IMPROVING MECHANICAL PROPERTIES OF CARDAN SHAFTS MANUFACTURED FROM AISI 4140 STEEL MATERIALS

by

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APPROVAL PAGE

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ABSTRACT

Cardan shafts and axle shafts such as motion and force transmission elements are used especially in automotive industry and in many machine systems. The damage that happens to a cardan shaft working under dynamic loading is caused as a result of fatigue damage and failure. The mechanical properties of preferred materials must have a substantial effect on mechanism of fatigue fracture and fatigue life of shaft.

In this study, AISI 4140 high strength low alloy steel was used, because it exhibits high fatigue life behavior and good mechanical properties. Also the mechanical properties development and the effect of mechanical properties on torsional fatigue of AISI 4140 steel was investigated.

Keywords: AISI 4140, DIN 42CrMo4, Torsional Fatigue, Heat Treatment

AISI 4140 ÇELİK MALZEMELERDEN ÜRETİLEN KARDAN ŞAFTLARININ MEKANİK ÖZELLİKLERİNİN GELİŞTİRLMESİ

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ÖZ

Kardan şaft veya aks milleri gibi hareket ve kuvvet iletim elemanları, özellikle otomotiv sektörü başta olmak üzere birçok makine sisteminde kullanım imkanı bulmaktadır. Dinamik yüklemelere maruz kalan kardan şaftlarda hasar, genellikle yorulma hasarları olarak karşımıza çıkmaktadır. Yorulma hasarı mekanizmalarında tercih edilen malzeme ve malzemenin mekanik özellikleri şaftın yorulma ömrü üzerinde önemli ölçekte etkiye sahiptir.

Bu çalışmada, yorulma ömür davranışı ve sunduğu mekanik özellikler açısından özellikle otomotiv sektöründe stratejik önemini koruyan AISI 4140 düşük alaşımlı yüksek mukavemet çeliği üzerinde çalışılmıştır. Çelik malzemenin, mikro yapısı yönünden mekanik özelliği gelişimi ve malzemenin mekanik özelliklerinin burulma yorulması üzerine etkisi incelenmiştir.

Anahtar Kelimeler: AISI 4140, DIN 42CrMo4, Burulma yorulması, Isıl işlem

DEDICATION

This study is dedicated to world.

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My special thanks to my advisor, Prof. Dr. M. Halidun KELEŞTEMUR for his all help.

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and

Aksan Kardan LTD ŞTİ.

Thanks you all!

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LIST OF SYSMBOLS AND ABBREVIATIONS

Ni	Nickel
Mo	Molybdenum
B	Boron
V	Vanadium
Cr	Chromium
Fe	Iron
AISI:	American Iron and Steel Institute
DIN	German Institute for Standardization
SANTEZ	Thesis with Ministry of Science, Industry and Technology
KOSGEB	Republic of Turkey Small and Medium Enterprises Development Organization
^{o}C	Celsius degree
S-N	Strain amplitude – number of cycle
Nf	Number of cycle
Fe3C	Cementite compound
TTT	Time-temperature-transformation
HR-C	Rockwell hardness C
MTS	Mechanical testing systems
Hz	Frequency
MPa	Mega pascal

CHAPTER 1

GENERAL POLICIES

1.1 INTRODUCTION

Fatigue is a form of damage on a material which is subjected to a cyclic dynamic loading, which mostly occurs in automotive, bridges, aircraft and machine component [1, 2]. Fatigue cracks start mainly on material surface [3]. Fatigue damage crack initiation and propagation usually occurs on the surface perpendicular to maximum tensile strength [1, 2]. In ductile materials the crack initiation is seen on the plane where they are a maximum shear stress. The progression of a fatigue cracks are seen in the maximum principal stress planes. Therefore, fatigue failures are permanent shear type damage [4]. In addition, Failure is also possible under statically loaded tensile strength and yield strength [1, 2]. In this case, surface of materials which show high fatigue resistance has to reach the highest yield stress and high strength in its core region with high ductility and toughness [5].

The studies on fatigue shows that the fatigue resistance can be related to the microstructure of the material, high strength, high ductility and toughness values. The studies also show that materials having bainitic, austenitic, ferritic, pearlitic and martensitic micro structures have an effect on the fatigue crack, fatigue crack progression and fracture in the steel [6,7,8]. Also it is not possible to achieve a high property of toughness, ductility and high strength together than the desired level in the traditional rough pearlitic-ferritic microstructure of hot rolled carbon steel. This situation had made the structures to have ultra-fine-grained structure with too much elements [9]. The properties of carbon steel had been improved by the addition of elements such as Ni, Mo, B, V and Cr up to about %6 percent. Thus, the fracture toughness and fatigue life of the materials was developed by applying appropriate heat treatment methods [10]. For example, ıt was observed that a tempered martensite structure has a higher fatigue limits. Also it was observed that if the structure is not fully martensite, fatigue limit reduction occurs on the material [11, 12]

M. E. Henna observed in his work that the fatigue life in the tempered martensitic structure is affected negatively when its ferrite content exceeds 20% [13]. In particular, coarse pearlite structure exhibits low fatigue resistant [12]. It was also observed that bainitic steels exhibited high ductility and impact toughness, especially in lower bainite which has high tensile elongation and volume fraction. But it has high notch impact energy similar to tempered martensite [14]. Which implies that steel with lower bainite exhibits good fatigue resistance? But, practically the fatigue life of tempered martensite shows better results compare to lower bainite [14, 15, and 16]. Also studies shows that duplex structured materials with 12% percent lower bainite gave similar results to tempered martensite [14, 17]. This is as a result of surface hardening in the materials [9, 18]

The transmission shafts, axles, crankshafts, pipes and springs and other various engineering components are exposed to torsional strength (torsional and axial stress). However, many studies on the torsional fatigue are described with axial loading which has significantly less fatigue data [19]. The effects of the static loading and stress concentration during torsional fatigue were examined. Additionally, available data about torsion were obtained for ductile materials [20, 21]. The studies show that torsional behavior depending on the type of material structure [22].

In this study, the effect of microstructure on mechanical properties and torsional fatigue were studied on AISI 4140 (DIN 42CrMo4) steel, which is widely used in manufacturing of cardan shaft. In this study, the heat treated cylindrical shaft material was optimize for a bainitic structure and compared to the martensitic structure. This work is supported by SANTEZ (668-STZ-2010-2) . Some part of the structure optimization on the bainitic and martensitic phases was published in this work, because AISI 4140 steel still retains its strategic importance in the automotive industry.

CHAPTER 2

LITERATURE VIEW

2.1 DRIVE SHAFT

Drive shaft is the shaft which connects gears, wheels or propeller. It also transmits rotational movement and forces to other component on machines [23]. In general, it is needed as an element for the transmission of motion from output of transmission shaft to differential and wheels on the automobile. This component is named cardan shaft on the car. Universal joints are needed to be connected to cardan shaft (drive shaft) in other to transmit movement and forces.

The cardan shaft has one or two universal joints by connecting two solid and hallows shafts. Figure 2.1 shows a cardan shaft. The cardan shaft is used in four-wheel with internal combustion engines to transmit torque and speed from the gearbox to differential input [24].

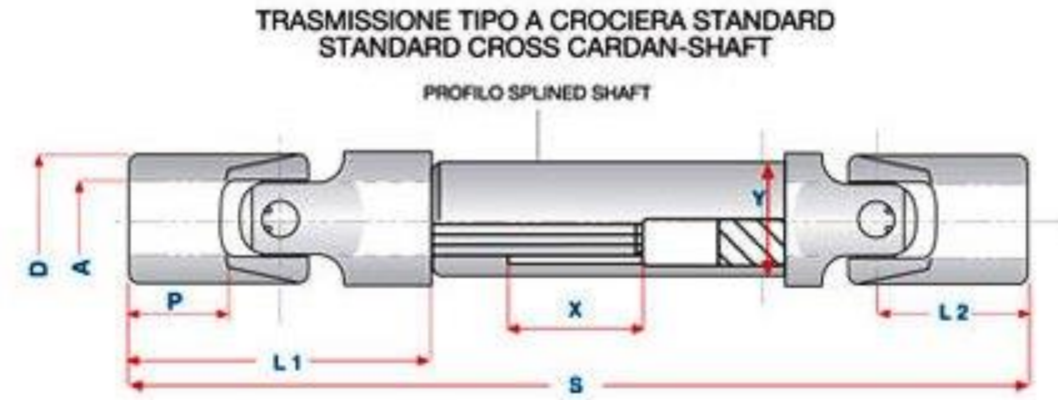

Figure 2.1 Schematic illustration of cardan shaft [25]

The universal joints formed from two opposite yokes are connected by the use of a circlips which join them at 90^{o} to each other. Two tubes are welded on the yokes, these are the outer tube and inner tubes which are key-lock interrelated with each other. The cardan shaft components are given in figure 2.2.

