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Araştırma Makalesi / Research Article

Heat Treatment and Microstructural Analysis of 54SiCr6 and 60SiMn5 Spring Steels

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ABSTRACT: Steels, the most widely used alloy in the world, are the most concrete example in the study of the structure-property-performance relationship in materials, which is the clearest function of the science of materials. Steels exhibit very different properties when other types of atom are present in the solid solution. Due to these changes in properties, the performance of the material in the area of use is determined. When silicon is added to steels in certain proportions, it is important to provide the necessary mechanical properties in steel industry as spring steel, and these steels are generally classified as silicon spring steels. Heat treatments are applied to determine, regulate and improve the properties and performances of steels other than their chemical properties. These heat treatments are carried out with different methods for different purposes. In this study, the hardness of silicon containing spring steels when it is produced, then how hard it reacts in sudden cooling, when water or oil is used as cooling medium, the final hardness and microstructures are examined by tempering followed by hardening. Results showed that 54SiCr6 produced martensite+bainite structure as opposed to fully martensitic 60SiMn5 specimen after quenching process.

Keywords: 54SiCr6 Steels, 60SiMn5 Steels, Heat treatment, Microstructure

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54SiCr6 ve 60SiMn5 Yay Çeliklerinin Isıl İşlemi ve Mikroyapısal Analizi

ÖZET: Dünya üzerinde en fazla kullanılan alaşım olan çelik, malzeme biliminin en net işlevi olan malzemelerdeki yapı-özellik-performans ilişkisinin incelenmesinde en somut örnektir. Çelikler katı çözeltide başka bir element atomlarıyla buluşmasıyla çok farklı özellikler sergilemektedir bu özellik değişimlerine bağlı olarak ise kullanıldığı alanda malzemenin performansını belirlemektedir. Silisyum elementi çeliklere belirli oranlarda eklendiğinde endüstride çeliğin yay çeliği olarak kullanılmasında gerekli mekanik özellikleri sağlamakta önem taşır ve genelde bu çelikler silisyum yay çelikleri olarak sınıflandırılır. Çeliklerin kimyasal karakterin dışında özellik ve performanslarını belirlemek, düzenlemek ve geliştirmek için ısıl işlemler uygulanır. Bu ısıl işlemler farklı amaçlarla farklı yöntemlerle yapılmaktadır. Bu çalışmada, silisyum içeren yay çeliklerinin üretildiğinde sahip olduğu sertliğin daha sonra ani soğutmada, soğutma ortamı olarak su kullanıldığında veya yağ kullanıldığında nasıl tepki verdiği sertleştirme işlemi akabinde temperleme ile nihai sertlik ve iç yapıları incelenmiştir. Sonuçlar göstermiştir ki, su verme işleminden sonra, 54SiCr6 çeliği, tam martenzitik 60MnSi5 çeliğine göre, martenzit+beynit yapısında mikroyapı üretilmiştir.

Anahtar kelimeler: 54SiCr6 Çeliği, 60SiMn5 Çeliği, Isıl işlem, Mikroyapı

1. INTRODUCTION

The advantage of improving the properties and performance of steel samples by various methods is also valid for spring steels. Silicon containing spring steels that exhibit certain mechanical properties in certain chemical compositions can be used for their microstructural advantage, hardness etc. by various heat treatments. Spring steels are often subjected to hardening process i.e. heat treatment in order to provide maximum performance in the area where they are used (Çalik, 2009; Canale and Penha, 2007).

Springs are the basic mechanical components found in many mechanical systems. Steel is an important engineering material for the production of high-strength components of any mechanical system. Technically, the spring is an elastic component that can store an applied force effect. Spring steels have the unique feature of being able to withstand significant bending or twisting forces without any distortion (Canale and Penha, 2007). This property is defined as high yield strength and is the result of hardening of certain compositions and steels. Spring steels are used as special requirements are expected for hardness or wear resistance. Most spring steel is hardened and tempered to about 45 RC. In general, springs are made with high carbon spring steels, alloy spring steels and stainless spring steels (Dindar, 2019; Rehrla, 2012).

