that result from hardening at work. The main types of surface hardening by plastic deformation: blasting, rolling, stamping, diamond smoothing [34].

Blasting consists in hardening the surface layer with a stream of hardened balls (diameter 0.5 - 1.5 mm) formed by centrifugal shotgun blades. During this process, the surface quality is slightly reduced. Flat surfaces are hardened by rolling with balls mounted in a rotating chuck [32]. The work piece is given the movement of the longitudinal and transverse feed, with the correctly selected rolling mode, the residual compressive stresses in the surface layer are 600 to 1,000 MPa. The compaction depth of the layer is 0.2 - 0.5 mm. This process improves the surface quality of the part. The surface of the rotation is hardened by rolling with hardened steel rollers. The pressing force of the roll is selected with such an increase as to create a stress in the surface layer which exceeds the yield strength of the material under conditions of uniform compression (for steel 5,000 to 6,000 MPa). The excavation is performed by strikers with a spherical work surface, which are vibrated by pneumatic devices. The oscillation frequency and the rotational speed of the workpiece must be matched so that the parts hardened by the workpiece overlap. Diamond smoothing consists in processing a previously ground and polished surface with rounded diamond cutters (radius 2 to 3 mm). The surface layer is compacted to a depth of 0.3 - 0.5 mm [35].

3.7.2. Methods of Chemical-Thermal Treatment (CTT)

High surface strength is ensured by isothermal hardening and thermomechanical surface treatment of the part [33]. During surface hardening (flame hardening) and chemical-thermal treatment (carburization), hardening is mainly caused by the occurrence of residual compressive stresses in the surface layer due to the formation of structures with higher specific volume (nitrides and carbonitrides during nitrocarbonization and nitriding) than the parent metal structure. The expansion of the surface layer is inhibited by the core, which retains the original pearlite structure, as a result of which two-layer compressive stresses are created in the surface layer [34].

Reactive tensile stresses, which have a small value, arise in the lower layers due to the insignificance of the section of the heat-treated layer compared to the section of the core. Compression preload reduces the average compressive stress, thereby increasing the fatigue limit. Gaseous cooling increases the endurance limit by 1.85 compared to the original untreated steel structure. The most effective treatment is nitriding, which almost completely eliminates external stress concentrators. Nitriding does not change the shape and size of the part. The nitrided layer has increased resistance to corrosion and heat. The hardness and strengthening effect are maintained up to a temperature of 500 - 600 ° C.

The optimum thicknesses of the compaction layer during carburization are 0.4 to 0.8 mm, carburization and nitriding 0.3 to 0.5 mm, cooling by heating and cooling of gas 2 to 4 mm. The surface quality has significantly improved. Electro spark, magnetic, ultrasonic hardening. These methods are rarely used to process cutting tools [35].

3.8. HEAT TREATMENT

Some types of hardening are mentioned below [36]:

- Induction Hardening
- Flame Hardening
- Electron beam hardening
- Laser Hardening

3.8.1. Induction Hardening

When we speak of induction hardening, we refer to exposing a piece of steel to an alternating magnetic field that causes heat to penetrate superficially into it. The objective of this process is to obtain a surface layer of hardness without actually modifying the structure of the core of the material [37].

The lower the working frequency, the greater the penetration on the piece. The energy of the magnetic field is transformed into heat (hysteresis effects and eddy currents on ferromagnetic materials), increasing the temperature of the surface of the piece until it reaches the tempering temperature (900 ºC approx.) In a few seconds [37].

When it exceeds a certain temperature (Curie temperature) the material loses its ferromagnetic properties and largely stops the production of heat. At this point, the magnetic field is eliminated, and the piece is cooled in various ways (air currents, water, aqueous solutions, oil and others), thus controlling the cooling speed. At higher speeds, higher harnesses are obtained [38].

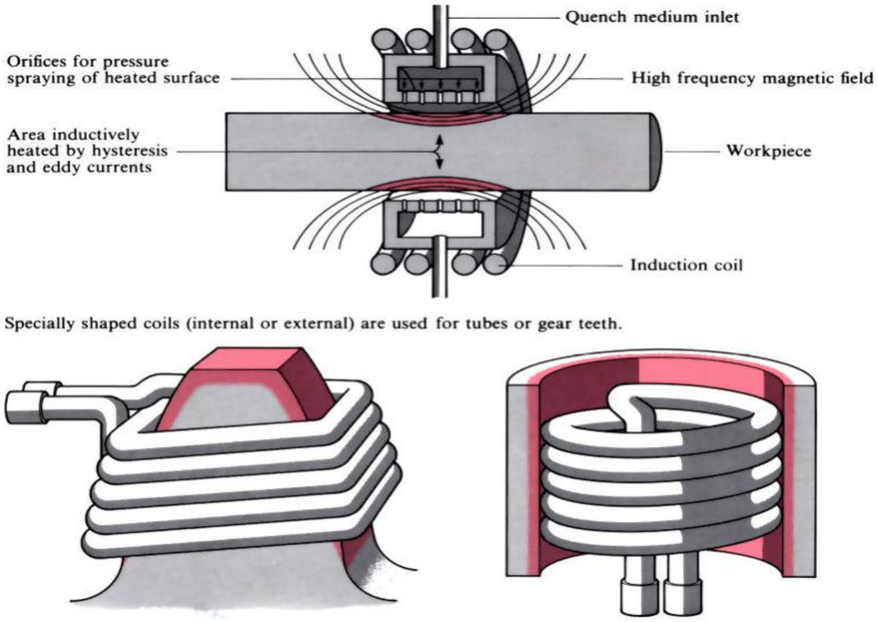


Figure 3.1. Induction hardening [39].

3.8.2. Flame hardening

Flame hardening. Oxy-acetylene flame, light gas, natural gas, or other hydrocarbons are usually used for heating. This method of hardening is mainly used for large products that cannot be hardened in any other way [39]. The burner moves along the hardened surface and the shower follows immediately after the burner [38]. Examples of use the technologies are used to increase the hardness of gear teeth, shafts, splined shafts, camshafts, connecting rods, bearing surfaces, scissor jaws [39].

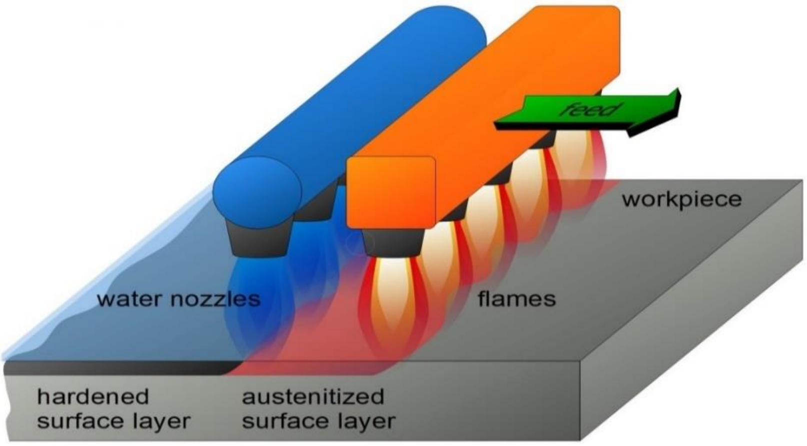


Figure 3.2. Flame hardening [40].

Examples of use the technologies are used to increase the hardness of gear teeth, shafts, splined shafts, camshafts, connecting rods, bearing surfaces and scissor jaws [40].

The selective zone is filled with a high intensity oxy-acetylene flame. In the area of austenite transformation, the temperature is raised high enough. Based on the experience of observing the stain color, the operator determines the "correct" temperature.

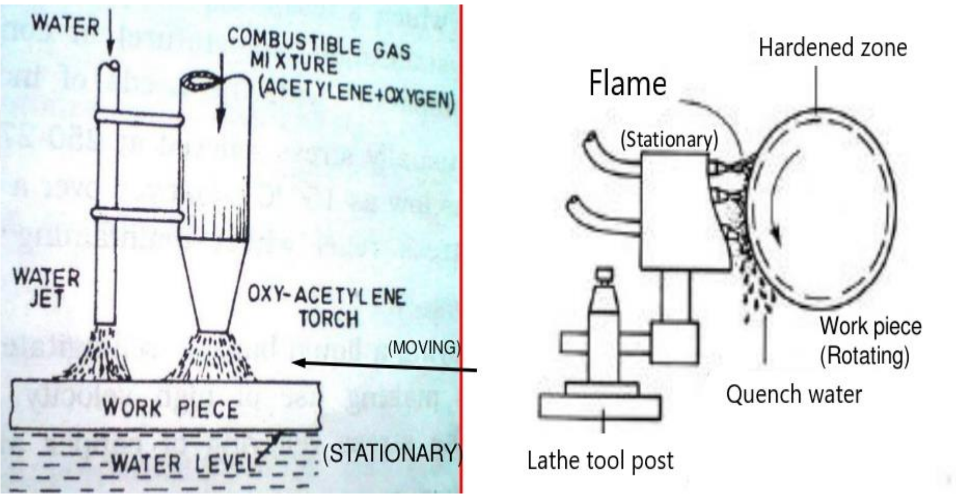


Figure 3.3 Flame hardening contains [41].

3.8.3. Electron Beam Hardening (EBH)

Electron beam hardening is an energy source using an organized column of electrons as a material hardening procedure. The bombardment of the electron column on the surface of the material generates heat that increases to a temperature that increases its hardness, whether the substance or the surface of the material. This makes it possible for a material to have exceptional resistance to wear while preserving ductility and toughness in its core [41, 42].

3.8.3.1. Explains Electron Beam Hardening (EBH)

The hardening of the electron beam usually is used to harden a very thin surface of the object by lifting it to a certain temperature and then cooling it quickly [41].

Unique about the hardening of electron beams in other hardening techniques is that they can harden only the external layer of a material, maintaining its original mechanical and chemical properties at the core of the material. The electron beam hardening technique can harden thicknesses below 0.004 inch (0.1 mm). The small surface layers of material which are influenced by the hardness of electron beams are usually sealed. The weight ratio affected by the hardness of the electron beam and the unaffected weight are small enough to make the surface cool enough to harden them by the unhocked weight [41].

Hardening electron beams includes exciting electrodes, which are usually made from tungsten or a tungsten alloy, and they emit electrons. To do so, the filament that thereafter starts to produce electrons moves thousands of volts. The electrons are ordered and concentrated by magnetic fields during the electron beam hardening process [42].