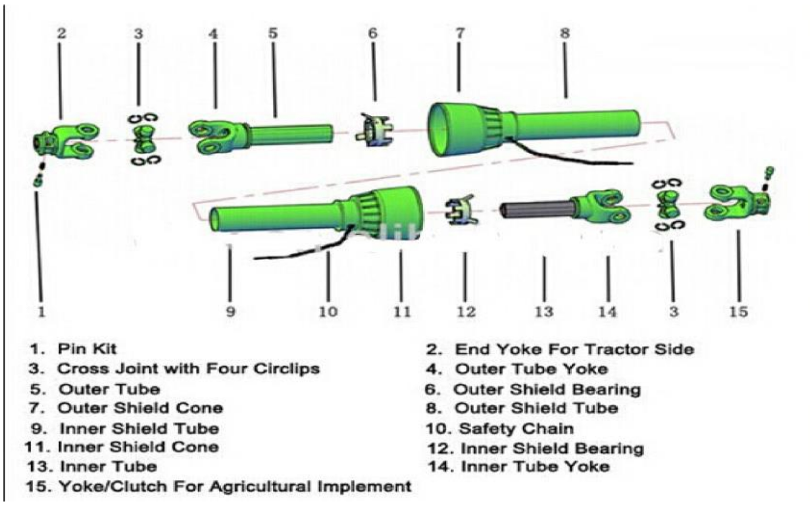

Figure 2.2 Components of cardan drive shaft [26]

In 1550 Geronimo Cardano who is mathematician, doctor and philosopher used these types of cardan shafts with universal joints. Arthur Hard and Robert Schwenke have received a patent for automotive joints in 1901 and 1902. Mass production of cardan shaft started in 1904 [24]

2.1.1 Drive Shaft Materials

The high strength steels which are AISI 4130, AISI 4140, AISI 5140 and AISI 4330 steels with high tempering hardness are used mostly in construction of shafts and axles. Some of the heat treatment temperatures of these steels are given below;

- Austenitising temperatures of these steel from 800 to 850 ^{o}C,
- Quenching temperature in oil environment is blow 650 ^{o}C,

- Tempering temperature is between 200 to 650 ^{o}C in other to achieve different strength and toughness [27].

The AISI 4140 and AISI 5140 steel is preferred due to the amount of molybdenum (Mo) content. Mo increases hardenability, tensile strength and resistance to temperature. Also it reduces temper brittleness with chromium and nickel alloys. The Mo is added between 0.15 and 0.30% in the steel [28].

The AISI 4340 and AISI 4140 steel is preferred due to the amount of Nickel (Ni) content. Nickel together with chromium provides high ductility, hardenability and high fracture resistance. Also it contributes to the grain size reduction [29].

There are many researches on different types materials used in fatigue application. R. Ranganath and friends [30] and G. Das and friends [39] used AISI 4330 steel in their works. H. Bayrakçeken and friends [28] used AISI 4140 steel in their works. B. Smoljan used AISI 5140 steel in his work.

AISI 4340 steel shows the most needed fatigue life property as a shaft material, but it is cost expensive compare to the others due the presence of nickel in its alloying. AISI 4140 steel is more appropriate due to its good fatigue life property and less cost expensive.

2.2 FATIGUE

Fatigue failures occur due to periodic loading on the machine components. In particular, the fatigue cracks start developing just below the surface of the component. The fatigue damage can occur below the yield stresses as a result of dynamic stresses [31].

In literatures, they have been several definitions of fatigue. Generally, the use of word as fatigue is usually specified to the behavior under cyclic stress and elongation unlike the behavior of materials under static stress and elongation [31].

Fatigue is defined in ASTM 206-72 as follows;

‘*the process of progressive localized permanent structural change occurring in a material subjected to conditions which procedure fluctuating stress and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations.*’ [32]

As can be seen there are four emphases on key definition of fatigue;

1. Continuous development of case
2. Localized (Regional)
3. Progress of cracks
4. Crack growth and the occurrence of fractures

The first work on fatigue was studied on the iron chains with some applying loads by W.A.S Alber in 1829. The first result of fatigue fractures which was observed under operating conditions was on axle shafts of the cars. In the mid-19th century, fracture caused by fatigue on train axle was observed. These observations create room for the investigation of fatigue under yield strength because of unknown reasons [32, 33].

Experiments were repeated again below the yielding strength under laboratory conditions while these unknown results frequently occur. August Wöhler who is the German railway engineer developed first systematic research on the fatigue between 1850 and 1870.He also developed bending, torsion and repeated loading behavior on railway axles for several materials. August Wöhler revealed and commented S-N (stress- number of cycles) diagram known as Wöhler graphics [32, 33].

In early 20th century known as technology age, the understanding importance of the fatigue problem with the use of high speed machines, turbines and the development of aerospace industry increased. The case studies of fatigue were studied in two groups until the mid-20th century. The first group comprise of metallurgist and physicists which carried out investigation at microscopic level. The second group, experimental data’s was evaluated on the macroscopic level by engineer in the laboratory [33]. Understanding fatigue at the microscopic level preceded the development of dislocation theory during this technologic period. Computers are used and developed to estimating fatigue life and stresses in the macroscopic level. Finally, the idea of fracture mechanics has provided a significant contribution about fatigue life and to the understanding of crack propagation behavior [32, 33]. Although metallurgists identify material behavior, but do not explain the reasons of fatigue fracture, because of fatigue plausible theory development [34].

2.2.1 Basic Factor of Fatigue

The fatigue strength is influence by many factors. Knowledge of these factors makes it possible to obtain more uniform results in fatigue tests [35].

2.2.1.1 Effect of Stresses

The stresses on the specimen significantly reduce fatigue strength. The stress enhancers are notches, holes, gears, keyways and geometrical irregularities on the specimen. Also, the metallographic discontinuities such as surface roughness, porosity, inclusions, decarburization, overheating and secondary phases reduce the fatigue life [35].

2.2.1.2 Geometry and size effect

The stress concentrations on the samples affect the fatigue life. The stress concentration is known to vary on the cross-section of material. The important factor on fatigue is the dimensions of the tested sample.

Experiment shows that the fatigue strength is reduced with increase in the diameter of the sample. This effect is thought to occur for two reasons. Firstly, the fatigue fracture occurs easily due to the increase on the external surface as a result of increase in the volume. Secondly, the material loses its fatigue resistance due to increase in the volume of the material as a result of the increase in amount of defective spots in the material. [36].

2.2.1.3 Effects of Surface Treatments

It is clearly shown that the fatigue fracture begins from surface of the specimen. Therefore, surface cleanliness is very important. The fatigue strength increased with surface treatments such as forging, cementation, coating and induction hardening. [37].

2.2.1.4 Corrosive Environment Affects

Corrosion fatigue occurs because the specimen remains below the variable forces in the corrosive environment. This is the most dangerous form of fatigue case. Because, the corrosion makes roughed surface on the material which causes notch effect [35].

2.2.1.5 Effect of Metallurgical Factors

The type of inclusion, shape and size are effect on crack initiation of fatigue. Studies show that, oxide inclusions are known to affect the fatigue life and the probability of fatigue crack initiation. The fatigue strength increases with decrease of the particle size. Usually all heat treatment processes affect the fatigue strength [35].

2.2.1.6 Effect of Temperature

The fatigue strength increases with the decrease in temperature below room temperature and also on notched specimen. This increase is especially more than the mild steel to hard steel. This increase continues until – 200 ^{o}C in the fatigue strength. [38].

2.2.1.7 Effect of Manufacturing Process

Surface roughness and gaps often occurs after rolling, extrusion, forging and machining during manufacturing of materials. Also the surface discontinuities that are adversely affecting the fatigue strength occur as a result of adhesion and cohesive strength on the specimen. The manufacturing methods can create or remove surface irregularities and residual stresses. As a result, the manufacturing processes have an effect on the fatigue strength of specimen [39].

2.2.2 Fatigue Process

Fatigue damage occurs without any stimulus. The fracture surface should be normal of the principal tensile stresses (perpendicular to the principal stresses). Seeing deformation is not possible on the fracture surface. Usually, the crack propagation from the origin is seen as chevron marks or rings in the material. At the same time, the damage occurs in areas with sharp corners or notched points or matallugically stress intensity [40].

