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Research Article

Development and Design and Heat Treatment of Production, Storage and Mine Drilling Pipes in Petroleum and Geothermal Industries

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ABSTRACT

In this study, sequential and different temperature heat treatments were applied to steels after austenating heat treatment applied to different AISI steel types. The effects of tempering heat treatment applied on the mechanical properties of the steel after quenching were investigated. The production of prototypes of the materials to be used in the drilling industry and the improvement of the properties of the drilling pipes used in the geothermal, petroleum, storage and mining sectors by thermal processes determined according to the standards have been realized. Different heat treatments have been applied to the materials in AISI standards provided by considering the desired material properties of the drill pipes. In order to improve the mechanical properties, the heat treatment process was determined and applied by a wide literature review. The prototypes of the drill rods were produced in three different AISI standards (AISI 4130, AISI 4140). Seamless tubes are produced according to AISI 4340 and ductile, semi-ductile and brittle conditions. 946.4 MPa. In addition, corrosion tests showed significant corrosion resistance.

Keywords: *Heat treatment, Drilling rods, Petroleum industry, AISI 4130 4140 4340 steel grades*

Petrol ve Jeotermal Sektörü Depolama ve Maden Sondaj Borularının Üretimi, Geliştirilmesi, Tasarımı ve Isıl İşlemi

ÖZET

Bu çalışmada, farklı AISI çelik türlerine uygulanan östenitleme ısıl işleminden sonra çeliklere sıralı ve farklı sıcaklık ısıl işlemleri uygulanmış. Bu işlemlerden sonra su verme işlemini takiben uygulanan temperleme ısıl işleminin çeliğin mekanik özellikleri üzerine etkileri araştırılmıştır. Sondaj sanayinde kullanılacak malzemelerin protatiplerin üretilmesi, jeotermal, petrol, depolama ve maden sektöründe kullanılan sondaj borularının standartlara göre belirlenen ısıl işlemlerle özelliklerinin iyileştirilmesi gerçekleştirilmiştir. Sondaj borularının istenilen malzeme özellikleri dikkate alınarak temin edilen AISI standartlarındaki malzemelere farklı ısıl işlemler uygulanmıştır. Mekanik özelliklerin iyileştirilmesi için ısıl işlem süreci geniş bir literatür taramasıyla belirlenmiş ve uygulanmıştır. Sondaj çubuklarının protatipleri, üç farklı AISI standardında (AISI 4130, AISI 4140) malzemelerinden 3 er adet olmak üzere protatipler üretilmiştir. Dikişsiz tüpler olarak AISI 4340 ve sünek, yarı sünek ve kırılgan koşullara göre üretilmiştir: Yapılan Isıl işlem deneyleri sonucunda malzemelerin % uzama değerleri %9-18, Max sertlik değerleri 280-495 HB, gerilme değerleri 834,2-1578 MPa ve Minumun akma dayanımı 946,4 MPa ile dikkate değer iyileştirmeler göstermiştir. Ayrıca yapılmış olan korozyon testlerinde kayda değer korozyon direnci göstermiştir.

Anahtar Kelimeler: *Isıl işlem, Delme çubukları, Petrol endüstrisi, AISI 4130 4140 4340 çelik sınıfları*

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I. INTRODUCTION

Yelection of suitable materials and heat treatments applied to these materials are of great importance in the manufacture of machine parts. Corrosion steels used in the manufacture of machine parts AISI 4140 steel is widely used especially in the automotive industry[1,2]. Oil industry has large needs of drilling rods due to new discoveries of oil-wells. To produce drilling rods base material of steel is used widely. Main reason of use of steel is its hardening benefits, economical convenience and high strength for this heavy industry. Steel is an alloy contains iron and carbon essentially. Other elements added up to steel changes its mechanical, physical and chemical properties and its hardenability [3]. For example, the steels which are used in this study AISI 4130 AISI 4140 AISI 4340 steels are called chromium molybdenum steels. (for AISI 4340 steel is chromium nickel molybdenum).