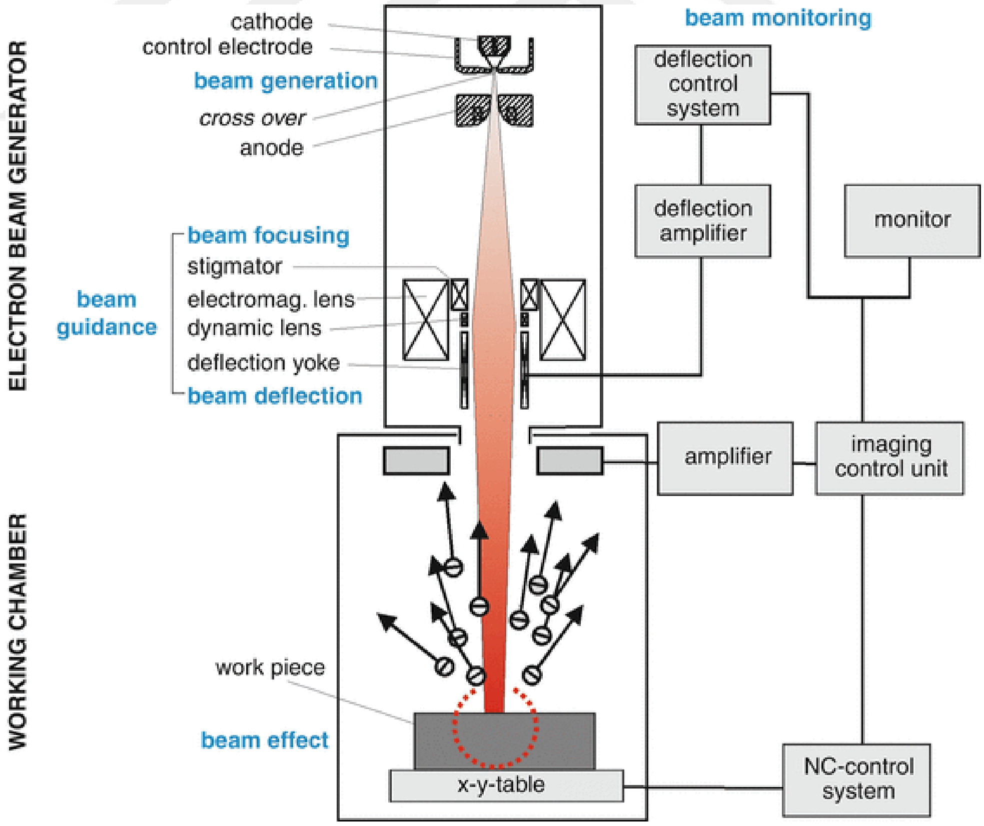


Figure 3.4. Electron beam hardening [42].

The electron beam hardening technique has a concentrated focus that offers the energy density needed to heat the material for the work. The beam also has to be moved over the component while the hardening process of the electron beam is being carried out, by combining the electron beam gun moving with extra magnetic fields. The entire work carried out is done in a vacuum to avoid contamination of the filament and material undergoing electron stray hardening as Figure 3.4 [43].

3.8.4. Laser Hardening

3.8.4.1. History

The component is heated to the necessary temperature in traditional heat treatment methods and then tamped in oil or water to obtain the correct surface hardness. Wear occurs exclusively in specified component locations for most industrial applications; hence these areas are hardened sufficiently to improve the component performance. The advantages of employing laser for surface processing include the extremely directed nature and the capability to supply regulated energy to targeted areas [44].

The input of energy depends on the material's absorption. The material absorbs only a proportion of the laser energy and reflects the rest from the surface. Addressing a polished metal surface is highly dependent on the irradiation wavelength. With steels, when the wavelength is short, the absorption increases. The Nd: YAG laser beam has a wavelength of 1.064 µm with a carbon laser beam of 10,6 µm. Thus, the YAG laser is appropriate for surface hardening in steel with a short wave length [44].

Due to its greater wavelength, CO2 laser interacts with metallic materials low. The painting or coating has to be put on the base metal in order to improve the absorption rate prior to CO2 laser hardening (LH). Pollution and dangerous consequences on the environment arise from the employed paint or coating. On the other hand, Nd: YAG laser is a competitive instrument for surfacture modification since the materials and the coating of the basis material have a shorter wavelength and high absorption rate, which are of benefit compared with CO2 laser [45].

3.8.4.2. Laser heat treatment

Laser is employed as a heat source in laser heat treatment, in which beam energy is employed to harden the surface on a localized area with the remaining component as a heat sink. Given the strong thermal flow produced by lasers are particularly good heat conductors to heat the surface layer to certain levels levels without altering the bulk temperature of the sample. The subsequent self-watering is sufficiently rapid to avoid the necessity for external wetting to form hard marten site in the heated surface. A highly wear-resistant surface can therefore be created with the appropriate core qualities of the element [46].

LSH therapy components comprise heavily stressed machine components such as gears, gears, camshafts, gear hinges, cylindrical liners, axles and exhaust valves and valve guides. Many of these uses are in the car industry, one of the first mass production industries to use lasers for surface treatment [41].

Substantially strained machine components such as gear, gear, cameras, gear shafts, cylindrical lining, axles and exhaust valves, and valve guidelines are the components for LSH therapy. LSH is a fast and efficient hardening technique for several materials, including tools, die steel, cast iron and steel. The development of alternative hardening technology has created new opportunities to build locally in material locations with unique characteristics and to increase the quality of the whole product [45].
This technology is utilized to process the specific areas depending mainly on the size of the laser beam, given that the processed area is highly localized and the heat transfer is made into a massive material allowing the essential cooling rate for the martensitic transformation, without requiring the refrigerating medium. The LSH process is extremely suitable for medium carbon steel. The hardness rate is also high due of the high refrigeration rate. For these reasons, LH is the optimum choice for the heat surface treatment of components small and complicated [45].

3.8.4.3. Laser hardening method

This technology uses a bigger laser beam (about ten millimeters) to process larger regions without any substantial form complexity [47]. It is particularly suitable. The softer, tempered structure is derived from the "overlap" section when the hardened tracks must be overlapped. The treated part can very well survive wear resistant applications but in a tempered area dynamic stresses can lead to irreparable degradation of the component [48].

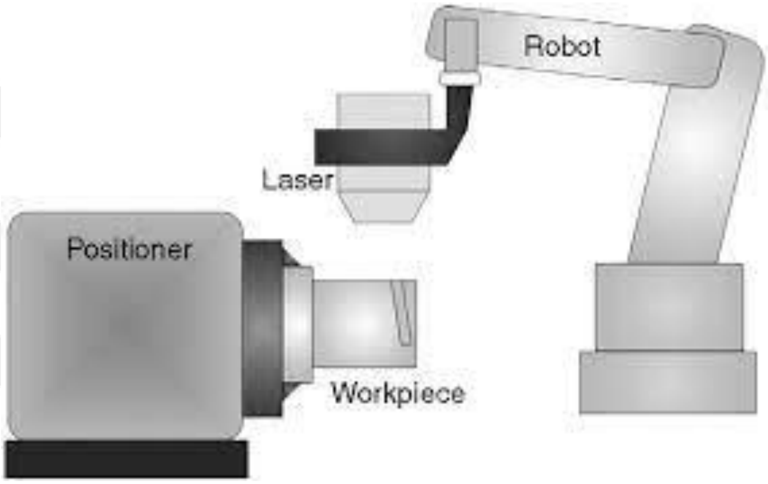
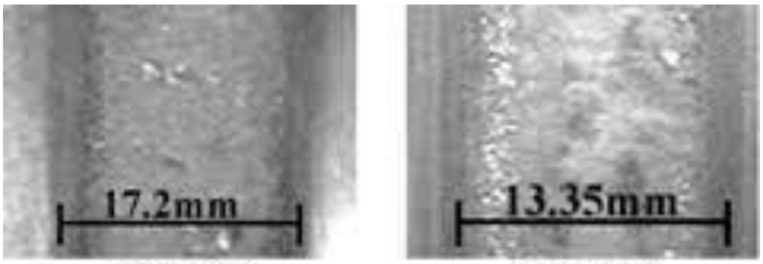


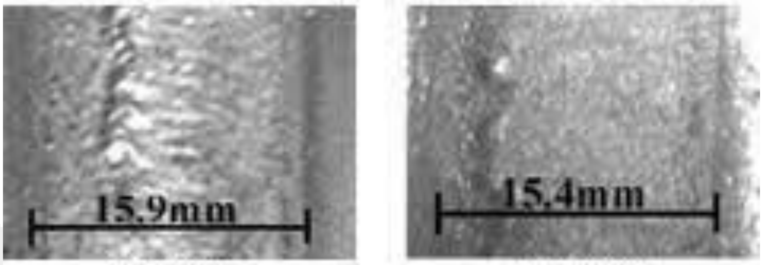
Figure 3.5. Laser hardening [47].

Figure 3.6. Laser hardening work [48].



(a) SNCM220
V=2mm/s

(b) SNCM220
V=3mm/s



(c) SCM440
V=2mm/s

(d) SCM440
V=3mm/s

Figure 3.7. Laser “wide-beam” hardening [49].

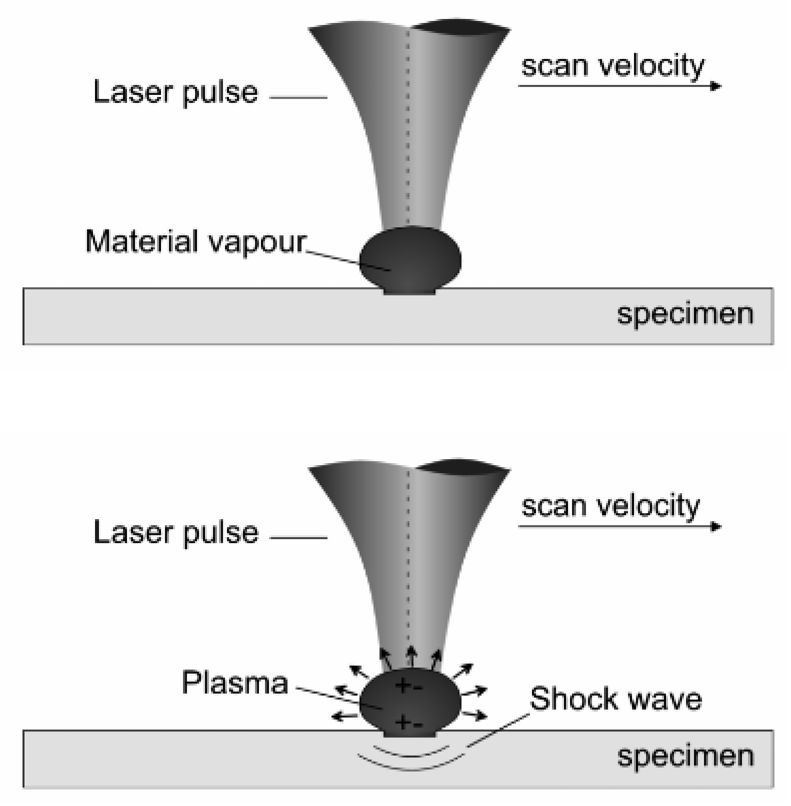


Figure 3.8. Scanning laser hardening [45].