The damage failure is followed by a series of steps before the failure occur (Figure 2.3);

1. The crack initiation; the stage including early development of fatigue damage. The region where there is stress concentration is regarded as the crack initiation region. However, it can be removed by annealing.

2. Slip band crack growth; this is the crack initiation deepening on the high shear stresses.

3. It includes crack growth on the plane with a high tensile stress. It described crack growth on the normal plane with maximum tensile stress. These stages often referred the second stage.

4. The ductile fracture occurs when the crack reaches sufficient length. The material will not have sufficient strength over the remaining cross-section.

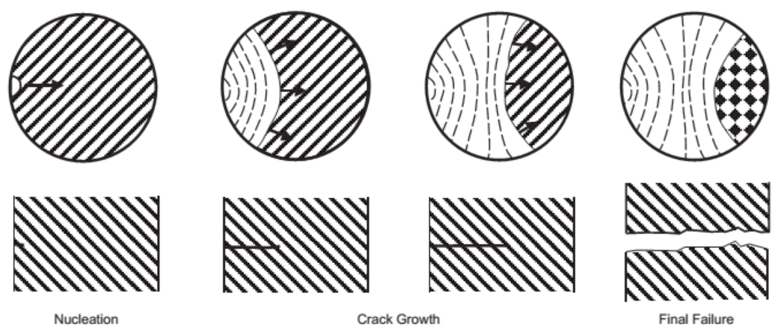

Figure 2.3 Typical crack propagation of cylindrical material [47]

The first stage cannot be seen in the sharp-edged material, because stress concentration automatically occurs on these sharp-edges. The crack formation stars directly [40]. The crack initiation stage is going to occur on the free-surface, as result of maximum principle stresses. The crack initiation may also be in the material but in rare cases. The surface hardened steels can be mentioned as an example [41].

2.2.3 S-N Curve

The Wöhler diagram is determined by material to be broken under different stresses in several cycles. This diagram is called the S-N curve in English technical literature. The stain amplitude is located on vertical axis. Also the number of cycles (Nf) detected until failure is located on the horizontal axis. The average stress is fixed for different periodic stresses [40, 42].

The stress as at when a material shows cracks or breaks after Nf cycles are defined as fatigue strength. The highest strength value at which they are no damage on the material is called fatigue strength. In this case, the Nf number of cycles is called fatigue life. Fatigue life is the number of cycles until fracture or damaged in the material. The stress in which the curve is horizontal is called ‘fatigue limit’ or ‘fatigue strength limit’. Fatigue life has to be infinite cycles under the S-N curve [42].

The fatigue strength limit is between 10^6 and 10^7 number of cycles for ferrous alloys. Also nonferrous material fatigue strength limit is between 10^6 and 10^8 number of cycles [43].

2.2.4 Torsional Fatigue

Torsional loading creates highest tensile stress at 45^o in both components in vertical and horizontal directions. The highest stresses occur at the workpiece surface. Therefore, the highest tensile stresses are aimed to improve the fatigue strength on the material surface. The surface coating or induction hardening is given as an example [43, 44].

The weak fatigue strength is being seen on the plane which is perpendicular to the slip axis because of the effects of torsional fatigue on low strength materials. The higher-strength material tends to damage in the shear plane at 45^o. On this material tensile stress is weaker than shear stress [43].

2.3 HEAT TREATMENT

The heat treatment is an applied process to change physical and mechanical properties of materials. Heat treatment steps are heating under control rate, holding at determined temperature and cooling under control rate. The structure and phase change occur after heat treating the material [45, 46].

Improve the mechanical properties of material is possible with appropriate heat treatment temperature and suitable holding time. Generally, the tensile strength hardness, impact resistance and toughness would be changes depending on heat treatment process. Though we can see that the heat treatment effect is small on corrosion and thermal conductivity [45].

It seems that heat treatment has an effect on the fatigue behavior of the material. In this case, the martensite and bainite microstructure has better results than ferrite-perlite structure on the steel material [13, 14, 15, 16]. Thus it is possible to define different heat treatment processes in order to obtain a suitable microstructure.

2.3.1 Normalizing

Normalizing heat treatment process is the cooling to room temperature of the material in air medium after suitable heating and holding stages at austenitising temperature. Thus, steel material, except for some special steels, will have a homogeneous balanced phase of ferrite-perlite or perlite-cementite structure in the normalized process. The normalization process temperature is 55 ^oC above on the Ac_3 temperature for hypo eutectoid materials. Also this temperature is 55 ^0C above on the Acm line for hypereutectoid materials. The heat treatment ranges are given on typical Fe-Fe3C equilibrium at figure 2.4 [47].

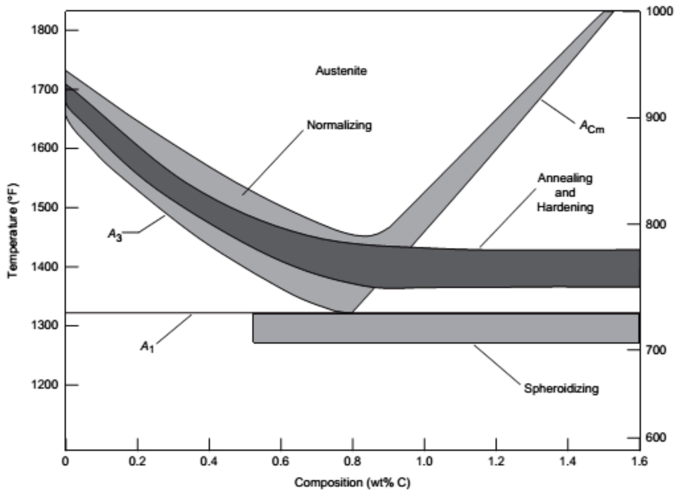

Figure 2. 4 Heat treatment range for steel specimen on Fe-Fe3C equilibrium [47]

2.3.2 Quenching

The quenching process is the rapid cooling process from austenitising temperature to room temperature in medium order than air. The martensitic phase which undergoes deformation of crystal structure occurs in the steel structure. This martensite phase exhibits high hardness and strength. There are many quenching medium, these are salt, oil, water or air considering the alloying elements [48].

2.3.3 Tempering

The martensite structures are hard and brittle structure obtained after quenching heat treatment process. Therefore, the tempering heat treatment gives ductility and toughness to material. This process is generally the process of heating at a temperature between 205 – 650 ^{o}C. The tempering heat treatment process also can be applied on normalized material [48]. The tempering heat treatment process determines the toughness and final properties of material [50].

The brittle fracture also called blue brittleness or tempering brittleness of material may occur after tempering heat treatment. This behavior is seen between 400-500 ^{0}C in AISI 4140 steel because of some alloying elements or secondary phases. However, it was not possible to reach a definitive judgment [51].

2.3.4 Austempering

The austempering process is known as isothermal quenching heat treatment method. In this process, the material hold at austenitising temperature is quickly immersed in a warm environment such as heated oil or salt bath. [52].

The final structure is bainite. Process steps of Figure 2.5;

- holding above the A_3 temperature until fully austenite is formed in this temperature,
- fast cooling to austempering temperature without letting any different phases occur
- Applying isothermal process until the formation of bainitic structure [53].

Advantages of austempering heat treatment processes;

- It provides lower distortion and cracking risk
- There is no need for final tempering process
- Bainitic structures improve the toughness and ductility properties.

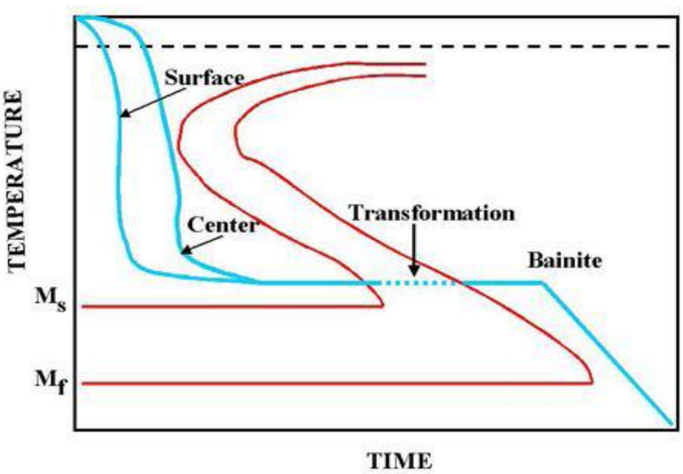

Figure 2. 5 Austempering process line on eutectic steel TTT diagram [53]

2.3.5 Martempering

The final structure is tempered martensite. Heat treatment steps process for martempering is given below (Figure 2.6)

- holding above the A_3 temperature until fully austenite is formed in this temperature,
- fast cooling above the Ms temperature without letting any different phases occur (Martempering environments may be hot oil, molten salt)
- holding above the Ms temperature until fully homogeneous structure occur [53].