Heat treatment often alters the properties of material beside alloying [4]. Quenching is a heat treatment process used for strengthening of steel as heat treatment. Basically, rapid cooling causes the production of martensite and martensite in steel has brittle and hard structure in its self-existence caused by chemical energy difference in the matrix [5]. Main cause of hardness and brittleness of the martensite since lack of slip planes in the martensitic structure [6]. To avoid the brittleness of the steels the second process runs after quenching called tempering [7]. Series of 4xxx chromium-molybdenum steels has a contribution to the strength of the martensite distributed various effects on microstructure such rearrangement of carbon in quenching process affects up to 750 MPa [8]. So, this change effects dramatically the mechanical behaviour of AISI 4xxx steel series [9]. Approaches to yield strength (YS) and ultimate tensile strength (UTS) is indirect way to estimate the values of YS and UTS. In this study tensile testing values are estimated in the lights of this approximation [10]. Drilling rod production is a typical pipe production such as Mannesmann process and ERW pipe manufacturing. ERW is a welding process (Electric Resistance Welding) [11]. For seamless pipe production Mannesmann process comes up [12]. In this study, the pipes were brought from industry has been used. Seamless pipes should be quenched and tempered conditions for the oil and petroleum industry [13]. During drilling fluid is pumped from the compressor by drilling rods. The main functions of drilling fluids include providing hydrostatic pressure to prevent formation fluids from entering the well bore, keeping the drill bit cool and clean during drilling, carrying out drill cuttings, and suspending the drill cuttings while drilling is paused and when the drilling assembly is brought in and out of the hole. The drilling fluid is alkaline and pH of it about to 8.5. The corrosion of iron in alkaline solutions from Pourbaix diagrams tends to passivation. [14] Although plain-carbon steels can be produced in a great range of strengths at a relatively low cost, their properties are not always adequate for all engineering applications of steel [15]. Alloying and heat-treating effects the mechanical properties even the austenitising temperature of the steel affects the hardenability during heat treatment process [16]. Typically, low alloyed steels measured with Rockwell C scale [17], to get ultimate tensile strength values estimations this scale should be turned to Brinell scale [18]. Drilling rods in industry subjected to torsional forces during working. Also, torsional strength is important for this study. Fatigue cracks, under the torsional loads have a big impact on the material lifetime [19]. For steel with combination of high strength and toughness, along with low cost, the designed structure should be low-temperature tempered, fine lath martensite with high density of dislocation [20]. Fatigue crack growth in compact tension samples of high purity 4140 steel quenched and tempered to various strength levels was investigated. Tempering temperatures of 200, 400, 550, and 700 °C produced yield strengths from 1600 to 875 MPa, respectively [21-22]. Microstructural observations reveal that the carbide precipitates have a plate-like structure at low temperatures but are spheroid-like at high temperatures [23,24].

II. MATERIALS AND METHODS

AISI 4130, AISI 4140, and AISI 4340 steel grade rods which were produced by Mannesmann process were supplied from the industry. Three specimens for three steel grades were designed for this study. The reason of choosing three specimens from the same steel grade was three different heat treatment procedures have been carried out on each different specimen in the specimen group. They were named as ductile, semi-ductile, brittle conditions for comparison. For AISI 4130 ductile, semi-ductile and brittle conditions of the heat treatment has been run. Same heat treatment procedures have been done to AISI 4140 and AISI 4340 steels. After heat treatment procedure, metallographic examinations have been carried out in Marmara University Engineering Faculty (MUEF) Metallographic Examinations Laboratory. Specimens after heat treatment were cut from vertical and horizontal sections after mounting with Bakelite ground by 180, 320, 600, 800, 1000 Silicon Carbide grinding discs then polished by alumina water suspension.

A. DESIGN REQUIREMENTS

Quality of Material: DIN 30CrMo4, DIN 42CrMo4, SAE/AISI 4130, SAE/AISI 4140, SAE/AISI 4340 or their equivalents. Pipes need to have those mechanical properties
Minimum Tensile Strength of 880 N/mm².
Minimum Yield Strength of 780 N/mm².
Elongation at break minimum 12%.
Minimum hardness 262 Brinell approximately 27 Rockwell C.