Using scanning optics is the key distinction from conventional laser hardening. This is used to create hardening patterns in the working field arbitrarily complex. Then a laser beam scans the hardening pattern [49]. At high speed, the tiny laser beam is oscillated to the direction of treatment. The oscillation amplitude can be selected in a relatively broad range. During the processing process, processing parameters can readily be modified and the parameters can therefore adjust directly to the indentation geometry of the part. This approach is ideal for smaller components with complicated surfaces [45].

In recent years, systems based on mobile optics, also called scanners, have been developed and manufactured to provide motion to the laser beam at the highest linear speeds at 7000 mm / s. These systems are extremely versatile and open the door to new laser surface treatment processes as well as remote variants in other types of laser operations such as cutting or welding. On the other hand, tempering or laser hardening is a surface treatment that is used in a variety of industrial applications where hardness is achieved on the surface of the piece, while the core remains solid, with minimal engineering distortions [45].

By contrast, laser stiffness in the distant variant is much unknown. Hence, in the present work, it is intended to study the remote laser tempering process which, as it is a heat treatment, requires precise control and knowledge of the thermal record that occurred during the process [45].

It is likely that conventional laser sclerotherapy is the most widely used and fastest growing laser treatment process in the industry today. If laser hardening is compared to other traditional surface treatment processes, such as induction or flame hardening, it is possible to obtain a highly localized treatment area on complex 3D surfaces with minimal dimensional distortions, and the process can be eliminated in some cases. End of milling [31]. In addition, the benefit of this process is that a versatile laser source can be incorporated directly into the production chain without the need for additional hardening methods and that two completely different microstructures, a core, can be produced on the same ductile material with a solid surface layer with residual compressive pressures [50].

It is a process that is used to smooth out the molds. Specifically, at the cutting edges [51], given that a high hardness surface can be obtained after the die setting procedure, practically without introducing geometric distortion. On the other hand, in recent years, systems based on mobile optics to guide high-power lasers have been developed and manufactured. These systems are also called scanners and are usually attached to the wrist of a serial robot [52], as shown in Figure 1. The main feature of scanners is that they can move the laser beam at speeds greater than 7000 mm / s. This is since the movement is carried out through the rotation of the mirrors with the extraordinary power of a very small mass that convert the small turns into the linear movements of the laser beam in the workspace [53].

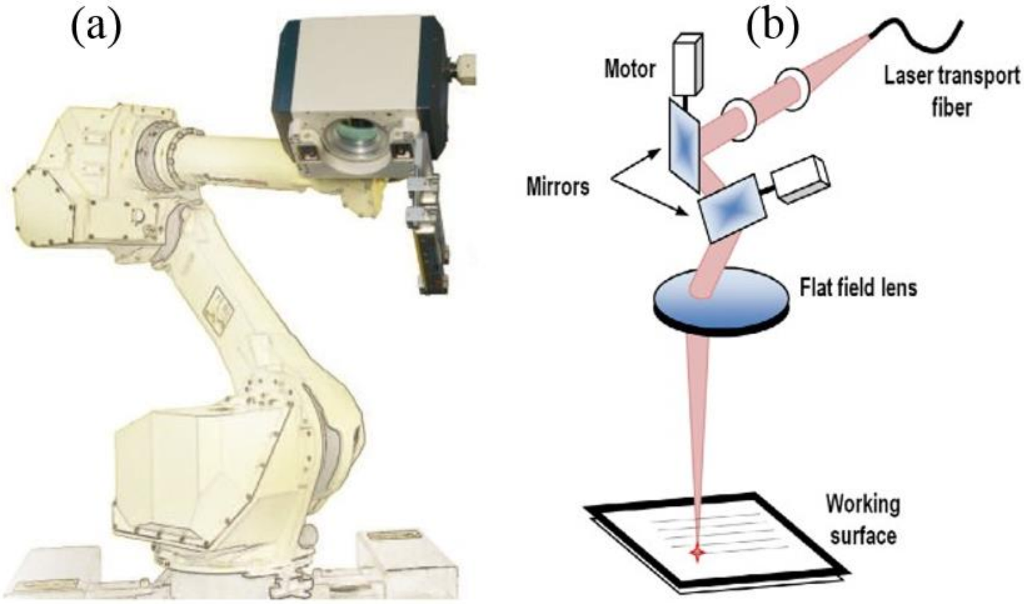


Figure 3.9. (a) Scanner positioned in the arm of a robot for remote laser processes (Blackbird); (b) Schema of the basic components of a scanner system [53].

The main advantage of the scanners is that they operate far from the area to be treated, thus they can reach areas that are not easily accessible, with good quality of laser beam [53].

The remote laser hardening method offers two separate rates, the scanning speed and the feed rate, as opposed to traditional laser hardening. The scanning speed [mm/s] is the parameter of this operation [48]. The actual movement of the laser beam is this speed and operated by the scanner's optical mirror mechanism reaches over 7000 mm/s. The feed rate [mm^2/s] is on the other side. This is the actual speed of the hard track on the surface of the part [49]. The measurements are indicated by speeds of a honeycomb, not linear speeds, as it depends not only of the relative speed between the machine tool or robot and scanner but also of the scanning speed [mm/s] and of the width of the sleep region. It will depend on how the laser path is programmed. Also, it is necessary to control the real temperature of the part surface which is usually done by two color pirometry [54]

This system is able to accumulate up to 1000 data per second without thermal delays. In the case of remote laser hardening two distinct temperatures may be distinguished, a baseline or base temperature and peak temperatures above the base temperature, close to the ones used in the grinding process [55].

Hard and resistant to wear surface layers with a typical thickness of 0.5 to 1.5mm are a process used for transformation hardening [55]. The principle of the procedure, comprising laser beam and gas protection, is shown in Fig. 3.10.

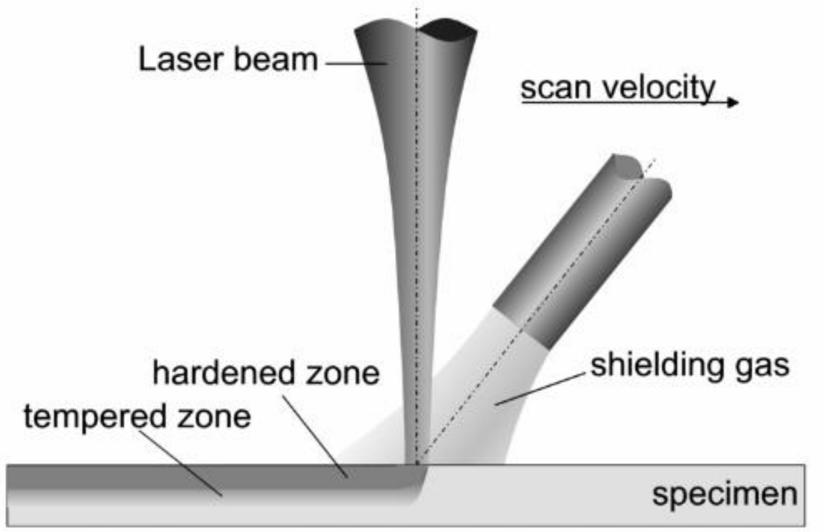


Figure 3.10. Laser transformation hardening [45].

It is used on 0.4 to 1.5% C carbon steels. The laser process hardening approach is seen as the reverse of conventional hardening. When the product is conventionally hardened, flame or in the oven heats it to a temperature higher than Ac where the structure is transformed from the initial ferritic/pearl structure (a+ Fe3C) into an austenitic μ phase when the carbon is dissolved in the steel [54].

Hardening takes occurs if the material is cooled down thereafter at such a high cooling rate that time for reverse transformation and carbon secretion is not sufficient. The highly tough martensite is formed instead of the ferritic structure. The austenite very instantly converts to martensite below the Ms temperature of around 250°C. The carbon is not yet expelled but is in the structure of the crystal. This transformation leads to a volume expansion that imparts beneficial residual stresses to the surface and improves mechanical qualities including the resistance to wear and fatigue [55].

It is used on 0.4 to 1.5% C carbon steels. The laser process hardening approach is seen as the reverse of conventional hardening. The product is warmed by fire or fire during conventional hardening to a temperature above Ac when the structure is converted from the ferritic/pearlitic starting construction (a + Fe3C) into the austenic μ phase in which carbon is dissolved in stainless steel [35].

This process is a transformation of the reversible balance, which takes a few minutes depending on the temperature and the structure. Hardening takes occurs if the material is cooled down thereafter at such a high cooling rate that time for reverse transformation and carbon secretion is not sufficient. The highly tough martensite is formed instead of the ferritic structure. The austenite very instantly converts to martensite below the Ms temperature of around 250°C. The carbon is not yet expelled but is in the structure of the crystal [55].

Together with this transformation a volume expansion occurs, which introduces advantageous residual stresses into the surface improving the mechanical properties like wear-and fatigue resistance [56].

In laser hardening, the skin of a carbon-containing work piece made from steel or cast iron is heated up to just below the melting temperature – this is generally around 900 to 1400°C. Around 40% of the irradiated power is absorbed. The high temperature causes the carbon atoms in the metal lattice to rearrange (austenitization) [57]. When the nominal temperature has been reached, the laser beam starts to move, thereby steadily heating the surface in the direction of feed [58]

As the laser beam continues, in a phase called self-watering, the surrounding material cools off the hot surface very rapidly. The metal bars are unable to revert to their original configuration, forming martensite as a result of the fast cooling. This leads to considerable hardness increase [58].

