The Effect of Accelerated Cooling on Microstructure and Impact Strength of S355J2 Quality Steels Used in Power Transmission Line Construction

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Abstract Heat treatment is the most commonly used production step which can change the overall mechanical properties of the material without changing the chemical composition. Among the heat treatment methods, accelerated cooling has been regarded as one of the most important method for obtaining good mechanical properties. Today, this method is used in the manufacture of thin pearlitic steel, double phase steel, bainitic steel in the production process of many different quality and size products from construction bar to profile. In the scope of this study, investigations were carried out on S355J2 equal angles section profiles produced by hot rolling method. It was observed that intensive inclusions were found in all of the materials and the mechanical strength could not be met at low rolling ratios. Particularly, these materials with low impact resistance have been subjected to accelerated cooling process in order to increase their impact strength. As a result of the accelerated cooling process, significant increases in impact strength have been observed, particularly with the change of microstructure.

Keywords S355J2 Quality Steels, Accelerated Cooling, Microstructure, Charpy Impact Test, Fracture

1. Introduction

The accelerated cooling process has changed dramatically in the last three decades in steel production and has become a very important process. This process was first used in the 1960s to shorten the roll exit tables of hot rolled strips, but unexpected benefits were identified. In the determination of these benefits, an intensive research work has begun on this area, and this process has been examined under different perspectives. Changes in different alloying compositions and different cooling routes, which are

concentrated on alloy designs and process variations, have been examined. Many steel types, such as dual-phase steels, ferrite-bainite steels, and fine pearlitic steels, are the products of this process [1].

Especially after earthquake disaster on 17.08.1999 in Turkey, the toughness of the steels used in reinforced concrete structures became a matter of debate and some conditions were placed on these materials. One of them is that the ratio between tensile strength and yield strength of S420 grade steel bars cannot exceed 1.15. To achieve this, the yield value of the material must not exceed 420 MPa, but it must have a value of tensile strength so as not to exceed the rate. To achieve this, an accelerated cooling system called TempCore has been developed. The austenite bars passing through a water channel after the rolling rapidly cool their outer surfaces. Then, in the cooler, the heat in the core of the material moves rapidly towards the outer shell, resulting in a tough structure in the material. Thus, the steel bars achieve both the necessary yield strength and toughness [2, 3].

Accelerated cooling process is used to increase wear and fatigue resistance of pearlitic rails used in today's railway materials. The wear resistance of coarse pearlitic rails in the eutectoid compound known as R260 quality is insufficient in bends with a radius of curvature less than 2000 m. In this context, a special cooling regime was determined and the distances between the pearlite lamellae were reduced, resulting in improvement on yield and tensile strengths of the materials. In this way, the RS (rail surface) zone with 260-300 Brinell hardness reached 350-390 Brinell hardness and the yield strength increased from 880 MPa to 1175 MPa [4,5].

S355J2 grade steels are preferred as high strength structural steels used in the production of all kinds of machine and machine parts, general construction, road and railway vehicles. It is also classified as general structural steels [6, 7]. It is widely used from summer with

high-temperature environments to very harsh winter conditions. In Turkey, it is mostly needed in important applications such as energy transmission lines. In these steels, 27 J notch impact strength is expected at -20°C . The billets, which are the raw materials of the rolled steel sections, can be manufactured by the atmosphere-controlled casting method which prevents the liquid metal from air and the conventional open casting method in which the surface of liquid metal is in contact with air.

2. Materials and Methods

In this study, steel equal angle with dimensions of $100 \times 100 \times 10$ mm manufactured by hot rolling of S355J2 grade steel billets with 130×130 mm cross-section, which were produced by continuous casting method without any vacuum process which is called as open casting and which are not subject to air contact with liquid metal, were used. Accelerated quenching parameters have been determined to improve the impact strength of these materials, which cannot provide a value of 27 J, which is the limit for notched impact strength. The chemical composition of the used angle brackets is given in Table 1.

Table 1. Chemical composition of equal angle with a dimension of $100 \times 100 \times 10$ mm

Chemical Composition (wt.%)						
C	Mn	Si	S	P	Nb	V
0,12	1,36	0,20	0,01	0,01	0,0022	0,085

2.1. Heat Treatment

150 mm long specimens cut from equiaxed steel profiles were heated to reach the outlet temperature of 950°C and held at this temperature for 30 minutes to achieve a complete austenite phase. All of the equal angles heated to 950°C were taken from the furnace and placed in a device designed for accelerated cooling experiments as shown in Figure 1 and cooled with air + water mixture for 5, 10 and 15 seconds. During the cooling process, air + water mixture was used with 2.3 l/min water flow from each nozzle and the air is pumped with 5 atm pressures in total.

