THE INFLUENCE OF HEATING TEMPERATURE AND COOLING RATE AFTER FREE FORGING ON THE MICROSTRUCTURE AND THE MECHANICAL PROPERTIES OF AISI4140 STEEL

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The modern technique of free forging imposes new requirements for the obtained semi-finished forgings, each operation requiring time, energy, human and financial resources. In order to evaluate this process, the importance of the application of primary heat treatments after free forging a part on a 1200 tf hydraulic press was put in evidence, the studied material being a heat trated AISI4140 steel. Both types of heat treatments (full annealing and normalizing), lead to hardness values and mechanical characteristics according to ASTM A29/A29M standard, meaning that their application is required after free forging or molding operations.

Keywords: AISI4140, free forging, microstructure, mechanical properties

1. Introduction

Forging is a technological process for processing metals and alloys (in a plastic state) under the action of dynamic (shock) or quasi-static external forces.

Forging operations may be classified as follows:

1. free forging, in which the material flow is guided by the deformation anvils and some simple tools,
2. forging in a mold (molding), in which the material deformation takes place in some tool cavities called molds, so that in the end the part will take the shape of the cavity (which is the negative of the part) [1-5].

Generally, after forging, the parts are subjected to processing by chipping and heat treatments in order to bring them to the required shape, precision and characteristics [6-7]. There are also parts that do not undergo any processing after forging, this being actually the current trend [8].

The material capacity for being processed by forging is appraised by forgeability, which implies deformation resistance and deformability [9-11]. The

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level of forgeability is higher as the deformation resistance is lower and deformability higher. Forged metallic materials are those materials that can be deformed plastically by any of the two forging processes. The main forging materials include ferrous and non-ferrous alloys [12-15]. Ferrous alloys can also be divided in carbon steels and alloyed steels, and non-ferrous materials, in heavy metals and alloys and light metals and alloys. From a practical application point of view, the most widespread ferrous alloys are carbon steels [16].

In order to make them easily deformable, the most frequently used materials are steels with a carbon content up to 1.4%. Above this limit, they become difficult to forge. In the category of forgeable carbon steel are included OL ordinary carbon steels and OLC quality carbon steels. Another class of forging materials is that of alloy steels for machine building, refractory steels for springs, steels for bearings and other special steels [17-18]. The presence of some chemical elements in the steel composition influences their deformation behavior [19]. The standard that regulates the mechanical characteristics and the chemical composition of AISI4140 steel is ASTM A29/A29M. The chemical composition of the steel is given in Table 1.

Table 1

The chemical composition of the AISI 4140 steel

STANDARD	RANK	C%	Mn%	P%	S%	Si%	Ni%	Cr%	Mo%
ASTM A29/A29M	4140	0.38-0.43	0.75-1.00	< 0.035	<0.040	0.15-0.35	0.0	0.8-1.10	0.15-0.25
EN 10250-3	42CrMo4	0.38-0.45	0.6-0.9	< 0.035	<0.035	< 0.4	0.0	0.9-1.2	0.15-0.30
JIS G4105	SCM440	0.38-0.43	0.6-0.85	< 0.03	<0.03	0.15-0.35	0.0	0.9-1.2	0.15-0.30

This may vary depending on the obtaining method, but without exceeding the ranges provided by the standard. The samples for mechanical tests were shared according to the following considerations:

1. Small pieces not exceeding 500 mm^2 in section, taken longitudinally along the forging axis;
2. For sections smaller than 100 cm^2 samples can be cut from the entire transverse section of the piece, starting from the forging axis 0 up to half the distance to the surface.
3. For part sections having a diameter of more than 100 cm^2, the sample diameter will be maximum Ø25 mm and the sample sectioning method is shown in Fig. 1.
4. The number of samples on the drafting / forging batch depends on the shape of the forged parts and the applied heat treatments.

Thus, for parts up to 15 tons, 4-6 samples can be taken for mechanical tests (unless otherwise agreed with the customer).

The austenitic grain size is determined according to the E112 Test Method (if at least 70% of the grain sizes fall within the class requirements of the standard, it can be considered an acceptance basis) [20]. The analysis of the temperature variation regarding heating and cooling can influence the mechanical characteristics and the size of the austenitic grain so that inadequate heating and cooling can lead to austenitic grain growth, inadequate ferrite/perlite ratio, cracks during the use of the work piece or even during mechanical processing.