The external hardness of the coating is usually between 0.1 and 1.5 millimeters, but it can be 2.5 millimeters or more for certain materials [58].

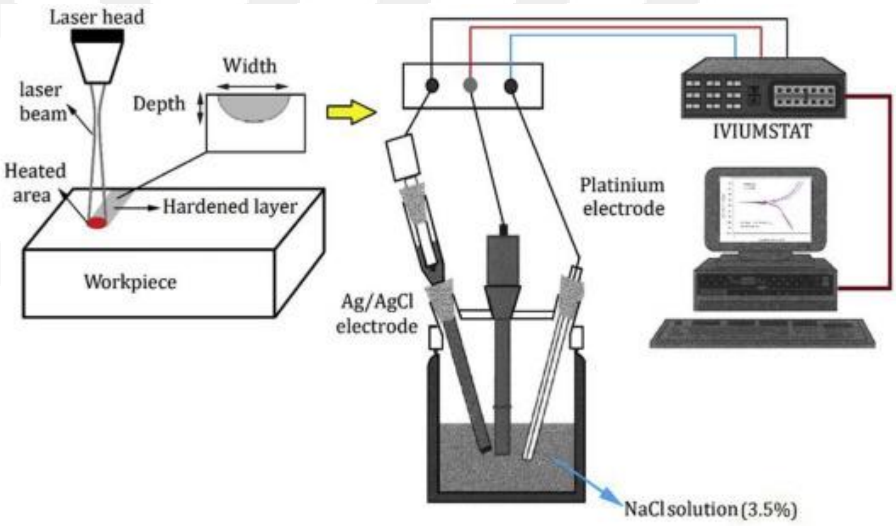


Figure 3.11. Laser hardening method [59].

PART 4

EXPERİMENTAL STUDIES

4.1. EXPERIMENTAL METHOD

In this study, AISI 4340, 5140 and 8620 quality steels were hardened by sending laser beams with different parameters to the materials. The chemical compositions of the steel materials used are given in Table 4.1.

Table 4.1. Chemical composition (wt %).

Elements	C	Si	Mn	Cr	Mo	Ni	Fe
AISI4340	0.41	0.19	0.77	0.82	0.23	1.74	Bal.
AISI5140	0.38	0.22	0.7	0,84	0,05	0.30	Bal.
AISI8620	0.21	0.25	0.80	0.50	0.20	0.55	Bal.

The starting materials supplied were cut on a hacksaw. In order to eliminate the thickness difference in the materials, 2 mm of sawdust was removed from the surface on the lathe. Afterwards, he polished the surfaces with the surface grinding device and carried out the first surface hardening trials on the laser device.

As the surface quality was not at the desired level, the results were not as predicted. For this reason, in CNC surface grinding, 0.3 mm was removed from the surfaces by 0.025 mm in each pass, resulting in a smooth surface.

In the trial laser hardening process, increasing the laser distance caused the machine to increase the power to keep the surface temperature at the same value and to heat both the head and the part. The only parameter affecting the measured values was the power of the laser. Then the feed rate was included in the parameters instead of the distance between the laser and the sample.

It has been seen that it is possible to work with lower Watts at a slower feed rate. Close results were obtained for these speeds in surface hardness, with slight differences from material to material. Melting behavior was observed in low feed rate and high-power material in some materials. In these tests, the thermocontrol activated, reducing the available laser power. The slow feed rate caused the parts to heat up more.

In order to see the effect of these parameters in depth, the materials were cut into small pieces by cold cutting, pressed with bakelite powders, and then their structures were examined after grinding and polishing at 3000 scale in order to see the surfaces under the microscope. The pool, the affected region and the phase regions were observed under the microscope. It was found that the carbon atoms were concentrated in a very dense amount, which significantly increased the hardness.

4.2. LAZER SURFACE HARDENING METHOD

In this study, as stated in Table 1, In order to save processing time, the feed rate was kept constant at 6mm/s, and all 3 materials at the same temperature were allowed to cool on their own after their first passes, and the second test was started at medium temperature. After the temperatures of 1300 to 1200 degrees at a speed of 6mm/s, the temperatures of 1300 -1200 degrees with a feed rate of 4mm/s were applied to the back surfaces of all samples, respectively.

Table 4.2. Process parameters and surface hardness.

		AISI 4340		AISI 5140		AISI 8620	
queue	Speed mm/sec	temperature	watt	temperature	watt	temperature	watt
1	6	1300	1400	1300	1460	1300	1400
2	6	1250	1350	1250	1390	1250	1340
3	6	1200	1290	1200	1330	1200	1200
4	4	1300	1180	1300	1250	1300	1200
5	4	1250	1100	1250	1116	1250	1130
6	4	1200	1050	1200	1100	1200	950

Figure 4.1. Materials surface after laser surface hardening process.

4.3. MICROSTRUCTURAL EXAMINATIONS

For microstructural analysis, the samples were precisely cut to the desired dimensions with a diamond cutter. The samples in METKON FORCIPOL 2V Figure 4.2 were sanded with a metallographic grinding and polishing device with 200-2500 mesh abrasives to remove the roughness on the surface, and the metallographic procedure was completed by polishing with 3 µm and 1 µm pastes.

Subsequently, the images of these samples under the stereo microscope were examined and the hardened depth of field was measured at this temperature and scanning speeds.

Figure 4.2. Metkon forcipol 2v metallographic grinding and polishing device.

Microstructure images were taken with the Leica DM ILM optical light microscope, shown in Figure 4.3, and the Carl Zeiss Ultra Plus SEM imaging devices, shown in Figure 4.4.

Figure 4.3. Leica DM ILM optical light microscope.

Figure 4.4. Carl Zeiss Ultra Plus Gemini Fesem scanning electron microscope.

4.4. HARDNESS TEST

Before measuring the hardness of the sample, the sample piece was treated with METKON FORCIPOL 2V grinding and polishing device with 1000 mesh sandpaper to ensure that the piece became suitable for hardness measurement. Hardness measurements were made on the samples under 1000 g load for 15 seconds with the SHIMADZU micro hardness measuring device seen in Figure 4.5. Measurements were made 10 times for each of the samples.

Figure 4.5. SHIMADZU brand microhardness device.

4.5. CORROSION TEST

After the laser hardening process, the materials were tested for potentiostat-dynamic corrosion using the Reference Electrode Ag/AgCl in 3.5% NaCl solution and the results were included in Figure 4.6.

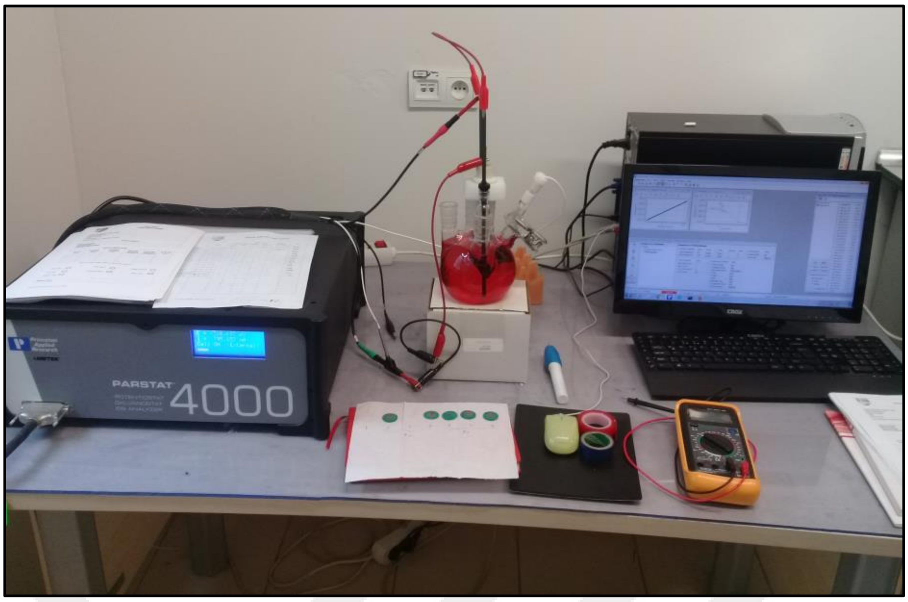


Figure 4.6. Parstat 4000 Potentiostat Galvanostat corrosion machine.

4.6. WEAR TEST

Wear tests were carried out in the UTS brand wear tester with linear back-and-forth motion type according to ASTM G33 standard and under loads of 30 N and 60 N, a total of 50 m with a stroke distance of 3 mm. The wear mark area is measured according to ISO 4287-1997 standard in the Mitutoyo SJ-410 surface roughness device.

Figure 4.7. UTS Tribometer T10/20.

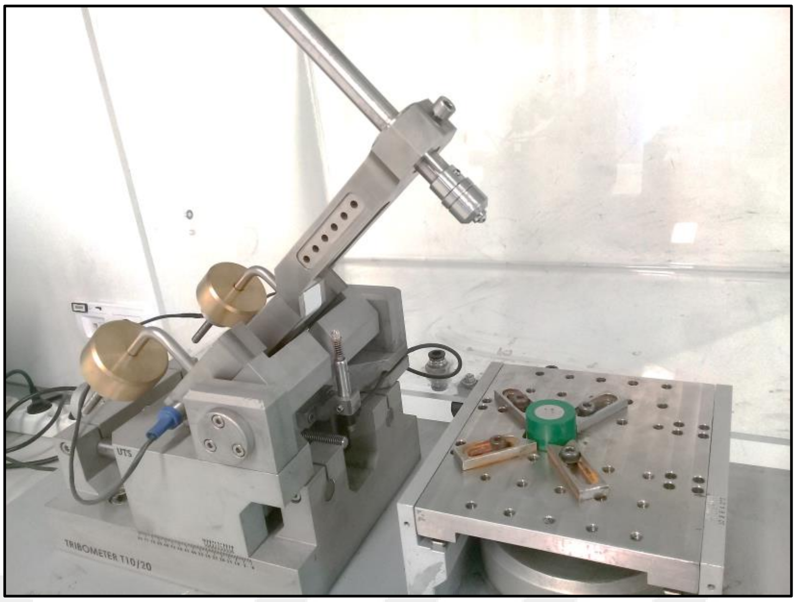


Figure 4.8. Wear test machine (Tribometer).