Figure 1. Accelerated cooling experimental setup

2.2. Microstructure Investigations

In microstructure studies, materials that have not been subjected to accelerated cooling process were first investigated. The effect of the open casting on the microstructure of the final product was determined. Afterwards, samples subjected to accelerated cooling process were examined and the differences between them were examined. To obtain microstructural images, samples were etched with 2% nital after sanding and polishing according to standard metallographic procedure. The microstructure images of the etched samples were taken with a Nikon Epiphot 200 model metal microscope. The samples for the inclusion control were examined with Carl Zeiss Ultra Plus Gemini FESEM without etching after polishing according to standard metallographic procedure. In this step, EDX studies were carried out in problematic areas and the composition of the inclusions in the material was determined.

2.3. Charpy Impact Test

The Charpy impact tests were carried out on the Zwick / Roell notch impact tester at a temperature of -20°C in the conditioning cabinet. The samples were taken from the location shown in Figure 2 according to EN 10025-1 standard and according to EN 10045-1 standard [8].

Figure 2. Location to take notch impact and tensile samples according to EN 10025-1 standard [8]

2.4. Tensile Test

The tensile test specimens were prepared according to EN 10025-1 standard, from the same position as the notch impact specimens, from the side surfaces of the brackets and according to TS 138 EN 10002-1. The Zwick / Roell universal test machine was used for the tensile tests of the samples.

3. Results and Discussion

3.1. Microstructure

In Figure 3, there are etched and unetched optical

microstructures of samples after accelerated cooling. In the un etched image, there were observed inclusions extending in the direction of the rolling. Ferritic and pearlite phases are observed in the microstructure.

Figure 3. Optical microstructures of (a) un etched and (b) etched samples.

In Figure 4, SEM studies were performed to specify the morphology and composition of the inclusions seen in the optical microstructures of the un etched samples in Figure 3(a). As it can be seen in Figure 4(a), there is a coarse and thin section extending in the direction of rolling, while in Figure 4 (b and c), there are circular and oblique inclusions. The EDX analysis results obtained from these inclusions are presented in Table 2. The elemental analysis results of regions 1 and 2 given in Table 2 show that there are oxides compounds which are rich in Si and Mn. Therefore, these compounds are thought to be SiO_2 and MnO inclusions.

Figure 4. SEM microstructures of the unetched sample taken from the locations having different inclusion morphologies

As it can be seen in Table 2, region 3 contains high

amount of O, Si, Mn and Al. The result of EDX analysis of region 4 shows that the inclusion is a rich oxide of Mg and Ca elements.

When looking at the SEM image in Figure 4(c) and the elemental analysis in Table 2, the high amount of Mn and S elements can be seen in region 5. This result indicates the presence of MnS inclusions in region 5. In region 6, Fe and O peaks are also present with C in high amounts.

Figure 5 shows the microstructure of the equal angles subjected to accelerate cooling for 5 seconds. Even though there are still inclusions in the surface, a great change has taken place in microstructure. According to the reference microstructures in ASM Handbook Volume 9, the microstructure of the material is reported to be in the form of bainite [9]. The accelerated cooling process, which was applied to the sample at a temperature of about 950°C with 2.3 l/min of water and 5 atm of air for 5 seconds. It transformed the unprocessed microstructure consisting of relatively coarse ferrite-pearlite grains into bainitic microstructure. The purpose of the accelerated cooling process is not to obtain a very hard phase such as martensite by suddenly and completely cooling the material, but to obtain phases such as fine pearlite or bainite.

Figure 5. Optical microstructures of the samples subjected to accelerated cooling for 5 seconds at (a) low and (b) high magnifications.

3.2. Mechanical Properties

As a result of the accelerated cooling process applied for 5 seconds, the yield strength of the as-received material increased from 422 MPa to a value of 438 MPa and the tensile strength increased from 525 MPa to 560 MPa. Prior to accelerate cooling, the elongation-to-fracture was obtained as 28.54 % and after the heat treatment process it increased to 34.7%.

Table 2. Chemical compositions of the regions indicated in Figure 4.

Region	Elements (wt.%)								
	C	O	Al	Si	Mn	Mg	S	Ca	Fe
1	3.0	46.3	0.9	19.3	29.1	-	-	-	-
2	3.7	38.2	7.6	16.1	23.4	-	-	-	-
3	3.8	43.3	9.6	17.7	20.8	-	-	-	-
4	18.2	51.4	-	0.1	0.4	8.9	-	17.9	-
5	4.1	-	0.2	-	61.6	-	28.8	-	3.5
6	45.0	18.6	0.6	-	0.5	-	-	-	32.8

As can be seen from Fig. 6, the impact strength of 11 J before heat treatment reached its maximum value of 105 J after accelerated cooling operation for 5 s, which is the most suitable exposure time. As the exposure time for accelerated cooling process increased above 5 s, the impact strength decreased rapidly. This is because the material lost too much heat and therefore with increasing exposure time and the undercooled material showed a brittle behaviour as presented in Fig. 7 (b).