Advantages of martempering heat treatment processes;

- The temperature gradient from center to surface is reduced
- It provides lower distortion and cracking risk
- The toughness and ductility of martensite improves with strength close to tempered martensite

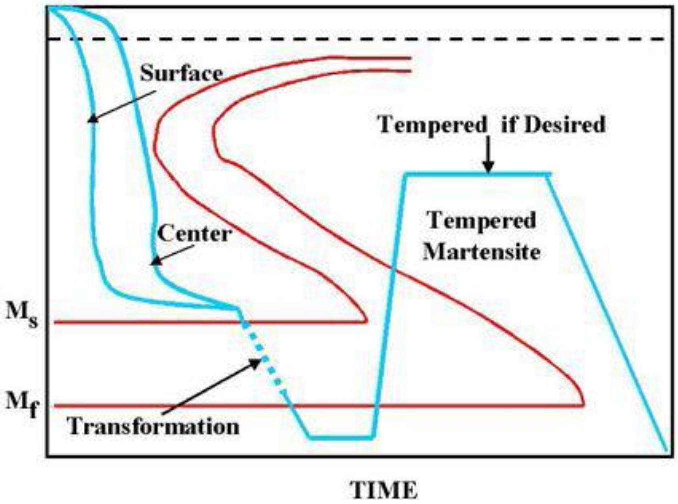

Figure 2. 6 Martempering process line on eutectic steel TTT diagram [53]

The phases which are martensite and bainite structure such as the ones obtained at high cooling rates is impossible to explain in conventional Fe-Fe_3C phase diagram. In this case, the TTT (Time-Temperature-Transformation) diagrams developed are maps of phase transformation up to time-temperature relation of phase transformation in steel [49].

TTT diagrams also makes possible to see phases which can be obtained under continuous or isothermal cooling conditions [50]. The TTT diagram of AISI 4140 steel is given below (Figure 2.7)

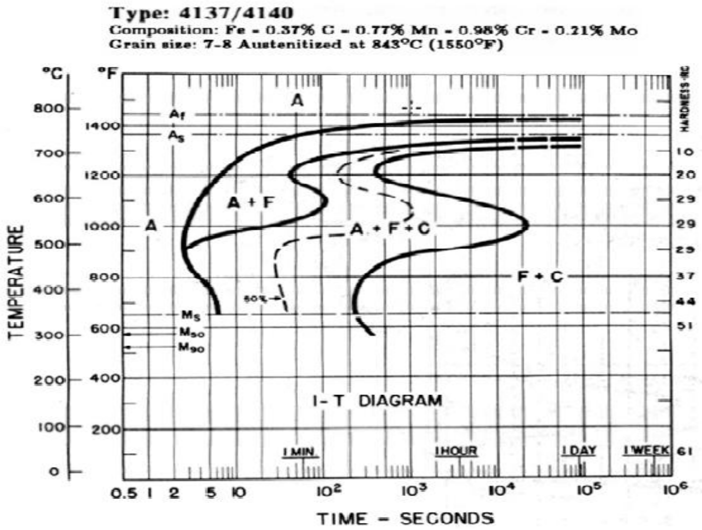

Figure 2.7 TTT diagram for AISI 4140 Steel [53]

CHAPTER 3

EXPERIMENTAL

3.1 SPECIMEN FOR TESTING

AISI 4140 steel has been used in heat treatment and experimental studies. This steel material has been obtained from Has Çelik Company. The Table 3.1 shows the chemical composition of AISI 4140 steel with very well-known standards.

Table 3.1: Chemical compound of AISI 4140 steel used in our processes and SAE (AISI) and DIN norms

Element	C	Si	Mn	P	S	Cr	Mo
SAE 4140	0,38-0,45	0,15-0,40	0,50-0,80	0,035	0,035	0,90-1,20	0,15-0,30
DIN 42CrMo4	0,38-0,45	0,15-0,25	0,75-1,00	0,035	0,040	0,80-1,10	0,15-0,25
%	0,43	0.26	0.87	0,001	0,005	1,10	0.18

3.2 EQUIPMENT NEADED FOR HEAT TREATMENT

The muffle furnace manufactured by Protherm is used for heat treatment processes (Figure 3.1). The austenitising step of heat treatment processes were conducted in this muffle furnace. The salt bath furnace is used for austempering heat treatment figure 3.2. The salt used tempering step is commercial AS 135 (working temperature is between 160-550 ^{o}C).

Figure 3.1 Muffle furnace which is used heat treatment processes (PLF 110/6 Protherm)

Figure 3.2 Salt bath furnace which is used austempering processes

3.3 HEAT TREATMENT

3.3.1 Austempering Heat Treatment Temperature Study

The austempering studies were conducted at 375, 380, 400, 425, 435 and 450 ^oC temperatures on AISI 4140 (DIN 42CrMo4) steel. The normalizing heat treatment was performed on three tensile test specimens at 870 ^oC temperature during 40 min. The austenitising process was subjected at 845 ^oC with 60 min after normalization heat treatment process. All specimens were cooled in salt bath during 20 min holding time at six different temperatures (375, 380, 400, 425, 435 and 450 ^oC)

3.3.2 Austempering Heat Treatment Time Study

The austempering heat treatment holding time is also important as much as heating temperature during heat treatment process. Time is required to complete the formation of bainite structure and elimination of residual austenite. The experiments to determine the austempering time were performed in 20, 40, 60, 80 and 100 min on AISI 4140 steel. The specimens having same dimensions were used in the austempering temperature study.

3.4 MATERIAL CHARACTERIZATION

The forcipol-2V grinding and polishing machine was used for sample preparation after heat treatment during the metallographic examination (Figure 3.3). Each specimen is grinded with abrasives paper in the order of 180, 320, 600 and 1000 and alumina suspension was used for polishing. The suspension includes 5% nitric-acid and rest of ethyl alcohol was used for identification microstructures. The optical microscope manufactured by Nikon Company was used for metallographic examination (Figure 3.4).

Figure 3.3 Grinding machine which is used metallographic Works

Figure 3.4 Optical microscope which is used metallographic works

3.5 HARDNESS MEASUREMENT

The Rockwell-C hardness system was used for hardness measurements. The analogue hardness taster was used in Aksan Cardan LTD. ŞTİ Company. The machine trademark is not known but it is calibrated.

3.6 TENSILE TESTING

Tensile testing results of AISI 4140 steel was measured on the heat treated specimen by KOSGEB. The tensile testing was prepared on three specimens for each austempering study. The results are given as the average of the tensile specimen.

3.7 TORSION TESTING

3.7.1 Static Torsional Test

The normalization process was performed at 870 ^{o}C temperature in 60 min for static torsional test. After normalization of the steel, the austenitising heat treatment process was performed at 845 0C in 50 min. The austempering treatment is applied at 375 oC in 30 min according to specimen thickness. Thus the fully bainitic structure were obtained in steel structure. The normalized steel is quenched in 5% synthetic polymer included water with 845 ^{o}C austenitising temperature in 50 min. The following process is the tempering process at 600 ^{o}C in 90 min holding time.

Static torsional tests were carried out on steels with different heat treatment process such as quenching tempered and also austempered steel specimens by TOBB University (report number is 13022010-3-1). The static torsional test was performed in room condition with 5 degree/second speed. Test sample size is given figure 3.5 as follows.

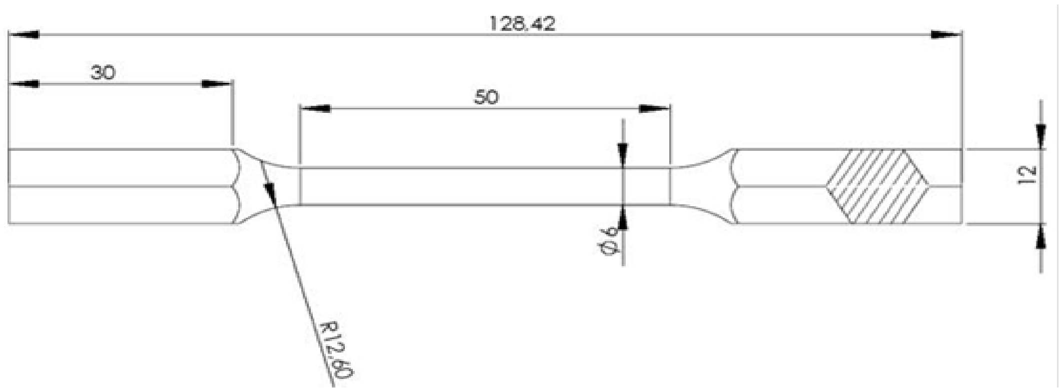

Figure 3.5 İllustration of static bending test specimen

3.7.2 Torsional Fatigue Test

The torsional fatigue test is carried out on both bainitic and martensitic AISI 4140 steel. The heat treatment conditions are given below. The torsional test is performed in 2000 N-m – 4 Hz, applied torque – frequency values (Figure 3.6). Test machine is manufactured by MTS Company in Aksan Cardan LTD. ŞTİ.

