The effect of different heat treatments on the mechanical properties of the steel forgings

Srba Mladenović[1], Jasmina Petrović[1]
[1]Technical Faculty in Bor University of Belgrade, VJ 12 19210 Bor Serbia[1]
smladenovic@tfbor.bg.ac.rs

Abstract: *The effect of different heat treatments on the microstructure and mechanical properties of the C45 and S355J2 steel forgings has been presented. Samples of the same forgings, but subjected to the different heating treatments, were prepared and tested by using optical microscopy, tensile machine, and hardness tester. It was observed that the requested mechanical properties of the forgings and uniform structure can be achieved by determining the appropriate heating treatment parameters.*
Keywords*: S355J2, C45 STEEL, FORGINGS, HEAT TREATMENT, PROPERTIES, MICROSTRUCTURE*

1. Introduction

Forging is a process in which the final shape of the work piece is obtained by compressive forces. This forces are applied through dies and tools by hammering or pressing the metal billet.

Classification of forging processes can be based on the temperature of the work piece and on arrangements of dies. When the temperature of the billet is above its recrystallization temperature than we have a hot forge process. Forging at room temperature is referred as cold, and forging at elevated, but below recrystallization temperatures is called warm. Open die forging is a process in which the flat dies of simple shape are used to deform material. In this process, there is no constraint to material flow in lateral direction. When the material is shaped to fill a die cavity formed by the upper and lower die halves, which are not completely closed and allow some material to escape (flash), than we have an impression die forging. Forging in which the material is fully constrained in the cavity formed by the die halves is define as closed die forging.

The grain microstructure of low and medium steels is dependent on recovery, recrystallization and grain growth mechanisms that occurs during the hot forging process. This mechanisms are affected by key forging parameters such as degree of plastic deformation, temperature, time and design of deformation passes [1]. Plastic deformation is responsible for the closure of the internal voids and for the reduction of non-metallic inclusions by breaking them into smaller particles and redistribute them uniformly [2]. High plastic deformation levels also contribute to reduce the thickness of segregated bands microstructure which is a common phenomenon in rolled-steel bars [3]. However there are some concerns regarding the microstructure of the forgings. Grain flow is preferentially oriented depending on the severity of the plastic deformation on the longitudinal or transverse axis of the forging. Furthermore, due to cooling rate variations a heterogeneous microstructure could be formed along the wall-thickness. Coarse grain structure can also be produced in the forgings.

Further improvement of the forgings mechanical properties can be achieved by heat treatment. The heat treatment (e.g. normalization, quenching, tempering) determines final microstructure and mechanical properties of the forgings. Normalization reduces the heterogeneity and microstructural anisotropy developed after the hot forging and refined the coarse structure. This treatment involves heating the material above it upper critical point (A_{c3}), holding it at austenitizing temperature until complete austenitization before being cooled in air. Quenching can be describe as follows: initially the material is heated to its austenitic range, then after the soaking time is over, the material is immersed in a quench medium to promote fast cooling in order to transform austenitic structure into meta-stable structures (martensite or bainite). This heat treatment can be regarded as a key technological process used in the forging industry to tailor the microstructure and properties of low and high alloy steels [4]. Tempering treatment is required after quenching process since the as-quench martensite is brittle, hard and consequently not suitable for structural applications. Tempering consists of heating the previously obtained martensitic structure to a determined temperature for a specific time period and the cooling in still air. The tempering time is calculated based on the thickness of the part, while the selection of the tempering temperature depends on the desired mechanical properties [5].

Design of heat treatment is consists in the definition of crucial parameters such as heat rate, temperatures, soaking times and cooling rates. The purpose of the present work is to show the effect of different heating treatment parameters on the mechanical properties and microstructure of the forgings made from hot rolled C45 and S355J2 steel bars.

2. Experimental

2.1. Forging

Hot rolled round steel bars were used as a starting material. The grade of the material was C45 and S355J2 according to EN10204/3.1. Chemical composition and mechanical properties of the material are given in table 1 and 2.