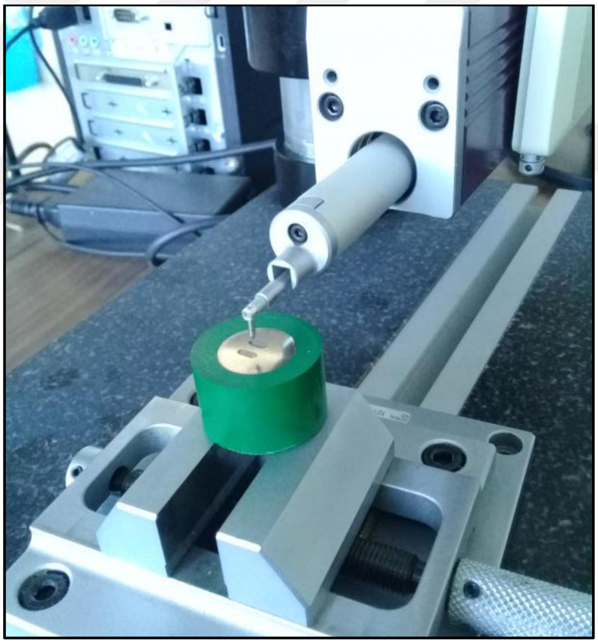


Figure 4.9. Surface roughness measurement machine.

PART 5

RESULTS AND DISCUSSIONS

5.1. MICROSTRUCTURE

Figure 5.1 includes the general image of the hardened area of 4340 steel in 50x magnification taken under an optical microscope (a) and the main material (e) in 500x magnification, the main material and hardened zone transition (d), the middle part of the hardened area (c) and the cross-sectional images of the surface section of the hardened area. As we descend from the surface to the main metal, microstructure differences appear.

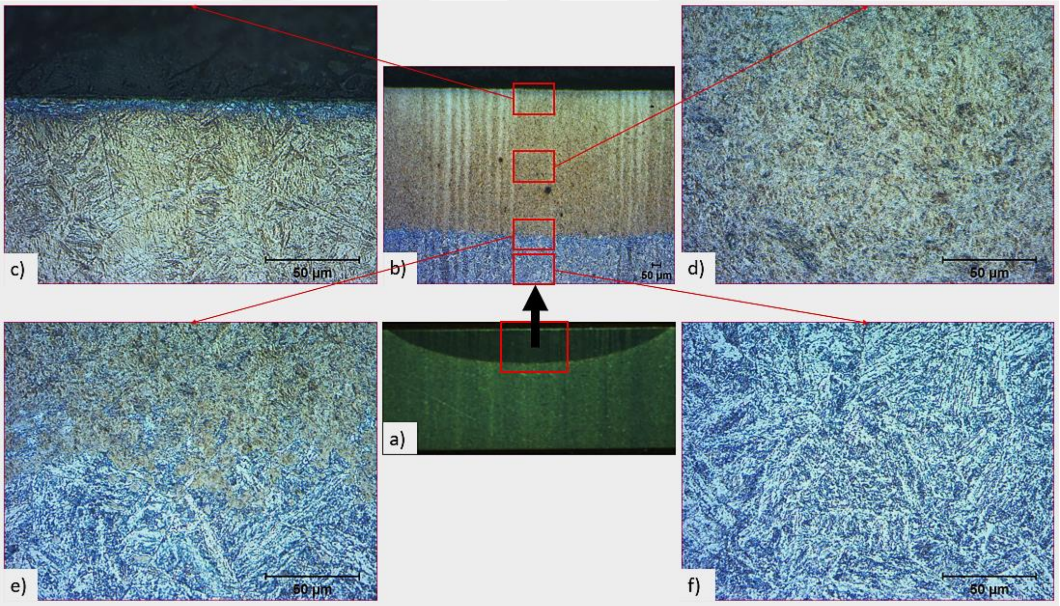


Figure 5.1. Optical microscope images of AISI 4340 Steel after laser hardening.

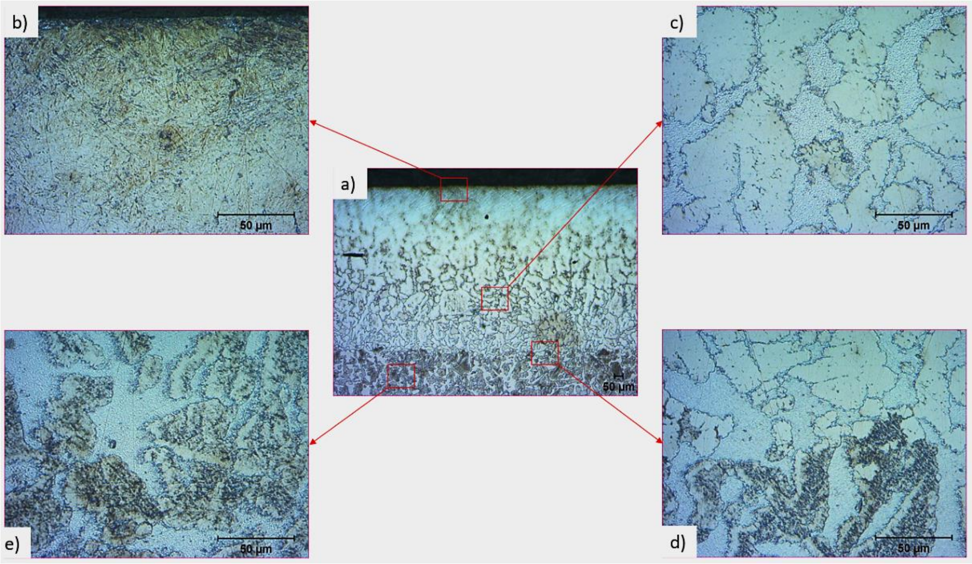


Figure 5.2. Optical microscope images of AISI 5140 Steel after laser hardening.

Figure 5.2 includes the general image of the hardened area of 5140 steel in 50x magnification taken under an optical microscope (a) and the main material (e) in 500x magnification, the main material and hardened zone transition (d), the middle part of the hardened area (c) and the cross-sectional images of the surface section of the hardened area.

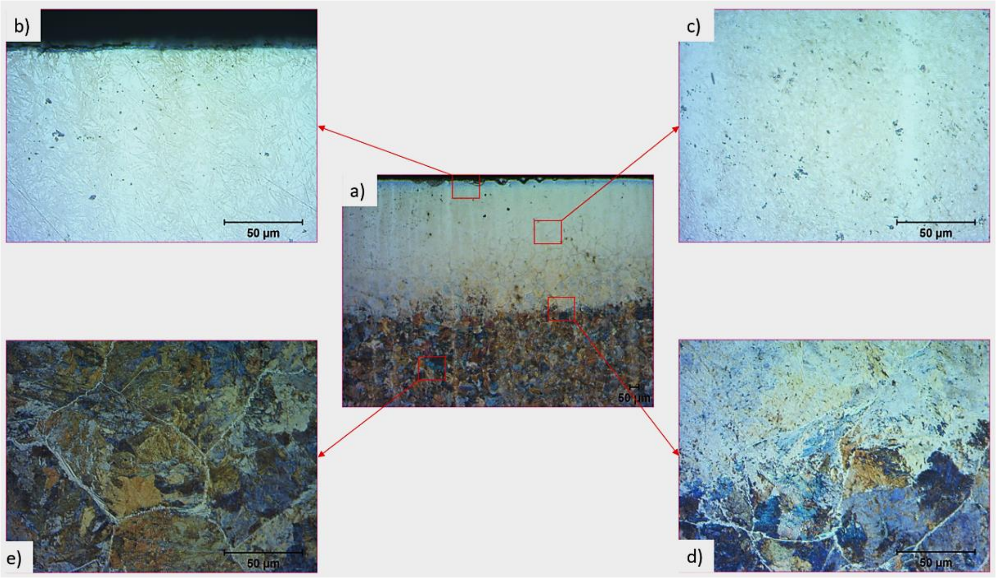


Figure 5.3. Optical microscope images of AISI 8620 Steel after laser hardening.

Figure 5.3. includes the general image of the hardened area of 8620 steel in 50x magnification taken under an optical microscope(a) and the main material(e) in 500x

magnification, the main material and hardened zone transition(d), the middle part of the hardened area (c) and the cross-sectional images of the surface section of the hardened area.

Figures 5.5 between Figure 5.7 steroid images of AISI 4340, AISI 5140 and AISI 8620 Laser hardened samples, respectively. Using these images, the width depth and areas of the hardened area are calculated and included in Figure 1. Studies have shown that with the increase of laser power, the depth of the hardened area increases more than its width, and the scanning speed decreases, the laser power increases, which leads to increased area and hardness of the hardened area.

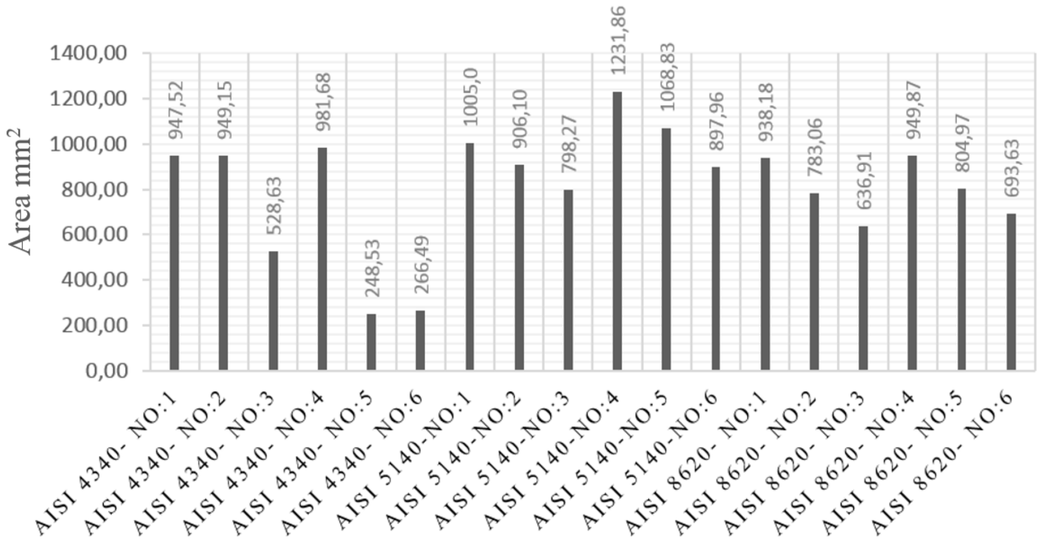


Figure 5.4. Area graph of laser hardened region.