Heat treatment, especially, annealing is applied to ensure that the microstructure of the steel that changes after various processes is returned to the normal microstructure. Normalization annealing is performed in sub-eutectoid steels to transform the microstructure into a round, fine-grained and homogeneous dispersed structure (Senthilkumar, 2012; Machado, 2006). It is applied in the hyper-eutectoid steels to facilitate the subsequent homogeneous process and to shorten the hardening process. The main reason for the high hardness of martensite is that the lattice structure is extremely distorted. Due to the fact that the atomic filling factor of martensite is lower than the atomic filling factor of austenite, some volumetric growth occurs in steel during martensitic transformation. This volumetric growth creates local stresses that can cause plastic deformation of the matrix atomic structure (Çalik, 2009; Villa et al., 2014; Weidner et al., 2015; Loewy et al., 2014). In other words, the volumetric growth that occurs during the formation of martensite creates very high local stresses and causes the matrix structure of the steels to distort excessively or undergo plastic deformation. The deformation of the lattice structure also increases the hardness and strength of the quenched steels by preventing the dislocation movement (Weidner et al., 2015; Morito et al., 2006; Morito et al., 2009).

In this study, the microstructural changes and variation in the hardness values of 60SiMn5 and 54SiCr6 silicon spring steels were investigated with respect to cooling medium in oil and water following the hardening and tempering heat treatment.

2. EXPERIMENTAL PROCEDURES

In this section, detailed information is given about 60SiMn5 and 54SiCr6 steel materials used in experimental studies, test devices and applied methods. Chemical analysis of 60SiMn5 and 54SiCr6 alloy steels used in experimental studies is given in Table 1 below.

Table 1. Chemical Composition of 60SiMn5 and 54SiCr6 Sample

	Chemical Composition (wt.%)					
	C	**Si**	**Mn**	**P**	**S**	**Cr**
60SiMn5	0.55-0.65	1.0-1.3	0.9-1.1	<0.05	<0.05	-
54SiCr6	0.52-0.59	1.2-1.6	0.5-0.8	0.03	0.03	0.5-0.8

For experimental studies, the commercially available 60SiMn5 and 54SiCr6 steel specimens were sliced from the 20mm diameter bar section and the as received samples were passed through 120-1200 grit sandpaper grinding process for metallographic investigation. The polishing process was carried out on polishing cloth with 1μm alumina solution. Polished specimens were etched for 4-5 seconds using 3% Nital solution. For heat treatment, the samples were cut in sizes suitable for facilitating the application of metallographic processes and examinations, i.e. ∅20mmx20mm long. After slicing the specimens, pieces of 60SiMn5 and 54SiCr6 steels were placed in a cold furnace at room temperature for the heat treatment.

The heat treatment for hardening took place in furnace for 90 min at 850 ºC and tempering at 200 ºC for 2h. To ensure a successful the hardening process, it is necessary to cool the samples quickly after reaching the temperatures determined by the heat treatment furnace and hence, quenching was applied to the samples following the heat treatment in the furnace. Still water (room temperature) and oil mediums were chosen for quenching operations. With the universal microhardness tester (Shimadzu HMV2), the hardness values of all samples were measured three times, and their average values were taken and recorded. Microstructure images were taken with Nikon optical microscope at various magnifications and linear intercept method was used for grain size measurement. Heat treated, tempered after heat treatment and all non-treated samples were examined by the metallographic processes described above.