Table 1: *Chemical composition and mechanical properties of C45 steel bars*

Element	C	Mn	Si	P	S	Cr	Ni	Cu	Mo
Wt%	0,43	0,61	0,26	0,01	0,01	0,1	0,12	0,29	0,01
Tensile strength, MPa	Yield strength, MPa			Elongation, %		Impact toughness, KV, J (-20°C)			
677	434			22		73,3			

Table 2: *Chemical composition and mechanical properties of S355J2 steel bars*

Element	C	Mn	Si	P	S	Cr	Ni	Cu	Mo
Wt%	0,17	1,01	0,2	0,01	0,02	0,08	0,09	0,29	0,01
Tensile strength, MPa	Yield strength, MPa			Elongation, %		Hardness, HB			
517	369			28		197			

For the production of the forgings, impression die forging process was used. Three identical forgings were produced. First forgings was produced from C45 steel and the other two was produced from S355J2 steel.

2.2. Heat treatment

Finished forgings were subjected to different heat treatments. The first one was subjected to normalization treatment. It was heated in the chamber furnace, holded for some period of time and then slow air-cooled until its temperature drop to the room temperature. The temperature-time diagram of heating and holding of the first forgings is presented at fig 1.

Second forgings was normalized at 905°C, and then air-cooled, and third forgings was heated at 860°C, oil-cooled and after that it was subjected to tempering process in which it was heated at 420°C and then air-cooled.

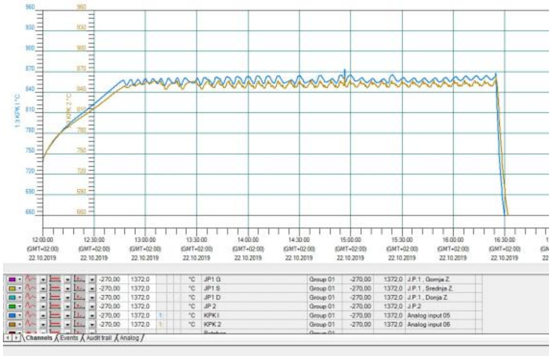

Fig 1. Heat treatment graph

2.3. Structure characterization

Tested forgings were cutted in small pieces and the samples were prepared from the surface and the central parts of the forgings (fig. 2.).

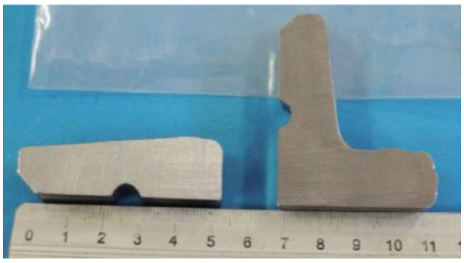

Fig. 2. Metallographic specimens

The preparation of the metallographic specimens for microstructural studies was carried out according to standard methods. The grinding papers of different roughness were used and polishing was carried out on a Al_2O_3 suspension with a polishing particle size of 0,3μm. The specimen were etched with a 4% solution of HNO3 in alcohol in order to reveal and identify its microstructure morphology. The exposure time was 4s, followed by washing and drying.

Microstructure analyses, for the first forgings, was performed with *„Leica DM 2700M“* light microscope equipped with Leica Grain & Phase Expert software package for materials analysis (fig. 3.).

Fig. 3. Leica DM 2700M light microscope

Microstructure of other two forgings samples were analyzed with Carl Zeiss Jena EPITYP 2 light microscope and for this samples average grain size was evaluated by applying the linear intercept method.

2.4. Tensile test and hardness measurements

Tensile test of the heat treated steel forgings were conducted on the cylindrical samples with a 6 mm diameter (type II following ISO 6892:1998) (fig 4). The tests were carried out at an ambient temperature.

Fig. 4. Specimens for tensile testing

The mechanical properties, namely the yield strength (YS), tensile strength (TS), plasticity (elongation), and hardness for the investigated steel forgings after the heat treatment, are given in table 3.

The tensile and hardness measurements were conducted at Technical faculty in Bor in laboratory for mechanical testing of the metal materials.

3. Results and discussion

The microstructure of the forgings 1 is shown in Fig. 6.