III. EXPERIMENTAL PROCEDURE

Specimens are heated up at 850ºC which is called austenite field in the vacuum furnace. Avoiding from the specimen distortion heating runs in three stages which are 450 ºC first pre-heating, 650 ºC second pre-heating, 850 ºC hardening temperature for austenitising stages. After austenitising, salt bath is done at 180 ºC. After quenching, specimens are tempered at 580 ºC. Until tempering stage, austenitising and quenching are the same with the first heat treatment process since to get harder and stronger material. In this process tempering temperature is changed to 460 ºC. To get hardest material, specimens are subjected to harsh condition which is very low tempering temperature 320 ºC. Tensile testing of pipe is slightly different from the regular testing. In pipe tensile testing, the pipes are supported with the metal fillers by the two ends of the specimen. The main purpose of those fillers is preventing the material from material distortion during the tensile test and keeping the material stable due to pressure of claws. Metal fillers are AISI 1040 steel and having 30mm length 19.8mm diameter. Tensile testing is done in MUEF, Mechanical Properties Laboratory by 250 kN Instron 8802 Servo Hydraulic Tensile Testing Machine. Hardness' of specimens are measured by the Rockwell C testing. Hardness of specimens were measured from the vertical section of the specimens. The deformation amount of the pierced specimens does not affect the other tests, so the deformation amount is negligible. Hardness testing is done in the MUEF, Materials Laboratory by Zwick Universal Hardness Testing Machine. Before degradation tests, cut specimens are soldered with the electrical wire with lead. Then specimens are moulded with epoxy, and moulded specimens are ground and polished. The pH of the drilling fluid is found 8.5. Then artificial drilling fluid was prepared with water and sodium carbonate. The amount of corrosion is measured as cathode standard calomel electrode (SCE) is used.

IV. RESULTS AND DISCUSSION

Metallographic examination of the AISI steels condition. Microstructure consists of martensite and pearlite in the Figure 1.

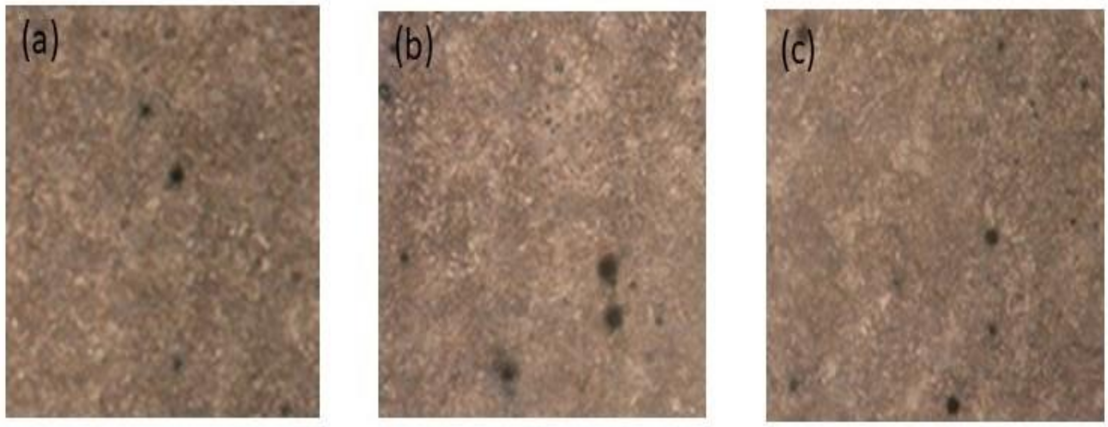

Figure 1. (a)*AISI 4130 semi-ductile condition micrograph.* ***(b)****AISI 4140 semi-ductile condition micrograph* ***(c)****AISI 4340 semi-ductile condition micrograph*

Estimating the Tensile Strength by hardness approximation. An approximate relationship (shown in the Equation 1 below) between the hardness and the tensile strength (of steel) is,

$$Tensile\ Strength\ (MPa) = \begin{cases} 3.55\ x\ HB\ where\ HB \leq 175 \\ 3.38\ x\ HB\ where\ HB > 175 \end{cases}$$ Equation 1. Approximate values of

UTS are estimated by this relationship.