3. RESULTS AND DISCUSSION

3.1 As Received Steel Microstructures

Microstructure images and hardness values of 60SiMn5 and 54SiCr6 alloy steels used in experimental studies are given in as received form in Figure 1, obtained from Aktaşlar Agriculture Machinery Company. Figures 1a and b show that the dominant microstructures are fine pearlitic or fine pearlite+ferrite. As can be seen from the figure 1 that the composition of both steels with similar microstructures decomposes with only difference being the presence of Cr. Cr in steels is one of the important elements for general matrix hardness, and at the same time, when C is present, secondary phases for example by forming carbides of Fe and Cr, provide wear resistance (Razzak, 2011). Cr, which increases the matrix hardness, causes carbide form in special circumstances, and if it is homogeneously distributed, the dispersion of carbides adds more efficiency for high wear resistance and matrix hardness. In the microstructure of the 54SiCr6 alloy (Figure 1b), a greater amount of ferrite structure is observed on the grain boundaries than 60SiMn5. The average grain sizes in both microstructures of 60SiMn5 and 54SiCr6 are approximately 37±9 µm and 43 ±12 µm in average, respectively.

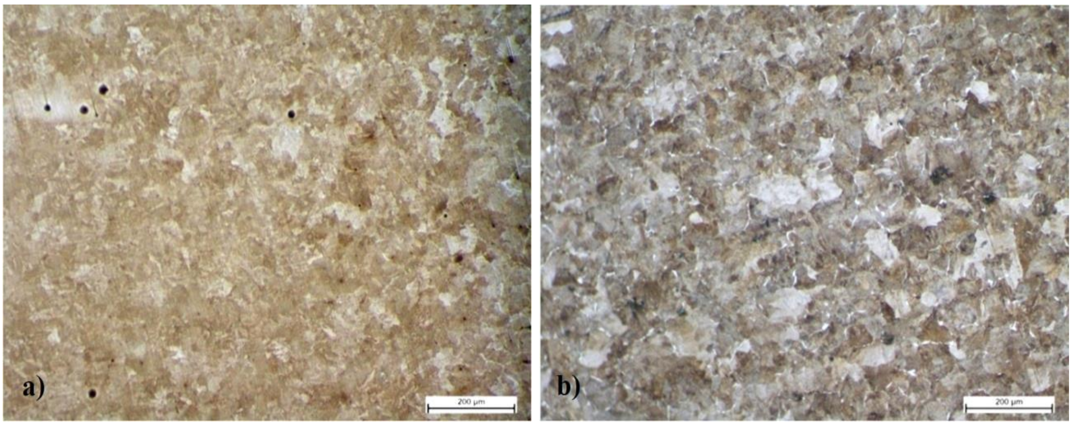

Figure 1. a) Microstructures of 60SiMn5 steel and b) 54SiCr6 steel in as received condition. Scale bar is 200 µm

3.2 Heat Treatment Results of 60SiMn5 and 54SiCr6 Samples

Quenching of 60SiMn5 steel provided various microstructures which mostly contain martensite in general (Figure 2). The effect of tempering is very pronounced as seen in other steel, 54SiCr6, (Figure 3). Fine pearlitic or fine pearlite+ferrite in as received state of 60SiMn5 steel have transformed into martensitic structure after holding at 850ºC for 90 minutes followed by quenching, figure 2a, and its tempered form is given in figure 2b. The microstructures are fully martensitic in 2a and martensite+bainite in figure 2b. However, figures 2c and 2d show that the dominant microstructure in 60SiMn5 quenched in oil is mostly bainite+martensite and heavily tempered martensite (very small amount) with bainitic and ferrite presence in globular form, respectively. As indicated in 1a that the emergence of the lenticular martensitic structure with a dark colour gives relative information about the thickness or coarseness of the structure. The tempering causes these individual martensite plates to align themselves in parallel and form tempered martensite plates. Extra Mn in 60SiMn5 steel facilitates the formation of martensitic structure even at lower transformation temperatures (Ghosh and Olson, 1994, Loewy et al., 2014). Lowering the temperature of transformation causes a difference in the number of microstructures and morphology. Wang et al (Wang et al 2000) proposed a formula to calculate the Ms temperature in steels. According to this formula, Ms temperature of steels studied are 232ºC for 54SiCr6 steel and 220ºC for 60SiMn5 steels, which are very close to each other. This explains difference in microstructures as well the addition of extra Si. The quenching medium is not expected to affect the outcome since the composition is very close in range, especially C and Mn. Cr, C and Mn will move the TTT curve towards right, which eases the formation of martensite and Cr also lowers the transformation temperature while Si reduces the amount of pearlite (Mesplont 2002).