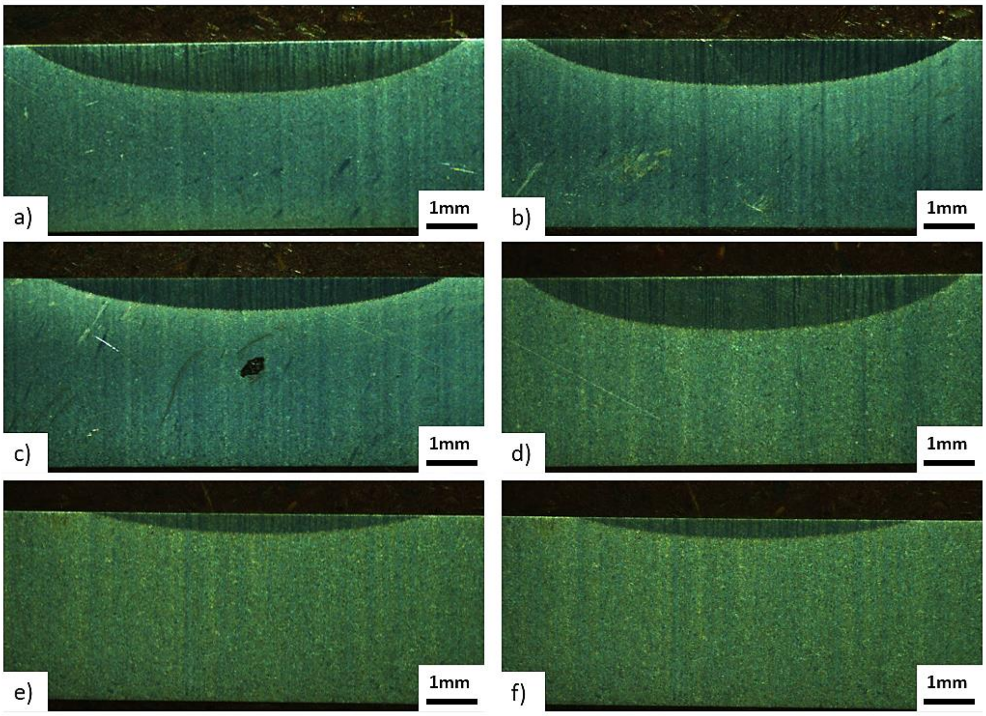


Figure 5.5. Steroid images of AISI 4340 steel; Sample 1(a), Sample 2(b), Sample 3(c), Sample 4(d), Sample 5(e), Sample 6(f).

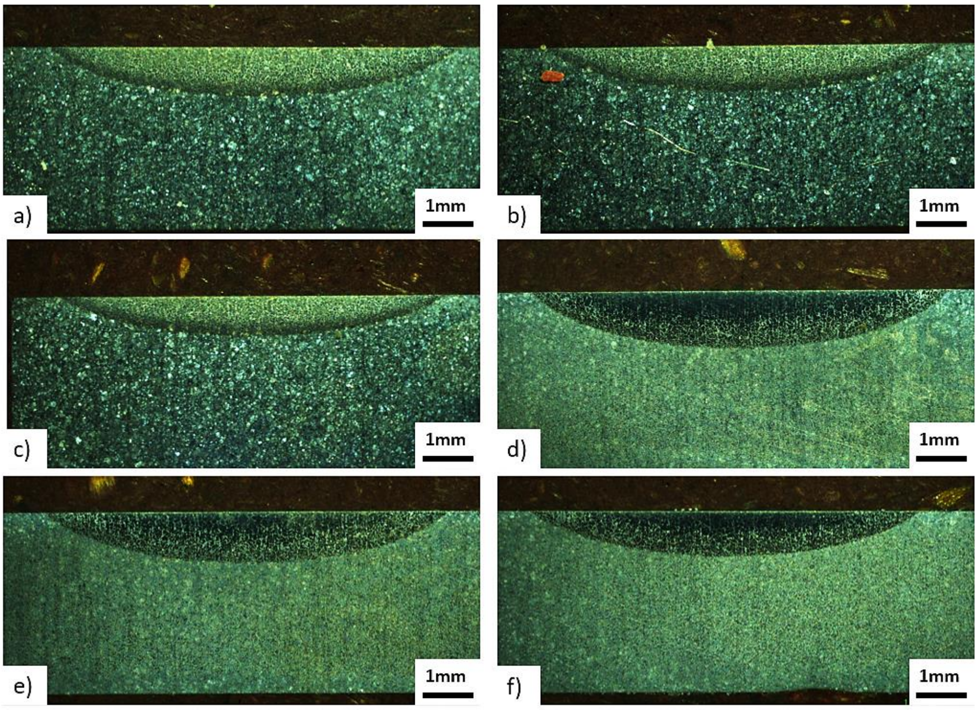


Figure 5.6. Steroid images of AISI 5140 steel; Sample 1(a), Sample 2(b), Sample 3(c), Sample 4(d), Sample 5(e), Sample 6(f).

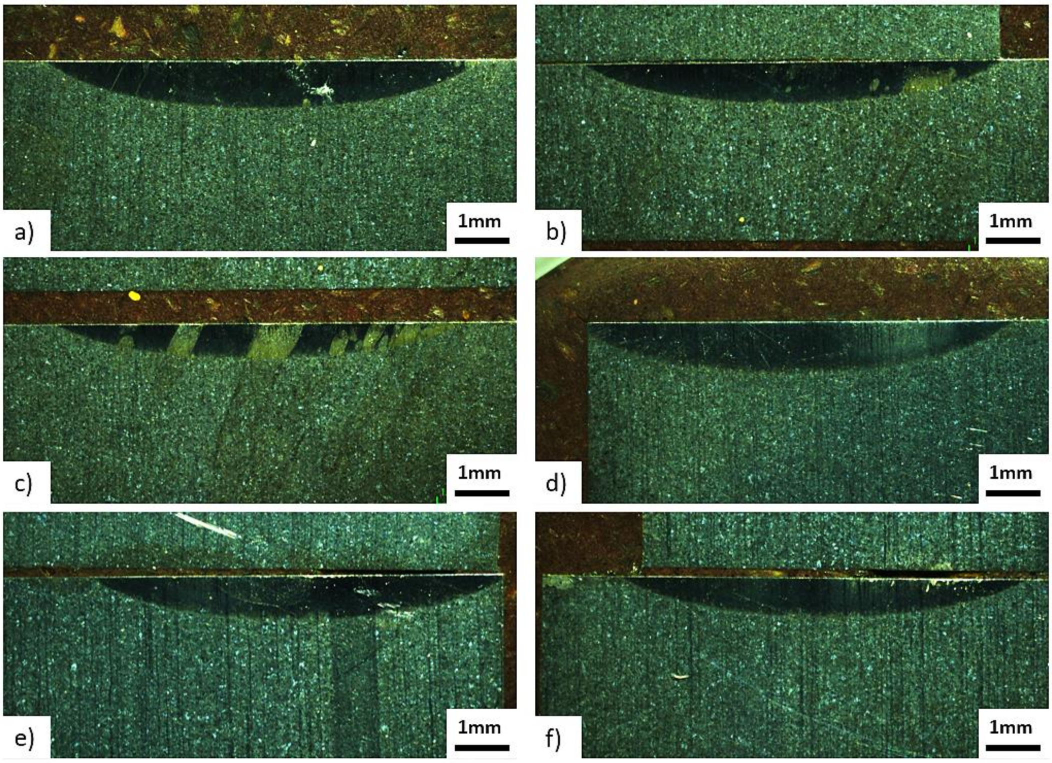


Figure 5.7. Steroid images of AISI 8620 steel; Sample 1(a), Sample 2(b), Sample 3(c), Sample 4(d), Sample 5(e), Sample 6(f).

5.2. HARDNESS RESULTS

In Figure 5.8 hardness test results of test samples numbered 4, which are produced at a speed of 1300C 4m/s, are seen. Hardness parameters were applied under 100g force and their hardness was taken at certain distances starting from the surface for 10s. According to these hardness results, AISI 4340 and AISI 8620 materials increased from the surface to around 30-80µ and the AISI 5140 material increased to a maximum hardness of around 200µ, and then the hardness decreased from the hardened area until it switched from the heat-less zone.

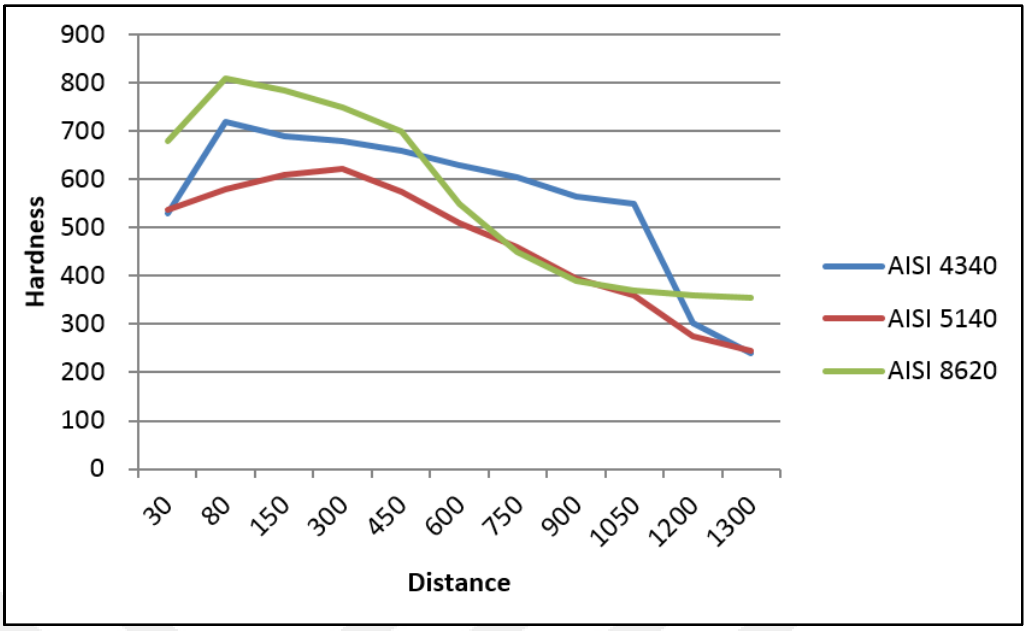


Figure 5.8. Hardness change graph of laser hardened area.