The experiments that were carried out, have shown that AISI 4130 and 4140 AISI 4340 steels partly satisfies the minimum percentage elongation %9 break point were mentioned in problem definition and contstraints as shown in Table 1 indicated grey colored background.

Table 1. *Percentage elongation values at break point*

Percentage elongation values at break point (%)				
Metals	**Ductile**	**Semi- Ductile**	**Brittle**	**2.00**
AISI 4130	17*	13*	11*	17*
AISI 4140	18*	13*	9*	18*
AISI 4340	13*	10*	10*	13*

The experiments that were carried out, have shown that AISI 4130 and 4140 AISI 4340 steels fully satisfies the minimum hardness values 262 Brinell scale were mentioned in problem definition and contstraints as shown in Table 2 indicated grey colored background.

Table 2. *Hardness values of steels with varying heat treatment conditions*

Hardness values of steels with varying heat treatment conditions			
Metals	**Ductile**	**Semi-Ductile**	**Brittle**
	HB (kgf/mm2)	*HB(kgf/mm2)*	*HB(kgf/mm2)*
AISI 4130	280	390	495
AISI 4140	285	400	495
AISI 4340	290	392	495

The experiments that were carried out, have shown that AISI 4130 and 4140 AISI 4340 steels fully satisfies the minimum tensile strength criteria (880 MPa) were mentioned in problem definition and contstraints as shown in Table 3 indicated grey colored background.

Table 3. *Tensile Strength values of the steels (MPa)*

Tensile Strength values of the steels (*MPa*)			
METALS	**Ductile**	**Semi-Ductile**	**Brittle**
AISI 4130	910.1	1192.7	1378.9
AISI 4140	834.2	1137.6	1434.1
AISI 4340	1172.1	1365.1	1585.7

The experiments that were carried out, have shown that AISI 4130 and 4140 AISI 4340 steels fully satisfies the minimum yield strength criteria (780 MPa) were mentioned in problem definition and contstraints as shown in Table 4 indicated grey colored background.

Table 4. *Yield Strength values of the steels*

Yield Strength values of the steels (*MPa*)			
METALS	**Ductile**	**Semi-Ductile**	**Brittle**
AISI 4130	946.4	1318.2	1673.1
AISI 4140	963.3	1352	1673.1
AISI 4340	980	1324.96	1673.1

The Fig. 3 illustrates the calculation of maximum torsional force can be carried by the pipe. The K represents the moment of inertia, sigma is yield of the material and d_0 is outer diameter. The yield results from results part are used for calculating the maximum torque of yield strength.

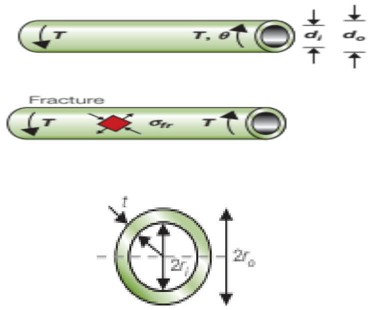

Figure 2. *Maximum torsional force can be carried by the pipe*

$$Tf\ (N.m) = \frac{2\,\pi \left(\frac{Do(m)}{2}\right)^{3} t(m)\ \sigma(Pa)}{Do(m)} \tag{1}$$

Table 5. *Maximum torque at yield point for some AISI grade steels*

STEELS	Yield Strength(MPa)	Max Torsion at Yield (N.m)
AISI 4130 (Ductile)	910.1	8997,49
AISI 4130 (Semi-Ductile)	1192.7	11785,6
AISI 4130 (Brittle)	1378.9	13624,7
AISI 4140 (Ductile)	834.2	8246,0
AISI 4140 (Semi-Ductile)	1137.6	11241,8
AISI 4140 (Brittle)	1434.1	14178,4
AISI 4340 (Ductile)	1172.1	11587,9
AISI 4340 (Semi-Ductile)	1365.1	13496,1
AISI 4340 (Brittle)	1585.7	15671,4

According to results from Equation 1 Table 5 shows AISI 4130 is the best candidate of the other 8 specimens.

As seen in the Fig. 3, on the surface of AISI 4130 steel there is not any pitting corrosion at pH 8.5.