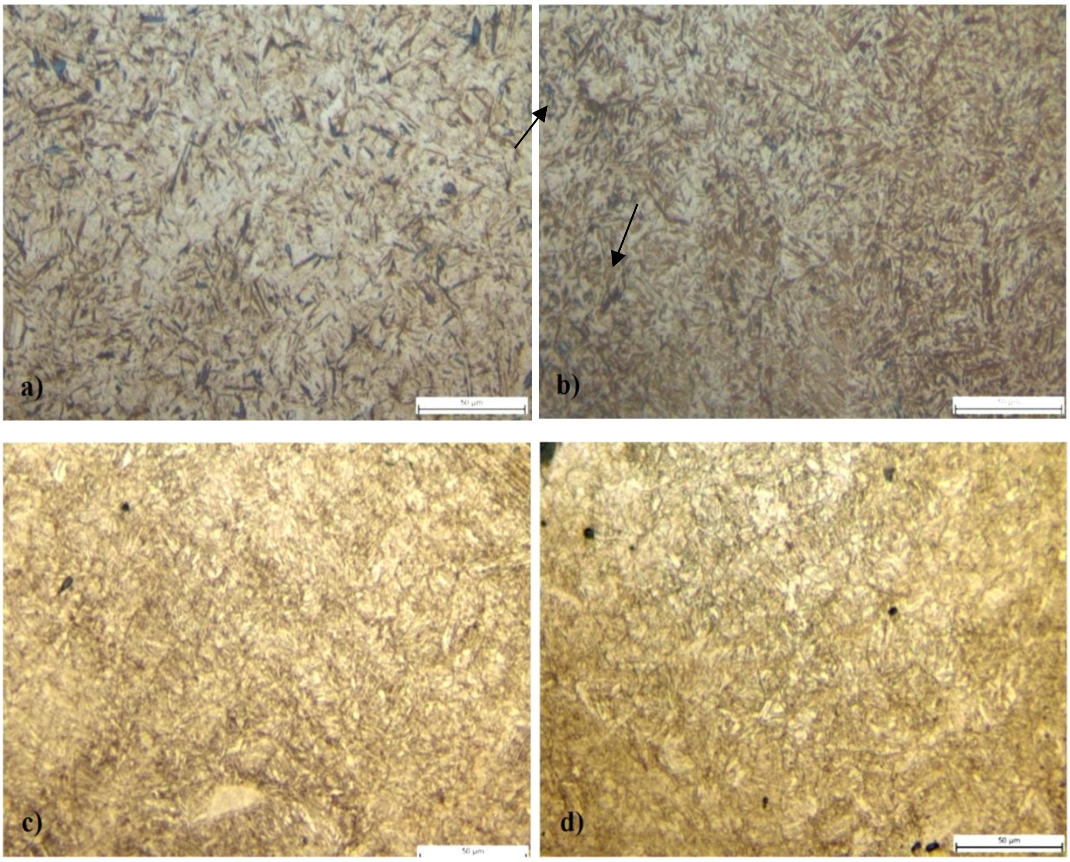

Figure 2. a) Water quenched, b) Oil-quenched, c) Water quenched and tempered d) Oil-quenched and tempered 60SiMn5 sample microstructure. The scale bar is 50 µm

Water and oil cooling generally result in different morphological effects in the microstructure. These effects can be of two types. The first is the refinement of the microstructure or the fact that a much finer structure is usually more profound and the other is the amount of the dominant structure compared to remaining microstructural features. It is expected that the structure prevailing in oil cooling/quenching is less complex and the appearance of martensite is likely to emerge differently. While the appearance of the martensitic structure that appears with the tempering process changes slightly, it is expected that the hardness values will also change according to the quenching environment and temperature. The shape change of acicular structures towards round form is usually very common and is the result of migration of interface active elements such as C, N and Cr etc... These elements have usually low solid solution forming capacity or low solubility comparable to other elements for a given temperature (Villa et al., 2015; Tsuzaki and Maki, 1981; Liu et al., 2003).