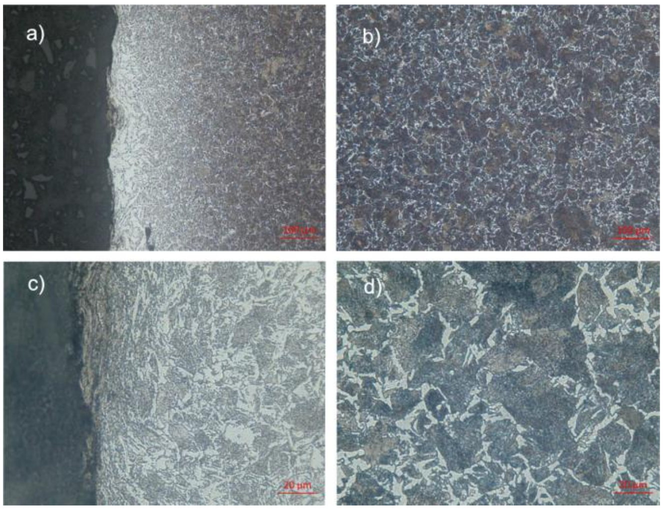

Fig. 6 Microstructure of first forgings a)100x and c)500x near the surface, b)100x and d)500x near the center of the sample, normalized at 860^{o}C for 4,5h and cooled in slow air

The sample has a predominantly pearlitic normalized structure with partially reticular arranged perlite. The microstructure are homogenized and pure. Light area at the surface of the sample (shown at figure 6a), can indicate that in this region maybe it came to the decarburization process. Blaoui et al. [6] studied the influence of cooling rate during the heat treatment on microstructure of the C45 steel. They found that the sample quenched in air after it was heated to 900^{o}C has combination of ferrite and pearlite with a low amount of spheroidal graphite. But the holding time was only 30min. Fadare et al. [7] investigated the efect of heat treatment on the microstructure of NST 37-2 steel. The steel samples were heat treated at different temperature levels and holding times, and then cooled in different media. It was observed that beside pearlitic matrix the structure contains graphite flakes.

After forging process a coarse grain structure is produced in the parts thanks to high forging temperature that was employed during the hot working operations. Coarse structure is refined after normalizing process. Average grain size, for forgings 1, evaluated by Leica Grain & Phase Expert image analyzer software is found to be 11 as it can be seen on photos that are presented on figure 7a. and 7b. for sample near the surface and near the center of the forgings, respectively.

The strength values for forgings 1 presented in table 3 are higher than those obtained for the starting material. The mechanical properties of the normalized specimen were found to be 780MPa, 489MPa and 21% for tensile strength, yield strength, and percentage elongation, respectively. The increase in tensile strength as compared to starting materials was due to proper normalization parameters which resulted in formation of pearlitic matrix structure.

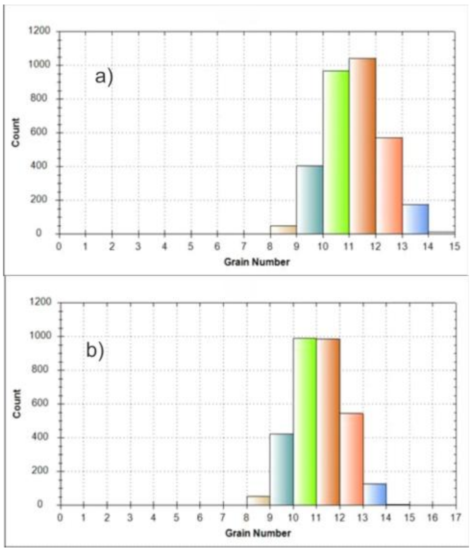

Fig 7. Determination of grain size by Leica Grain & Phase Expert software

The microstructure of forgings two and three are shown in figure 8 and 9 respectively.