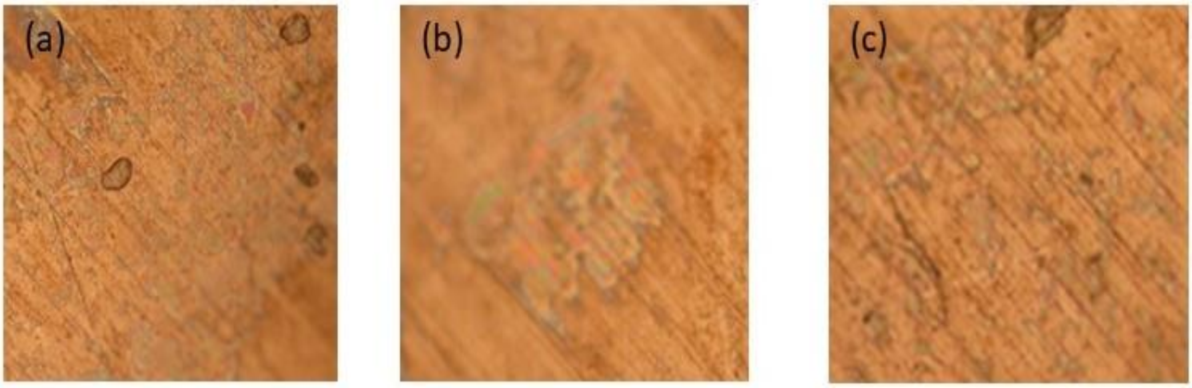

Figure 3. ***(a)*** *AISI 4130 steel after corrosion testing micrograph.* ***(b)****AISI 4140 steel after corrosion testing micrograph.* ***(c)*** *AISI 4340 steel after corrosion testing micrograph.*

The passivation occurs at the region shown in the Fig. 4 Tafel graph proves that at O_2(g) evaluation is observed at 1V due to oxygen overvoltage (~0.95 V).

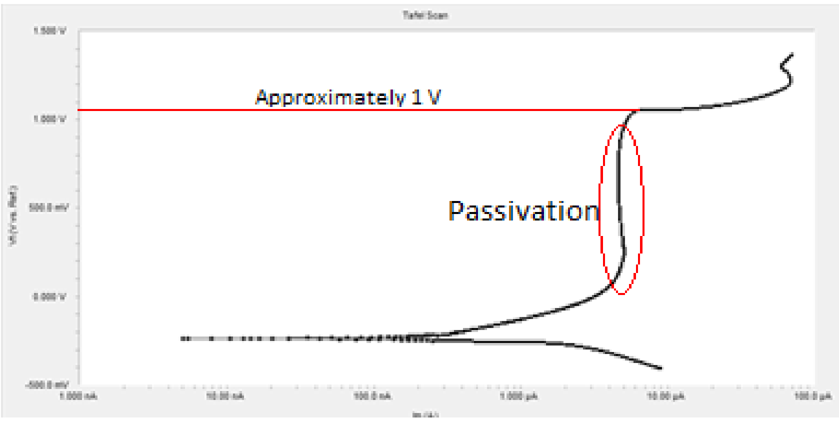

Figure 4. *AISI 4130 steel Tafel graph with passivation region and Ecorr Icorr values*

V.CONCLUSION

The ductile conditions of all steels satisfies all constraints but due to minimal cost, ductile conditions are undesirable besides they have low yield point than other conditions hereby ductile conditions of steels mentioned in this project are undesirable. AISI 4340 steel reaches the %12 limit at ductile condition which indicates high tempering temperature. If tempering temperature is that high indicates more energy thus more money is spent. Minimum cost is desirable when conditions are very similiar thus AISI 4340 steel is undesirable at that condition. Second comparison is semi-ductile conditions for AISI 4130 and AISI 4140 steels. They show the same percent elongation at break (%13) but AISI 4130 steel has higher yield point value (%4,619 high) than 4140 steel when compared. So AISI 4130 steel is more desirable than AISI 4140 steel in this conditions. When compared with the other candidates AISI 4130 steel gives the best results for design requirements. Yield point of the selected material AISI 4130 steel has higher value then the desired yield strength (%34,06) with low energy consumption, high torsion torque at yield point and better corrosion resistant material.

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