For bainitic structure; sample sizes are 24x250 mm

- Normalization heat treatment; 870 ^{o}C temperature in 60 min.

- Austenitising process; 845 °C temperature in 50 min.
- Austempering heat treatment; 375 °C temperature in 60 min

For martensitic structure; sample sizes are 24x250 mm

- Normalization heat treatment; 870 °C temperature in 60 min.
- Austenitising process; 845 °C temperature in 50 min.
- Quenching in water tank with 5% synthetic polymer and tempering at 600 °C in 90 min.

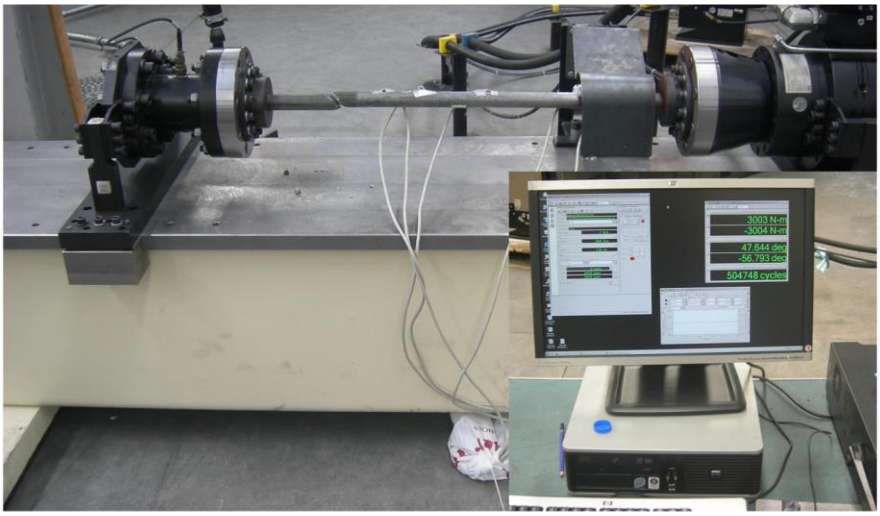

Figure 3.6 Torsional fatigue test machine

CHAPTER 4

RESULTS and DISCUSSION

4.1 OPTICAL MICROSCOPY

The salt bath temperature studies were carried out on austempering heat treatment. The selected holding time is 20 min for salt bath temperature optimization study on austempering heat treatment process for AISI 4140 steel using its TTT diagram. Looking at the TTT diagram 15min was given as minimum duration to bainitic transformation. Figure 4.1 shows the microstructural images obtained for selected austempering temperatures 375, 380, 400, 425, 435 and 450 ^{o}C.

A homogeneous carbide distribution analyzed in each of images is taken after austempering temperature study. Thus, it seems bainitic transformation takes place. However, The SEM imaging should be used to decide the final structure clearly. The carbide amount after 450 oC temperatures is obtained a bit more than other structural images. Furthermore, ıt is possible to see some ferrite islands formation on Figure 4.1 f. Referring to figure 4.1e, it shows the ferritic structure rather than upper bainite formation. The carbide structures can be seen located on the ferrite structure when the magnification increases (the brown microstructure images). The upper bainite can also be identified at 425 ^{o}C on figure 4.1d.

The lower bainitic structure can be seen on the microstructural result of 375 – 380 ^{o}C. But, SEM images are needed for determination of possible martensite structure. It is possible to mention the formation of lower bainite structure because the carbides are located between ferrites on figure 4.1a and figure 4.1b. It is possible to say we can prefer 375 – 380 ^{o}C as an austempering heat treatment temperature.

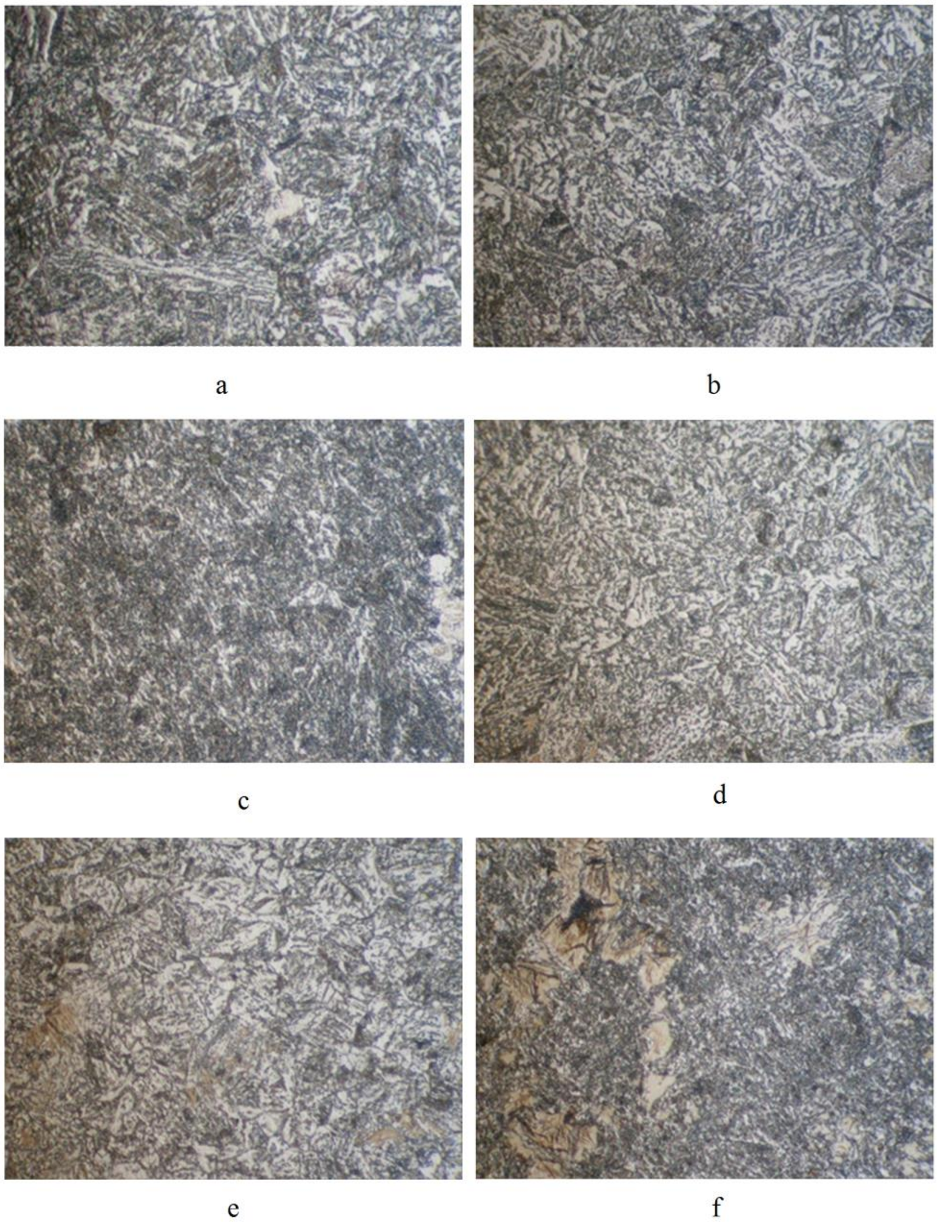

Figure 4. 1 Microstructural results after austempering process according to salt bath temperature changing; a) 375, b) 380, c) 400, d) 425, e) 435 and f) 450 oC [Magnification 100X]

The effect of holding time in salt bath on the microstructure was observed in five different times 20, 40, 60, 80 and 100 min. Distribution of the carbide in ferritic structure is studied and it is relatively homogeneous over 40 minutes. The plate type ferritic grains are observed in late holding time (Figure 4.2).