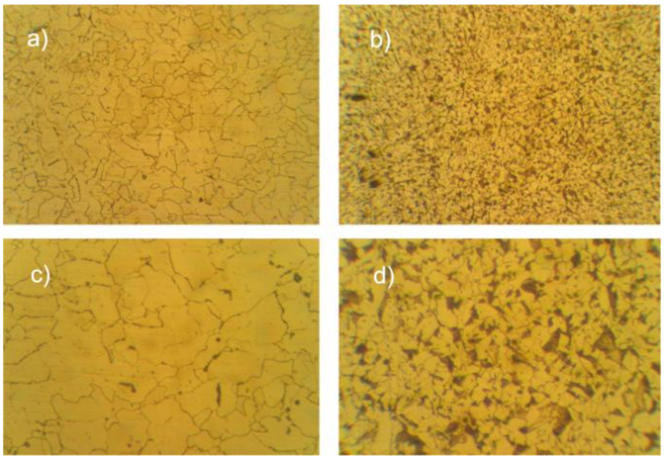

Fig. 8. Microstructure of second forgings a)100x and c)500x near the surface, b)100x and d)500x near the center of the sample, normalized at 905^{o}C, 1h for itch 2,5cm of forgings thickness and cooled in slow air

Microstructure of forgings 2, presented on figure 8 consists of ferrite and pearlite. The samples material was clean regarding nonmetallic inclusions.

The strength values for forgings 2 are presented in table 3. The limited values requested from the customer were 490-630MPa, min. 345MPa, min.20% and hardness 140-187HB for tensile strength, yield strength, percentage elongation, and hardness respectively. Obtained values, after the heat treatment, were on lower limit for tensile strength and hardness, and lower for yield strength.

Considering that forgings 3, was heated at 860^{o}C and then cooled in oil at intermediate cooling rate, microstructure was probably a mixture of lower bainite and martensite. Tempering process, conducted after the heating and oil cooling of the forgings 3 has influenced on transformation of martensite and formation of ferrite and carbide (fig. 9).

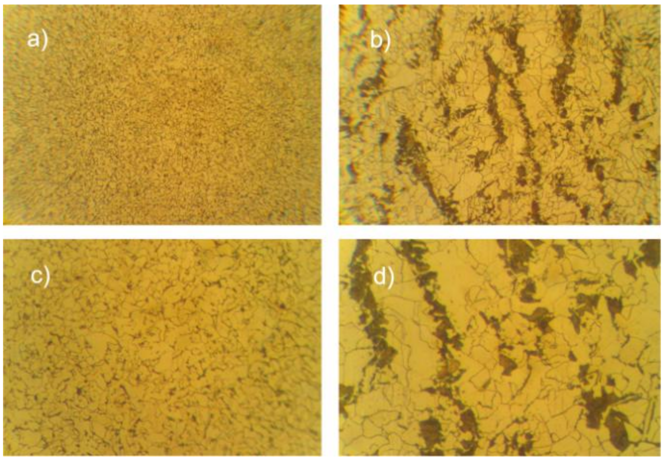

Fig. 9. Microstructure of second forgings a)100x and c)500x near the surface, b)100x and d)500x near the center of the sample, heated at 860^{o}C, 1h for itch 2,5cm of forgings thickness, oil-cooled, and tempered at 420^{o}C and finally air-cooled.

The strength values for forgings 3 are presented in table 3. The limited values requested from the customer were 490-630MPa, min. 345MPa, min.20% and hardness 140-187HB for tensile strength, yield strength, percentage elongation, and hardness respectively. Obtained values, after the heat treatment, were are higher than those requested from the customer.

Table 3: *Mechanical properties of forgings after heat treatment*

	Tensile strength, MPa	Yield strength, MPa	Elongation, %	Hardness, HB
Forgings 1	780	489	21	
Forgings 2	495	297	34,3	145
Forgings 3	520	366-	33,3	168

4. Conclusions

The effect of the high-temperature heat treatment on the mechanical properties and microstructure of the C45 and S355J2 steels forgings have been presented. Despite the improvement on its properties after forging, sometimes forgings cannot be used in the "as-forged" condition since the microstructure and mechanical properties are still not within the specification requirement.

Applying the heat treatment leads to increase the strength of low and medium carbon steels. Different cooling rates result in different phases during a treatment process. The tensile strength, yield strength and hardness decrease with the increase of the holding time.

However, if all the heat treatment parameters are design properly the inappropriate heat treatment conditions (control of temperature and atmosphere inside the furnace e.g.) can be a cause for developing undesired mechanical properties and processes (decarburization e.g.).

5. Acknowledgment

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6. References

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