Figure 3 shows the effect of cooling rate of 54SiCr6 steel in water and oil. Figure 3 shows that martensite is dominant structure in heat treated specimens. However, figure 4 show high magnification images. Although, martensite and bainite morphology appears in figure 4a and b. Upper bainite is defined as separated ferrite and carbide in parallel form, figure 4a. The rest of microstructure is dominantly martensite. Oil quenching, figure 4b, however, produced more interesting structure than water quenched specimens. The grain boundaries are clearly obvious and grain boundary ferrite (marked as GBF) exists along the boundaries in the form of either in continuous form or interrupted/discontinuous form; the GBF forms and grow into the grains until the Ms temperature is reached. It is noted that the shape of martensite is somewhat mixed. Figures 4c and 4d show water (Figure 4c) and oil (Figure 4d) quenched microstructures from 60SiMn5 steel.

In figure 4c, water quenching resulted in highly deformed plate like martensite as indicated but oil quenching generated fine mixed structure both lath martensite and plate like martensite with general appearance and light dark features. Below 0.6 wt.% C, lath type of martensite and above approximately 1 wt.% C, plate like martensite is observed to form, for 0.6 and 1 wt.% C range, it is a mixed martensite combination is suggested (Stormvinter, 2011).

Depending on cooling rates, for alloyed steels, lath martensite formation is expected in case of severe cooling, while slower cooling is expected to form plate type martensite. For low alloyed steels, the presence of martensite is in the form of large packets of martensite. However, the alloying elements addition creates finer martensite planes compared to low alloy or low C steel microstructures (Kitahara et al., 2006, Morito et al., 2009). In lath type martensite, lattice distortion appears to be the most effective mechanism (Morito et al., 2006; Morito et al., 2003), but in less severe structures, this change emerges as a wider range of martensite plate appearance with the shift of atomic planes which is forced to form twin martensite structure after quenching. Lath martensite is composed of multiple parallel martensite stripes and a group of such lenticular formations or rather packets are located in parallel, giving a high hardness and high mechanical strength to the steel. This is a classic appearance in C containing iron or steel structures whereas non-C containing martensite, usually plate form, is found in Fe alloyed with Cr, for example. Plate martensite has a midrib which is the starting point for the twining mechanism (Villa et al., 2014; Weidner et al., 2015; Loewy et al., 2014).