5.3. CORROSION TEST RESULTS

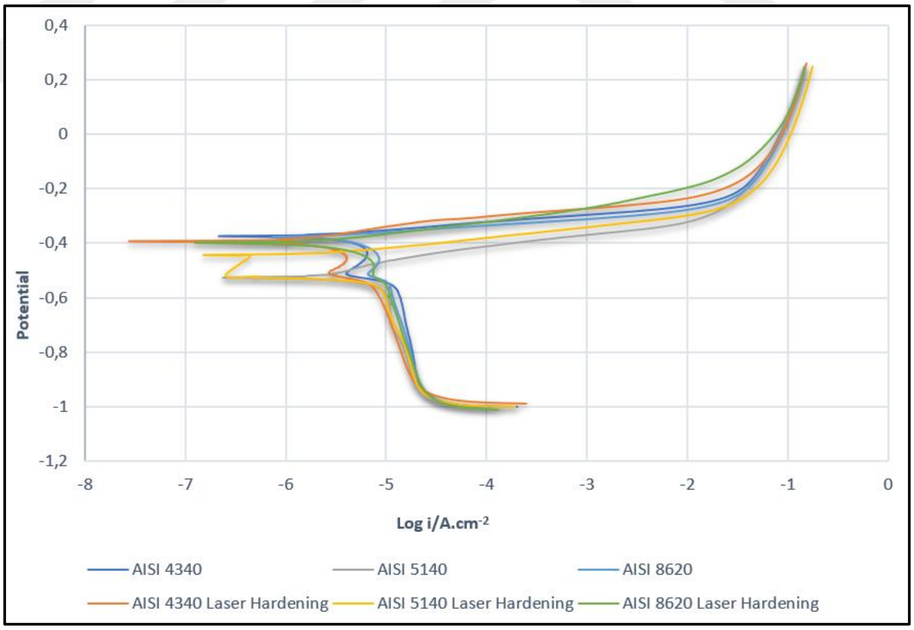


Figure 5.9. Poclosiodnamic corrosion test result graph.

After the laser hardening process, the materials were tested for potentiodynamic corrosion using the Reference Electrode Ag/AgCl in 3.5% NaCl solution and the results were included in Figure 16. When looking at the data in Table 5.1, the corrosion resistance of AISI 4340 steel doubled, there was no significant change in corrosion resistance of AISI 5140 steel, while AISI 8620 steel caused a decreasing corrosion resistance.

Table 5.1. Table of potentiodynamic corrroion test results

Specimen	Surface Area (cm^2)	CC (µA)	CCD (µA / cm^2)	CR (mm/ year)	Ecorr (V)
AISI 4340	0.126	0.747	5,928	0,046	-0.3729
AISI 4340 Laser Hardening	0.126	0.365	2,896	0,022	-0.3928
AISI 5140	0.126	0.948	7,523	0,058	-0.5277
AISI 5140 Laser Hardening	0.126	0.834	6,619	0,051	-0.4429
AISI 8620	0.126	0.362	2,873	0,022	-0.3751
AISI 8620 Laser Hardening	0.126	0.783	6,210	0,048	-0.3974

For this reason, corrosion resistance in laser hardening process has negatively affected AISI 8620 steel in addition to positively affecting AISI 4340 steel. In the AISI 5140 steel, there was not much change.

5.4. WEAR TEST RESULTS

Wear tests were carried out in the UTS brand wear tester with linear back-and-forth motion type according to ASTM G33 standard and under loads of 30 N and 60 N, a total of 50 m with a stroke distance of 3 mm. The wear mark area is measured according to ISO 4287-1997 standard in the Mitutoyo SJ-410 surface roughness device. Wear speeds and wear area depths are shown in Figure 5.10. Looking at this graph, it is seen that the wear resistance of laser hardened materials increases at 30N and 60N loads of each steel. In addition, a decrease in wear rates has been detected. In addition, AISI 4340 and 5140 steels saw an increase in the slope of the laser hardening process compared to the main material, while a decrease in the slope of AISI 8620 steel was observed.

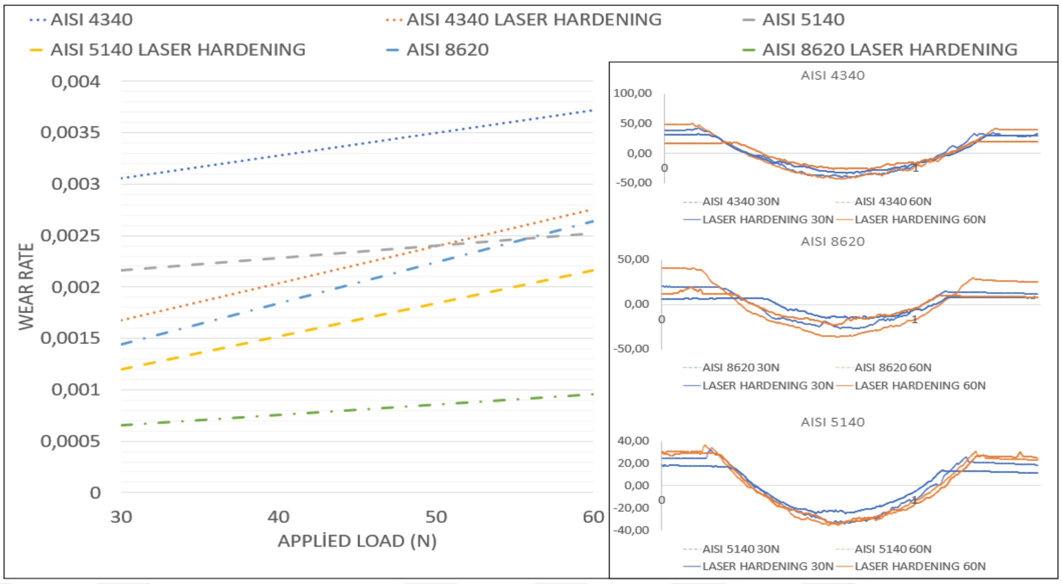


Figure 5.10. Wear speeds and Wear depth graph.

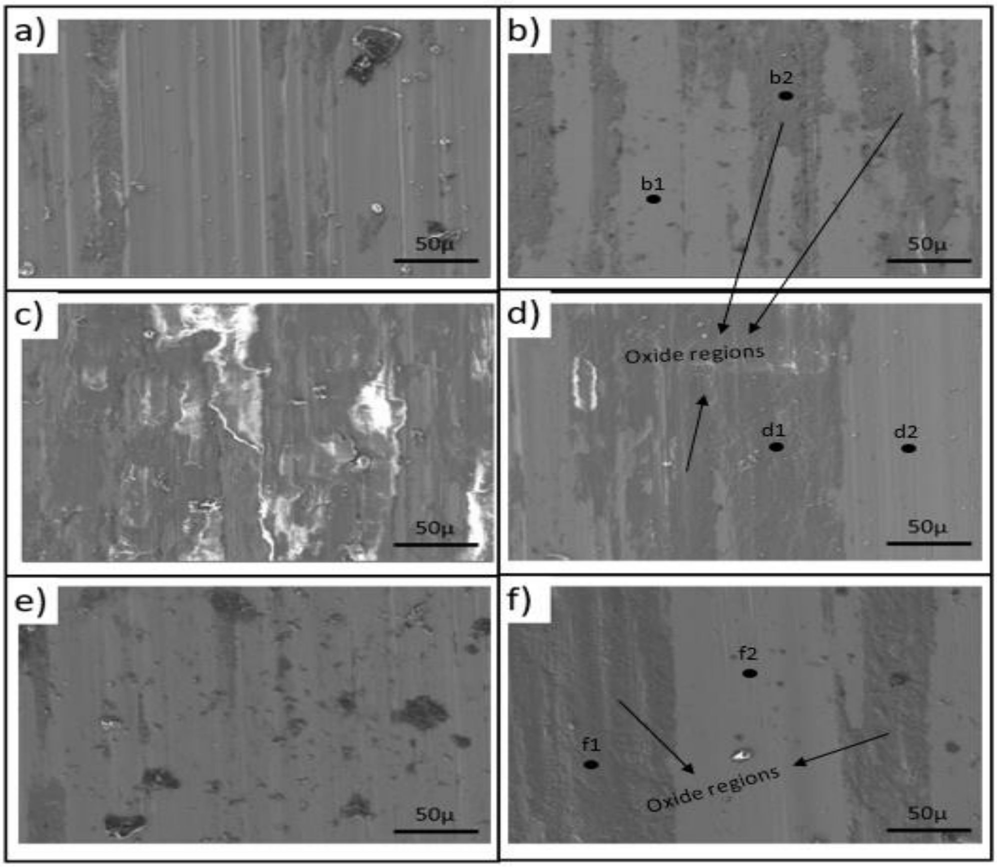


Figure 5.11. SEM images in 1000X magnification after wear; a) AISI 4340 1000X, b)AISI 4340 Laser hardened, c) AISI 5140 1000X, b)AISI 4340 Laser hardened, a) AISI 4340 1000X, b)AISI 4340 Laser hardened,

PART 6

CONCLUSIONS

- Considering the test results in this study, decarburization occurred on the surface at a distance of 30 microns in the laser hardening process. It is thought that the use of protective media to prevent this may yield positive results.
- Considering the wear results, it was determined that the oxide regions on the surface were the determining factor in the wear mechanism, and that the laser hardening process increased proportionally with the hardness.
- He confirmed that, considering corrosion resistance, laser traces should be considered alongside chemical composition in the laser hardening process.
- As a result, the most efficient material from laser hardening is AISI 4340. This showed that elements such as high chromium nickel molybdenum of AISI 4340 steel also positively affect the corrosion resistance after laser hardening.

REFERENCES

1. Pacheco-Torgal, F., & Labrincha, J. A., "The future of construction materials research and the seventh UN Millennium Development Goal: A few insights", ***Construction and Building Materials,*** *4(10):* 729-737 (2013).

2. Nathaniel, L., and Satullo, E., "The Innovation and Adoption of Iron in the Ancient near East", ***Journal of Archaeological Research***, 2(7): 557-607, (2019).