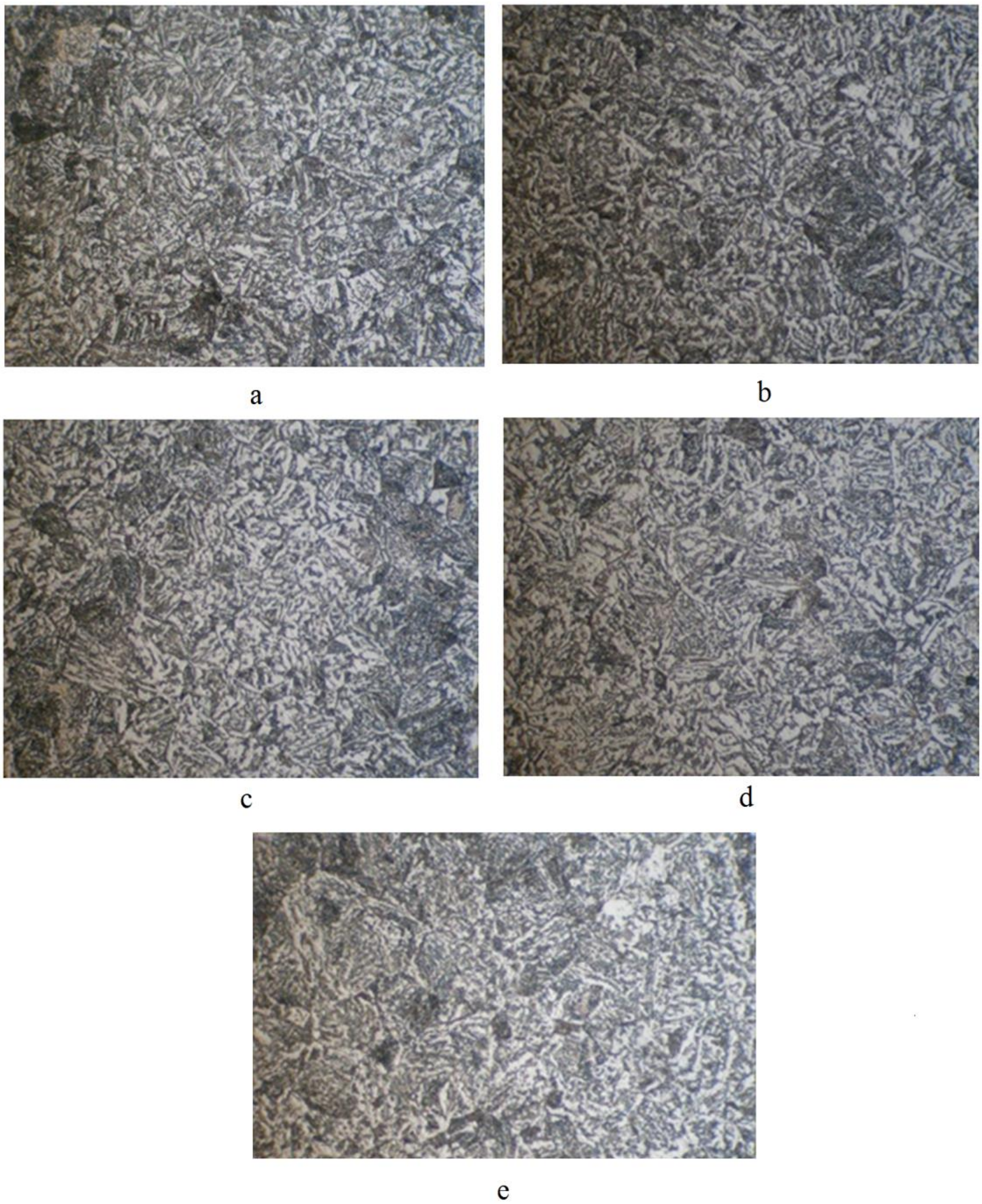

Figure 4. 2 Microstructural results after austempering process according to holding time in salt bath; a) 20, b) 40, c) 60, d) 80 and e) 100 min. [Magnification 100X]

4.2 HARDNESS TESTING RESULTS

The hardness was performed according to Rockwell-C testing method at Aksan Kardan LTD. ŞTİ.

4.2.1 Effect of Austempering Time on Hardness

The average hardness has been taken from cross-section between 30-32 HR-C (Table 4.1). However, the relatively higher hardness result was measured after 450 ^{o}C temperature. In this case, the optical microscope result shows us why hardness increases at 450 ^{o}C temperature. Also the temper brittleness may be mentioned at this temperature. The temper brittleness with tensile test will be able to confirm the effect.

Table 4.1: Hardness results after austempering process according to temperature changing in salt bath (AISI 4140)

Salt Bath Temperature	375 °C	380 °C	400 °C	425 °C	435 °C	450 °C
Cros-sectional hardness (HRC)	29 30 32 32 30 32 32 30	28 32 33 33 33 32 30 32	30 32 31 31 31 32 32 32	28 30 31 33 32 32 32 32	30 30 32 31 32 31 30 31	30 35 35 36 36 35 32 35

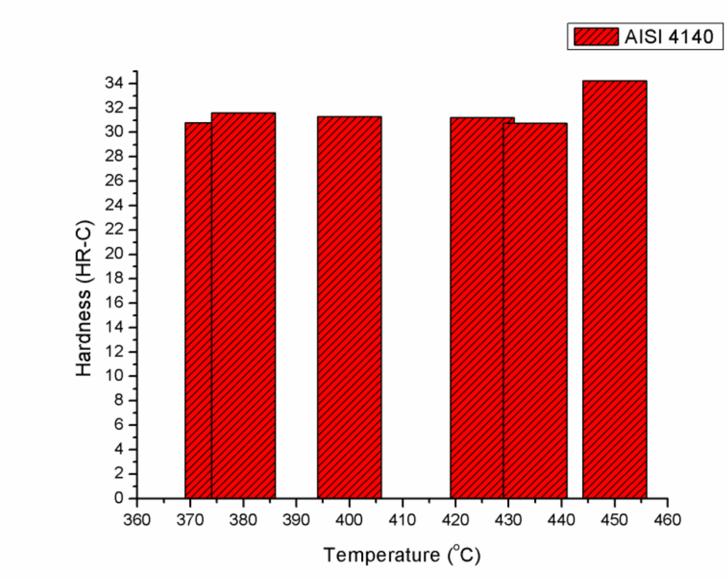

Figure 4. 3 Hardness results after austempering process according to salt bath temperature change

4.2.2 Effect of Holding Time on Hardness

The hardness results after austempering time preparation processes were observed to be between 28-30 HR-C (Table 4.2). The lowest hardness values are measured when holding time is increasing in austempering heat treatment of AISI 4140 steel. It is explained by the increase in grain size or coarsening of ferritic structure.

Table 4.2: Hardness results after austempering process according to temperature changing in salt bath

Duration in Salt Bath	20 min.	40 min.	60 min.	80 min.	100 min.
Cross-sectional hardness (HRC)	27	29	29	28	28
	29	28	28	30	28
	29	29	29	30	29
	29	30	29	31	29
	30	29	28	30	30
	29	29	28	29	29
	29	28	27	29	28

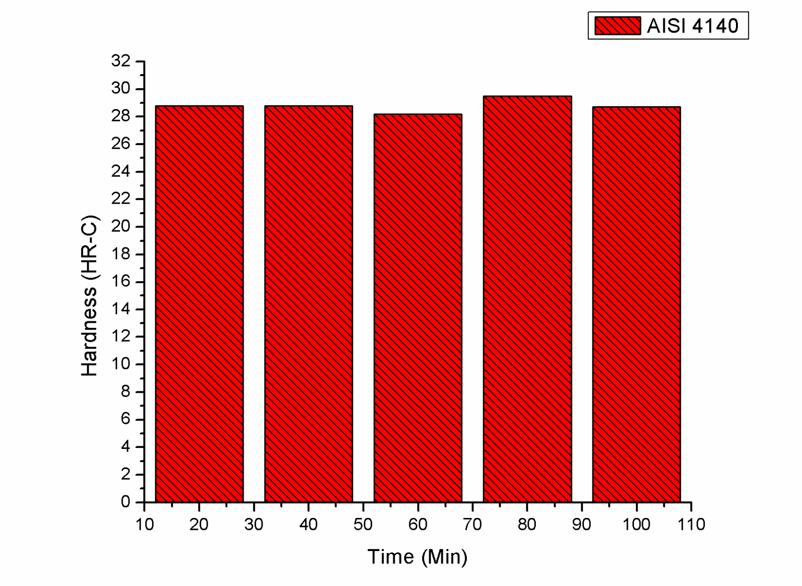

Figure 4. 4 Hardness results after austempering process according to holding time in salt bath

The hardness results after austempering time preparation processes were observed to be between 28-30 HR-C (Table 4.2). The lowest hardness values are measured when holding time is increasing in austempering heat treatment of AISI 4140 steel. It is explained by the increase in grain size or coarsening of ferritic structure.