Figure 6. Impact strength of the samples as a function of cooling time.

Figure 7. SEM micrographs of the fractured surfaces of the impact test samples subjected to accelerated cooling for (a) 5 s and (b) 15 s.

Figure 7 shows SEM images of fractured surfaces of impact test samples subjected to accelerated cooling for 5 s and 15 s. As can be seen from the SEM micrographs, the specimen subjected to heat treatment for 15 seconds exhibited a brittle fracture consisting of many cleavage planes while the specimen subjected to heat treatment for 5 seconds showed dimple type fracture. This indicates that the accelerated cooling sample exhibits a more ductile behavior for the sample cooled for 5 seconds.

As a result of the production of the steel billets which we can accept as the raw materials of the equal angles by open casting method, the final material contained high amount of inclusions. Both the presence of intense inclusions and coarse grain structure resulting from low rolling ratio caused poor impact energy on large size equal angles. Therefore, the use of a raw material free from inclusions and rolling the angles at a relatively high rolling ratio from billets having a larger diameter may suggest a solution. However, considering the cost parameter, it would be more economical to overcome the problems by an additional heat treatment process in the materials that already produced.

Experiments carried out in this study showed that the best result was obtained in 5 seconds among the specimens subjected to accelerated cooling for 5, 10 and 15 s. In this case, while there is a rapid cooling in the outer shell of the material, the heat in the internal structure quickly releases to the outer surface when the cooling process is interrupted and this generated a specific cooling regime forming the bainitic structure in the material. It can be deduced that this cooling time is only suitable for angles with dimensions of 100x100x10 and accelerated cooling times should be determined by making separate measurements for each profile size.

4. Conclusions

The general results obtained in this study, in which the mechanical properties of S355J2 quality equal angles with dimensions of 100x100x10 mm are changed by accelerated cooling for 5-15 seconds, are as follows:

1. In the structure of the investigated angles, extended and spherical inclusions in the direction of the rolling containing high Mn, Si, Al, Ca and Fe are found. It was observed that the sample subjected to the accelerated cooling process for 5 seconds had a bainitic structure while the microstructure of the as-received samples had ferrite + pearlite structure.
2. The mechanical properties of the specimens showed that their impact resistance during thermomechanical processing did not change depending on the accelerated cooling time. The impact strength of the as-received samples (11 J) increased to its maximum value (105 J) by accelerated cooling for 5 s and as the cooling time increased, it again decreased to the similar values as the as-received condition (21 J).
3. The sample subjected to accelerated cooling for 15 seconds showed brittle fracture behavior while the sample subjected to accelerated cooling for 5 seconds showed ductile fracture.

REFERENCES

- [1] A.J. DeArdo. Accelerated Cooling: A Physical Metallurgy Perspective, Canadian Metallurgical Quarterly, Vol.27, 141-154, 1988.
- [2] O. Celik. Investigation of Mechanical Properties of Ribbed Steels, Master Thesis, Karabuk University, 2015.
- [3] R. Abbaschian, R.E. Reed-Hill. Physical Metallurgy Principles, Cengage Learning, 2008.
- [4] S. Ozcelik. Investigation of Fatigue Behaviour of Head Hardened Rails, Master Thesis, Yıldız Technical University, Yüksek Lisans Tezi, 2013.
- [5] M. Başkonuş, E. Tekin. High Speed Train Case, Head

Hardened and Bainitic Rail Steels, International Iron and Steel Symposium, Karabuk, 2012.

- [6] Product Catalogue, Online available from http://www.erdemironline.com/Extranet/static/tr/static/Erdemir_Urun_Katalog.pdf
- [7] Product Catalogue, Online available from http://www.lucefin.com/wpcontent/files_mf/06s355j2ing45.pdf
- [8] TS EN 10025-1, Hot rolled products of structural steels - Part 1: General technical delivery conditions. Metalurji İhtisas Grubu; 2006. Online available from: <https://intweb.tse.org.tr/standard/standard/Standard.aspx?053107106111065067115113049116090107100056052055108081090071086075069085047110067109075073081116103090081086073108065117084119100066100080078116088108071079104108074071079104105070071070054077>.
- [9] G.F.V. Voort, ASM Handbook: Volume 9: Metallography And Microstructures, ASM International, Metals Park, Ohio, 2004.