3. Zheng, H., and Liu, K., "Machinability of Engineering Materials",,***Handbook of Manufacturing Engineering and Technology***, USA, 1-34, (2014).

4. Internet: Bell, T., "Steel Grades and Properties", **https://www.thoughtco.com/steel-grades-2340174/** (2019).

5. Baddoo, N. R., “Stainless steel in construction: A review of research, applications, challenges and opportunities”, ***Journal of Constructional Steel Research***, 11(1): 1199-1206 (2008).

6. Kisku, N., "Strengthening of High-Alloy Steel through Innovative Heat Treatment Routes", ***In Welding-Modern Topics,*** USA, 12-45 (2020).

7. Bell, S., Davis, B., Javaid, A., & Essadiqi, E., "Final report on effect of impurities in steel (No. 2005-41)", ***Kingston Process Metallurgy Inc,*** Canada, 34-45(2006).

8. Gaikwad, V. T., Mishra, M. K., Hiwarkar, V. D., & Singh, R. K. P., "Microstructure and mechanical properties of friction welded carbon steel (EN24) and nickel-based superalloy (IN718)", ***International Journal of Minerals, Metallurgy and Materials,*** *28*(1): 111-119 (2021).

9. Zaitsev, A. I., "Prospective directions for development of metallurgy and materials science of steel", ***Pure and Applied Chemistry,*** *89*(10): 1553-1565 (2017).

10. Aran, A., "Manuacturing Properties of Engineering materials lecture Notes", ***Mfg Prop V1***, Norway, 40-65 (2007).

11. Internet: Carbon steel: properties, production, examples and applications, **https://matmatch.com/learn/material/carbon-steel**/ (2021).

12. Callister, W. D., Rethwisch, D. G., Blicblau, A., Bruggeman, K., Cortie, M., Long, J., & Orwa, J., "Materials science and engineering: an introduction. wiley", ***Deakin University, School of Engineering,*** Turkey, 34-45 (2021).

13. Internet: “Classification of carbon and low-alloy steels”, **http://www. keytometals.com/Articles/Art62.htm/** (2018).

14. Yamagata, H., "The science and technology of materials in automotive engines", ***Elsevier,*** Germany, 67-78 (2005).

15. Callister, W. D., Rethwisch, D. G., Blicblau, A., Bruggeman, K., Cortie, M., Long, J., & Orwa, J., "Materials science and engineering: an introduction", ***John Wiley & Sons,*** USA, 56-64 (2021).

16. Rothstein, B., "What are the different grades", ***Mead Metals, Inc***, Canada, 78-89 (2019).

17. Braasch, G., "Rules for Classification and Construction Materials and Welding", ***Germanischer lloyd***, Germany, 35-59 (2009).

18. Internet: Anderson, J., "Malleability and Ductility of Metals", **https://www. scientificamerican.com/article/malleability-and-ductility-of-metal/**(2020)

19. Eliaz, N., "Corrosion of metallic biomaterials: a review", ***Materials,*** 12(3): 407 (2019).

20. Cunat, P. J., "Alloying elements in stainless steel and other chromium-containing alloys", ***Euro Inox,*** Italy, 1-24 (2004).

21. Jeremy, H., "Chemical Elements and Effects on 21 Steel Mechanical Properties", ***Special Steel***, Italy, 34-41(2015).

22. Chan, S., and Duh, J., "Materials Chemistry and Physics", ***Science Direct***, Germany, 269, (2021).

23. Ustinov, V., "Physics of Metals and Metallography", ***Springer,*** Germany, 12-19 (2019).

24. Quesne, M. G., Roldan, A., de Leeuw, N. H., & Catlow, C. R. A., "Bulk and surface properties of metal carbides: implications for catalysis", ***Physical Chemistry Chemical Physics,*** 20(10): 6905-6916 (2018).

25. Riggs, K., "Nickel-Cobalt Alloy Coating Protects Steel Fasteners from Hydrogen Embrittlement", ***Coatings & Lining***, 12(10): 34-67 (2020).

26. John, G., "Stainless Steel Alloy Having Lowered Nickel-Chromium Toxicity and Improved Biocompatibility", ***PCT/US2001/049312,*** USA, 67-91 (2002).

27. Bush, D., “Nickle – Copper Alloys", ***Materials Q & A,*** China, 45-56 (2012).

28. Lucon, E., McCowan, C. N., & Santoyo, R. L, "Impact characterization of 4340 and T200 steels by means of standard, sub-size and miniaturized Charpy

specimens", ***US Department of Commerce, National Institute of Standards and Technology,*** USA, 23-34 (2015).

29. Internet: Madhusha, M., "Difference Between Case Hardening and Surface Hardening",**https:/pediaa.com/difference-between-case-hardening-and-surface-hardening**/(2018).

30. Wanhill, R. J. H., Byrnes, R. T., & Smith, C. L., "Stress corrosion cracking (SCC) in aerospace vehicles", ***Stress Corrosion Cracking,*** Germany, 608-650 (2011).

31. Internet: Mouritz, A., “Introduction to Aerospace materials”, **https://doi.org/10.1533/9780857095152.232**/(2011).

32. Nath, A. K., & Sarkar, S., "Laser transformation hardening of steel in Advances in laser materials processing, ***Woodhead Publishing,*** Germany, 257-298 (2018).

33. Internet: "The editors of Encyclopedia Britannica, surface hardening, metallurgy", **https://www.britannica.com/technology/nitriding/**(2009).

34. Internet: "Surface Hardening", **http://www.fkm.utm.my/~nhayati/chp10.pdf/** (2021).

35. Internet: Dannana, S., "What are the different case Hardening processes?”, **https://extrudesign.com/different-case-hardening-processes**/(2021).

36. Czerwinski, F., "Thermochemical treatment of metals", ***Heat Treatment–Conventional and Novel Applications,*** 5(2): 73-112 (2012).

37. Kurek, K. and Dolega, D., "Modeling of Induction Hardening", ***International Scientific Colloquium***, Hannover, Germany, 24-26 (2003).

38. Vieweg, A., Ressel, G., Prevedel, P., Raninger, P., Panzenböck, M., Marsoner, S., & Ebner, R., "Induction hardening: Differences to a conventional heat treatment process and optimization of its parameters", ***In IOP Conference Series: Materials Science and Engineering,*** 11(9): 12-19 (2016).

39. Internet: "Induction/flame hardening", **https://www.open.edu/openlearn/science-maths-technology/engineeringtechnology/manupediainduction/flame -hardening/**(2018).

40. Internet: Science, T., "Flame hardening of steel (surface hardening)", **https://www.tec-science.com/material-science/heat-treatment-steel/flame-hardening-surface-hardening/** (2018).

41. Internet: Dave, N., "Heat treatment processes", **https://www.Slideshare.net/NamanDave/heat-treatment-part-2**/ (2016).

42. Zenker, R., "Electron beam surface technologies", ***Encyclopedia of Tribology; Wang, QJ, Chung, Y.-W., Eds,*** USA, 923-940 (2013).

43. Zenker, R., "Modern thermal electron beam processes – research results and industrial application", ***Metallurgia Italiana 1014,*** Italy, 55–62 (2009).

44. Lakhkar, R. S., Shin, Y. C., & Krane, M. J. M., "Predictive modeling of multi-track laser hardening of AISI 4140 steel", ***Materials Science and Engineering: A,*** 480(2): 209-217 (2008).

45. Vollertsen, F., Partes, K., & Meijer, J., "State of the art of Laser Hardening and Cladding", ***In Proceedings of the 3rd International WLT-Conference on Lasers in Manufacturing***, Germany, 12-18 (2005).

46. Ganeey, R, "Low-power laser hardening of steels",***Journal of Materials Processing Technology***, 3(2): 414-419,(2001).

47. Skvarenina, S., & Shin, Y. C., "Predictive modeling and experimental results for laser hardening of AISI 1536 steel with complex geometric features by a high power diode laser", ***Surface and Coatings Technology,*** 201(6): 2256-2269 (2006).

48. Internet: "Laser surface hardening", **https://www.lasertherm.cz/eng/technologies/laser-technologies/laser-hardening/** (2019).

49. Kim, J. D., Jung, J. K., Jeon, B. C., & Cho, C. D., "Wide band laser heat treatment using pyramid polygon mirror", ***Optics and Lasers in Engineering,*** 35(5): 285-297 (2001).

50. Soriano, C., Leunda, J., Lambarri, J., Navas, V. G., & Sanz, C., "Effect of laser surface hardening on the microstructure, hardness and residual stresses of austempered ductile iron grades", ***Applied Surface Science,*** 257(16): 7101-7106 (2011).

51. Groover, P. M., "Introduction to manufacturing processes", ***John Wiley & Sons***, USA, 7101-7106.

52. Taylor, J. R., Chow, R., Primdahl, K. A., Willis, J. B., & Wong, J. N., "Specification of optical components for a high-average-power laser environment", ***In Optical Manufacturing and Testing,*** 31(34): 11-22 (1997).

53. Martínez, S., Lamikiz, A., Tabernero, I. & Ukar, E., "Laser hardening process with 2D scanning optics", ***Physics Procedia,*** 3(9): 309-317 (2012).

54. Holmstrom, S, Baran, U, Urey, H., "MEMS Laser Scanners: A Review", ***Journal of Microelectromechanical Systems***, 23(2): 10-17 (2014).

55. Keeler, S, Kimchi, M and Mooney, P., "Advanced High- Strength steel application guidelines version 6.0", ***World Auto Steel***, 2(3): 207-314 (2017).

56. Al-Sayed, S. R., Elshazli, A. M., & Hussein, A. H. A., "Laser surface hardening of Ni-hard white cast iron", ***Metals,*** 10(6): 795 (2020).

57. Durand-Charre, M., "*Microstructure of steels and cast irons", **Springer Science & Business Media,*** Germany, 45-58 (2004).

58. Canale, L, Mesquita, R, Totten, G., "Failure Analysis of Heat Treated Steal Components", ***ASM***, Brazil, 500-636 (2008).

59. Moradi, M., Ghorbani, D., Moghadam, M. K., Kazazi, M., Rouzbahani, F., & Karazi, S., "Nd: YAG laser hardening of AISI 410 stainless steel: Microstructural evaluation, mechanical properties and corrosion behavior", ***Journal of Alloys and Compounds,*** 79(5): 213-222 (2019).

RESUME

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