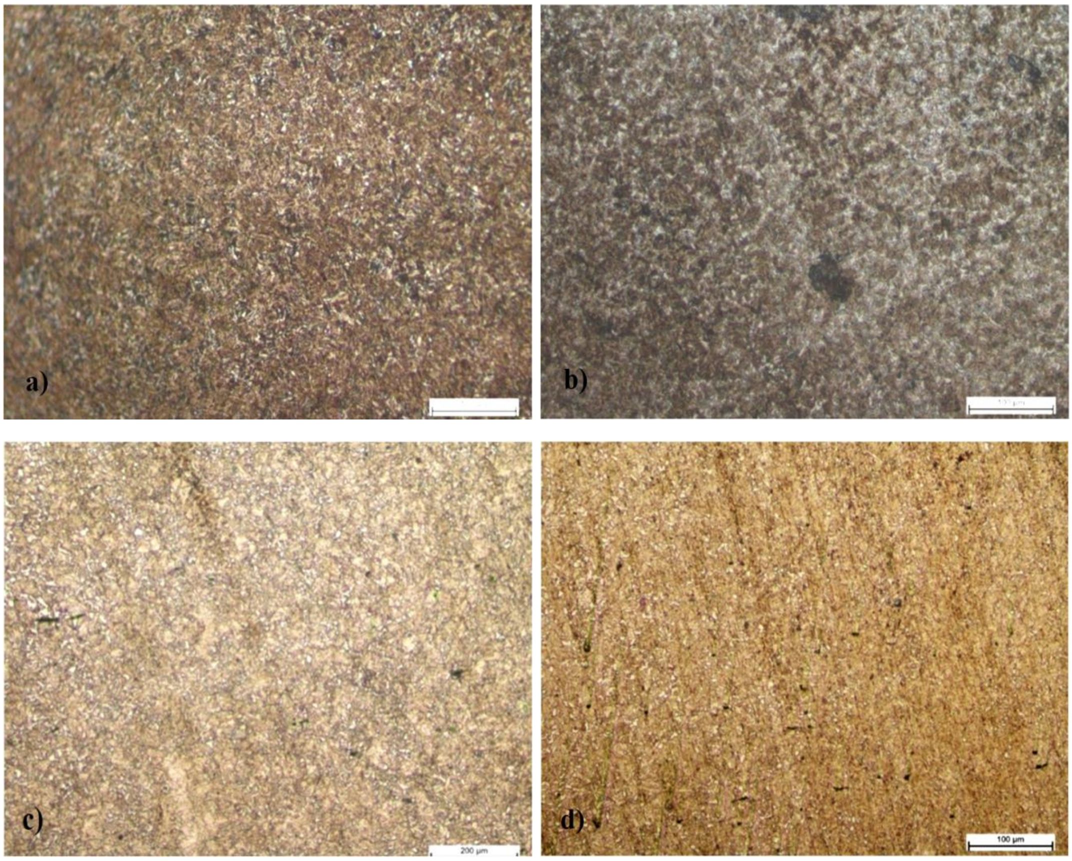

Figure 3. a) Water quenched, b) Oil-quenched, c) Water quenched and tempered d) Oil-quenched and tempered 54SiCr6 sample microstructure. The length of the measuring bars is 50 microns for a) and b)