Estimated reason is possible to mention the formation of lower bainite structure because the maximum tensile strengths are subjected in between 375-380 ^{o}C. Thus, the ideal holding time and temperature determined between 375-380 ^{o}C in between 40-60 minutes after heat treatment processes.

4.3 TENSILE TEST RESULTS

4.3.1 Effect of Austempering Time on Tensile Properties

The tensile strength, yield strength and elongation were determined depend on the austempering heat treatment temperature. The tensile test results were achieved between 1100 – 1300 MPa figure 4.3. The maximum tensile strength which is directly affected on fatigue life is obtained in 375 – 380 ^{o}C temperatures.

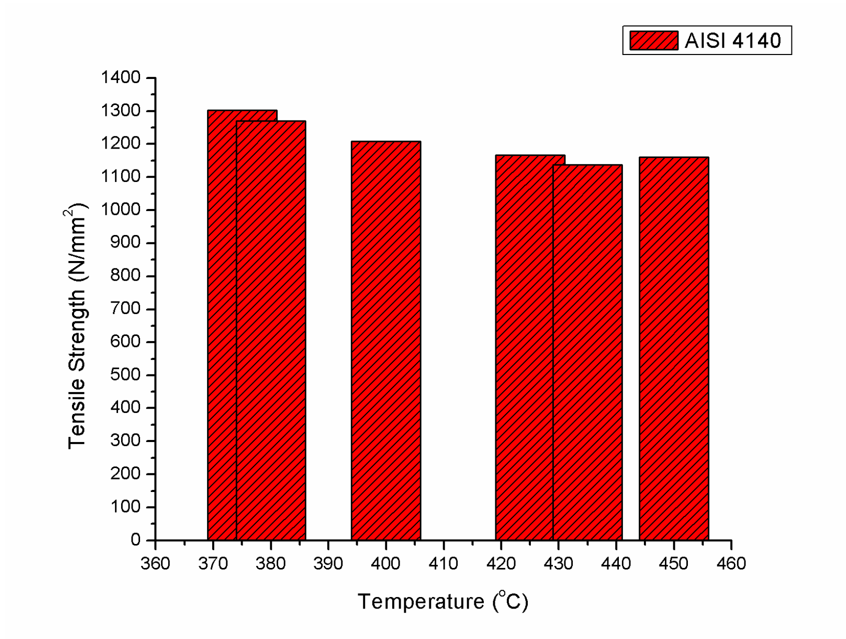

Figure 4. 5 Tensile Strength results after austempering process Tensile Strength results after austempering process according to salt bath temperature change

When the yielding point changes are examined, the maximum points are observed in 375 – 380 ^{o}C temperatures (Figure 4.4). The decline in values has been determined by pour point temperature increases.

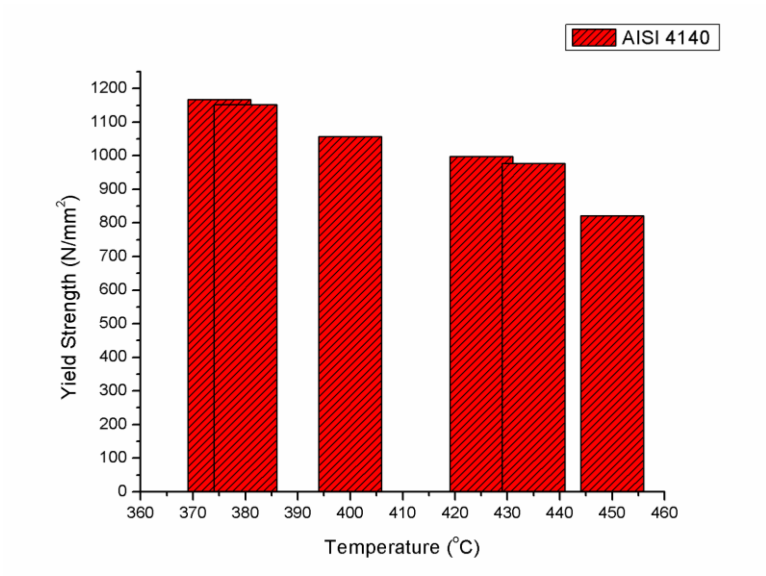

Figure 4. 6 Yield Strength results after austempering process according to salt bath temperature change

The result of elongation after austempering heat treatment processes were determined figure 4.5. The results can be seen between 10-13% values. The elongation is reduced after austempering temperature at 425 °C from %13 to %10. The elongation at this temperature can be explained by tempering brittleness of steel. Also ıt is possible to get lowest elongation and brittle fracture mechanism because of the blue brittleness. Thus, austempering temperature should be set below 400 °C for heat treatment of AISI 4140 steel.

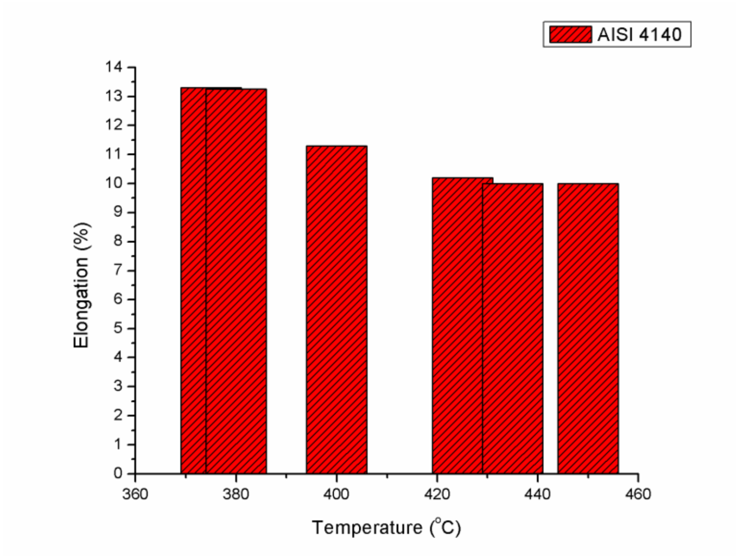

Figure 4. 7 Elongation results after austempering process according to salt bath temperature change

4.3.2 Effect of Holding Time on Tensile Properties

The tensile strength, yield strength and elongation were obtained after austempering heat treatment and holding time in salt bath. The tensile strength can be seen to be between 1200–1250 MPa after different heat treatment and holding time. The highest tensile strength values are relatively obtained after 40 min waiting time figure 4.6. But the microstructural images as the primary criteria are evaluated for holding time in salt bath. The relatively yield strength was measured between 40-60 min holding time after austempering process in same temperature conditions (Figure 4.7).

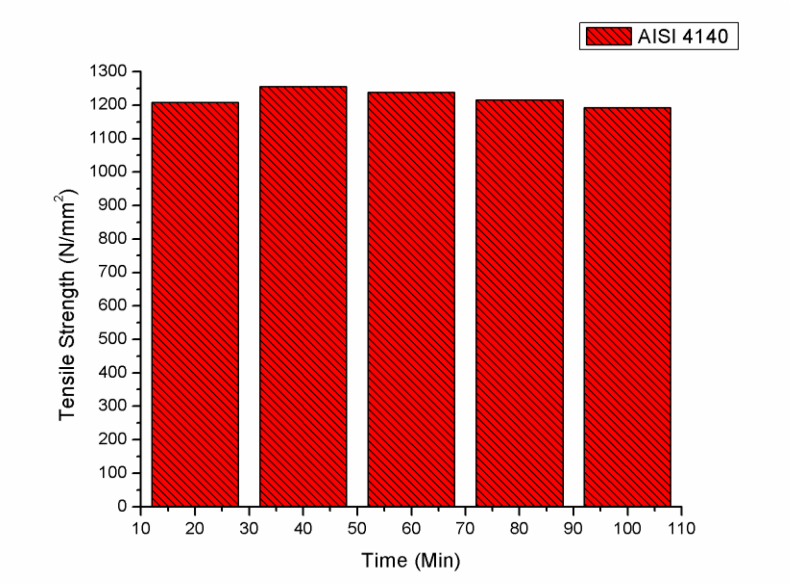

Figure 4. 8 Tensile Strength results after austempering process according to holding time in salt bath