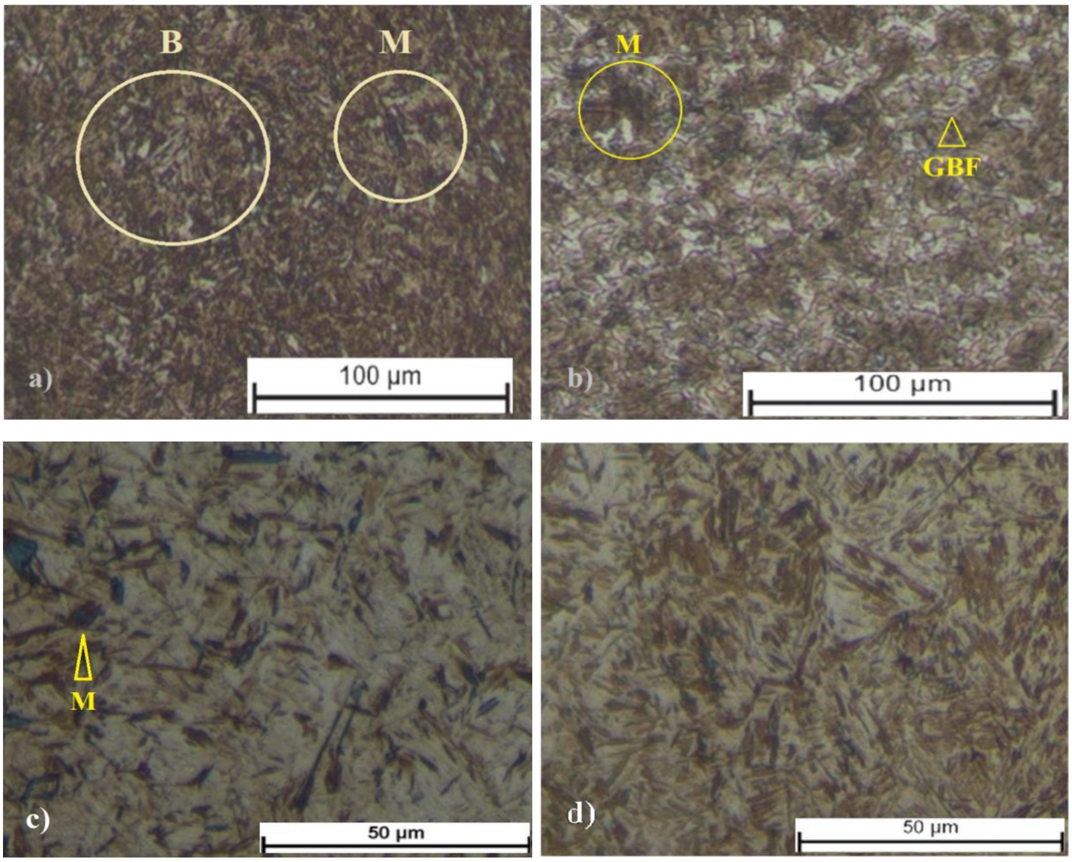

Figure 4. Microstructures from 54SiCr6 steel a) Water quenched images of b) Oil quenched specimen; Microstructures from 60SiMn5 steel c) Water quenched and d) Oil quenched specimens (M: Martensite, GBF: Grain Bundary Ferrite, B: Bainite)

3.3 Hardness Results

Table 2 shows that the hardness values are higher in the samples quenched in water in both steel specimens. When microstructures of both steels are examined (Figure 2 and Figure 3), it can be predicted that the martensitic structure is more evident in these samples. Detailed discussion of the effects of alloying elements on the formability of martensite is given in previous section.

Table 2. Hardness values obtained from the samples in HR_A unit

Specimen Code	**As received**	**Medium of cooling**			
		Water		**Oil**	
		Before Tempering	**After Tempering**	**Before Tempering**	**After Tempering**
60SiMn5	63.50	82.30	76.60	80.10	73.50
54SiCr6	60.30	75.80	74.20	72.20	71.40

The hardness values change according to the quenching environment and temperature in addition the content of alloying elements and most importantly C content (Tsuzaki and Maki, 1981). The main reason why these hardness values are different is that quenching provides more rapid cooling than oil cooling. Since the cooling rate is higher than the critical cooling rate, pearlitic and bainitic transformation is prevented and martensite structure is formed. Since the amount of martensite decreases when the cooling rate is low, the hardness of the oil-quenched samples is also less in steel with two different components of microstructures. The purpose of tempering is to comparably reduce the amount of hardness in the matrix of the solid solution alloy, emanating from the formation of martensite. In this study, the tempering is as expected prominent parameter in reducing the level of hardness of matrix due to quenching (Razzak, 2011). The amount of hardness drop in 60SiMn5 is higher than that of 54SiCr6 spring steels. This is due to the effect from Mn since Mn does not form directly carbides but generates solid solution hardening which in case of heat treatment becomes less effective. Mn also promotes carbide formation in steels resulting in the matrix softening faster than carbide containing matrix which preserves its hardness due to finely distributed carbides (Ghosh and Olson, 1994; Çalik, 2009; Mudasiru et al., 2014; Tsuzaki and Maki, 1981).

4. CONCLUSIONS

In this study, the microstructural and hardness values of water cooling i.e. quenching of 60SiMn5 and 54SiCr6 silicon spring steels in oil and water were studied with hardening treatment and followed by tempering at low temperatures. Following conclusions can be withdrawn from this study:

1. In both steels, the main microstructure in water quenching is less varied and the appearance of martensite emerges differently due to slow cooling in oil quenching. While the appearance of the martensitic structure that is treated with the tempering process changes little but, the hardness values change according to the quenching environment and tempering temperature as it is expected in other types of steels.

2. Quenching of 54SiCr6 steel provided various microstructures which mostly contain martensite in general compared to fully martensitic 60SiMn5. However, the effect of tempering is very pronounced in 54SiCr6.

3. The microstructural analysis showed that 54SiCr6 alloy contained a greater amount of ferrite structure on the grain boundaries than 60SiMn5 in as received condition. Pearlite+small amount of secondary phase structure appears dominant in both in as received microstructures.

4. The variety of microstructure in 54SiMn5 is less than that of 60SiMn5.

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