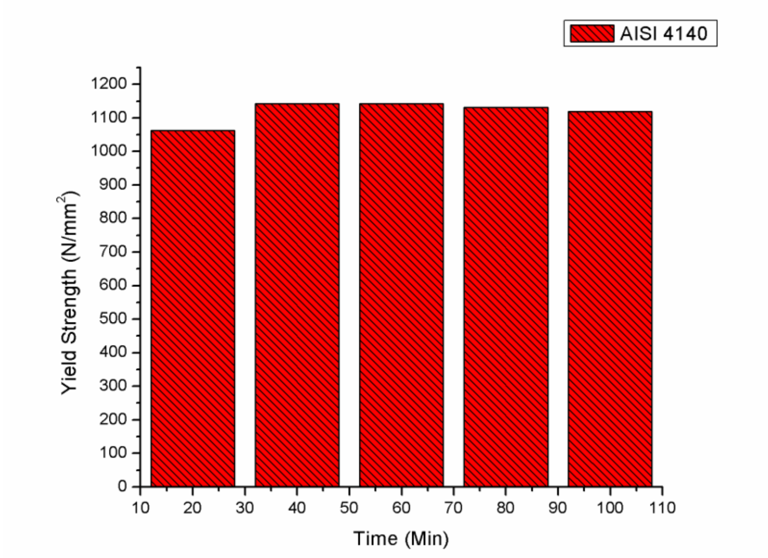

Figure 4. 9 Yield Strength results after austempering process according to holding time in salt bath

The elongation values result according to holding time in a salt bath are analyzed between 12,25 – 13,25% after austempering in same temperature. There is no relatively very low value difference between each elongation results after each holding time (Figure 4.8). When the holding time increase the elongation increase is expected.

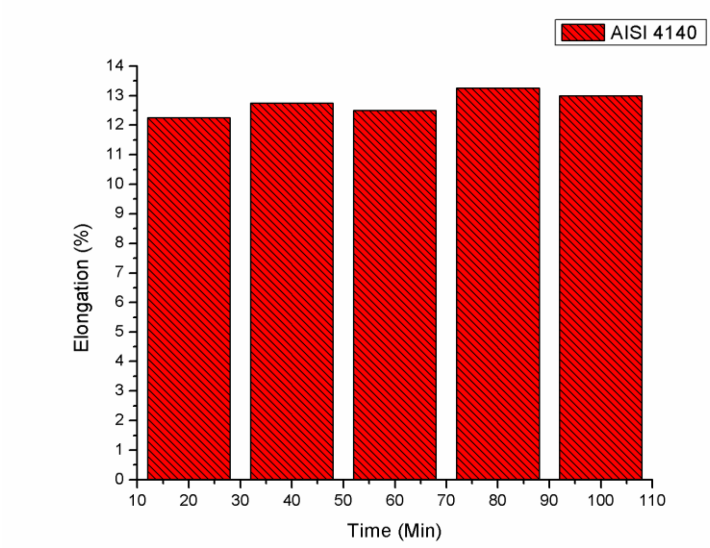

Figure 4. 10 Elongation results after austempering process according to holding time in salt bath

4.5 TORSIONAL TESTING RESULTS

4.5.1 Static Torsion Testing

The static torsion test results are received at TOMM University as in table 4 and table 5 on martensite and bainite structures. The three samples have been subjected under static torsion from each two microstructures. However, the broken sample which is early fractured because of its surface roughness is not included. The table 4.3 exhibits static bending result for austempering heat treatment study. The static bending test also was performed on quenching-tempered steel with martensitic structure given table 4.4. To considering torsional strength, the bainite structured samples showed relatively lower torque values. However, the bainitic structured samples has quite highly ductility as a result of the impact resistance (table 4.4).

Table 4.3: Static bending result for quenching-tempered AISI 4140 steel

Sample	Specimen	Diameter (mm)	Yielding Angle (^{o})	Yielding Torque (N.m)	Torsional Rigidity (N.m/^{o})	Maximum Torque (N.m)	Fracture Angle (^{o})
1	4140_1	6,2	85	63	0,74	128	183
2	4140_2	6,1	84	64	0,76	134	175
Avg.	-	6,2	84,5	63,5	0,75	131	179

Table 4.4: Static bending result for austempered AISI 4140 steel

Sample	Specimen	Diameter (mm)	Yielding Angle (^{o})	Yielding Torque (N.m)	Torsional Rigidity (N.m/^{o})	Maximum Torque (N.m)	Fracture Angle (^{o})
3	4140_1	6,2	35	32	0,91	40	436
4	4140_2	6,1	35	32	0,91	37	600
5	4140_3	6,1	55	32	0,58	39	540
Avg.		6,1	41,7	32	0,8	38,7	525

4.5.2 Torsional Fatigue Testing

The torsional fatigue testing was performed at Aksan Cardan LTD. ŞTİ. The three of specimen was tested from each of martensitic and bainitic structured samples. The obtained results are given on table 4.5 with constant torque and frequency. The samples which are quenching-tempered exhibit high torsional fatigue values instead of austempered samples. In this case there is no any surface hardening process on the heat treated materials.

Table 4.5: Torsional fatigue results of quenching-tempered and austempered steel

Heath Treatment	Quenching-Tempering			Austempering		
Code	Quenching Tempered 6	Quenching Tempered 7	Quenching Tempered 8	Austempered 9	Austempered 10	Austempered 11
Torque(Nm)	1000	1000	1000	1000	1000	1000
Starting Angle	+4,05 -3,94	+4,12 -4,07	+4,02 -4,15	+4,03 -4,01	+3,99 -3,88	+3,87 -3,88
Frequency(Hz)	4	4	4	4	4	4
Cycle	68.417	49.489	66174	39.200	54.921	46.641
Avg. Cycle	61.360			46.920		

The torsional fatigue fracture surface resulting images are shown on Figure 4.7. The classical fatigue fracture surfaces are analyzed for two structures; these are a) bainite structure and b) martensitic structure. The fish aye structure is seen clearly on both of the fracture surfaces. The bainitic structure shown figure 4.9a exhibit early cracked surface characteristic with frictional damages on the crack initiated zone.


a

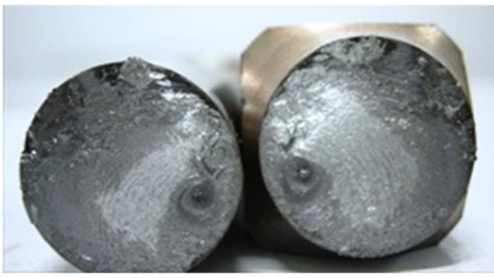
b

Figure 4. 11 Fracture surfaces after torsional fatigue; a) Austempered Specimen, b) Quenching-tempered Specimen

CHAPTER 5

CONCLUSION

In this study, the suitable heat treatment processes are determined after austempering heat treatment with the obtained bainitic microstructure. Thus, the structure having the high tensile strength was determined. Because the high tensile strength is known to have a direct impact on torsional resistance.

The selected six different heat treatment temperature 375, 380, 400, 425, 435 and 450 ^{o}C was performed in austempering heat treatment. Three samples were selected for testing such as tensile testing, torsional testing and fatigue testing. The suitable heat treatment with microstructural studies is selected after austempering heat treatment. The austempering heat treatment temperature in salt bath was determined as 375 – 380 ^{o}C, with the highest tensile strength as an indication of torsional fatigue resistance and elongation. In addition, the waiting time in salt bath is determined between 40-60 minutes.

The final heat treatment process is determined as 375 ^{o}C in 40 minutes. The holding time is determined according to the sample thickness. The specimen which used in austempering heat treatment showed relatively less distortion instead of quenching tempered heat treatment.

The samples used in quenching-tempered heat treatment exhibit static torsional strength (samples 1, 2). However, the samples showed quite brittle behavior. The samples used in austempering heat treatment are having low static torsional strength as compared to quenching-tempered structures (sample 3, 4, 5). However, the ductility to indicator impact resistance rises up with austempered structures.

The torsional fatigue test is applied on quenching-tempered (6, 7, 8) and austempered (9, 10, 11) samples in equal hardness measurement. The constant torque and frequency is selected as 1000 N-m torque and 4 Hz. Frequency. The fracture occurs in the higher number of cycles on quenched tempered AISI 4140 steel. İt is more than 30% percent from results of the austempered AISI 4140 steel.

This project supported by SANTEZ for investigation of bainitic and martensitic structured AISI 4140 steel as used in cardan shaft material. However, the whole of this research results have not been given in this thesis due to protection to all works strategic importance in the automotive industry.

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