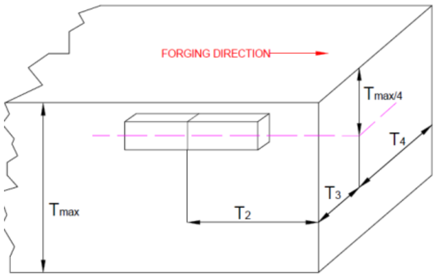

Fig. 1. Sampling method for forging AISI4140 (in this case $T_2=T_3=T_4 \geq T_{max}$; where T_{max} - the maximum section of the piece).

AISI4140 is a chromium-molybdenum alloy steel used in making axes, bolts, gears, shafts, etc. It is to be found under different steel grades, according to region and standard, with small variations of the chemical composition, as shown in Table 2. The forging temperature range is between 1150 - 1200°C and forging below 850°C is forbidden [21-25].

Table 2

AISI 4140 depending on the origin region

ZONE	USA	GERMANY	UK	JAPAN	CHINA	AUSTRALIA
STANDARD	ASTM A29	DIN17200	BS970	JIS G4105	GB/T 3077	AS 1444
RANK	4140	42CrMo4	42CrMo4	SCM440	42CrMo	4140

The primary heat treatments for AISI4140 may be:

- full annealing after forging consisting in heating at 700-820°C followed by furnace cooling;
- normalizing: heating at 820-900°C followed by air cooling;
- normalizing + sub-critical annealing (heating at 550-650°C, holding time 1 hour/25mm section followed by air cooling).

The secondary heat treatment may also be:

- normalizing + sub-critical annealing (heating at 450-550°C, holding time 1 hour/25mm section followed by air cooling) or
- quenching (heating at 820-900°C, holding time 10-15 min /25 mm section followed by rapid cooling in water, oil or polymer) + high temperature tempering, hardness control being required [26-27].

2. Experimental

The goal aimed by the application of the two types of primary heat treatments is the modification of the structure of the forged semifinished products and the improvement of the mechanical characteristics. The two types of primary heat treatments applied were:

1. Full annealing (heating at 700-820°C, holding time 1 hour/25mm section followed by furnace cooling) applied to samples 1 and 2.
2. Normalizing (heating at 820-900°C, holding time 1 hour/25mm section followed by air cooling) applied to sample 3.

The need to apply these two types of primary heat treatments is: removing the rough forged structures, decreasing austenitic grain size, improving machinability of forged semi-finished products, removal of internal stresses resulting from free forging, elimination of susceptibility to cracking during mechanical machining, superior characteristics and wear resistance after secondary heat treatments.

In order to investigate the effect of application of the two heat treatments, samples of 45 mm diameter and 250 length were taken and have undergone heat treatments with different cooling regimes.

According to ASTM A29, many samples of 8 mm length and 14 mm diameter were taken (marking and sampling is shown in Fig. 2).

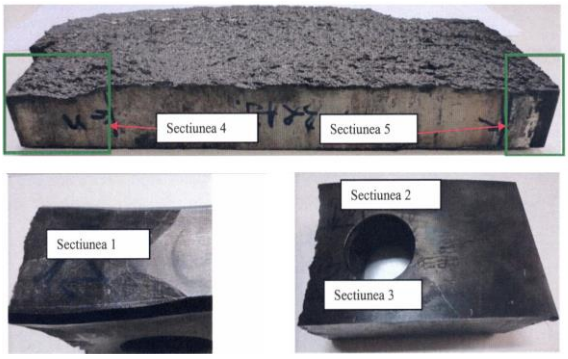

Fig. 2. Sampling of the steel specimens

The samples were used to check the alloy chemical composition and determine the size of the austenitic grain when reheating followed by slow or rapid cooling (the oxidation method was used).

Forging was performed on a 1200 tf press at a maximum deformation rate of 1:2 and a forging temperature of 1100 -1150°C.

The chemical composition of the samples submitted to tests are given in Table 2. Its analysis was carried out on alloy batch no. 83377 and heat treatment lot, the used equipment being Spectrolab M10/76004135 in accordance with LAR-PL-01 Rev.03 ASTM E415-14.

Table 2

Chemical composition of analyzed samples

Mark	C%	Si%	Mn%	P%	S%	Cu%	Ni%	Cr%	Mo%	V%	Al%	Ti%
Samples AISI4140	0.44	0.31	0.96	0.009	0.002	0.16	0.16	1.04	0.17	0.03	0.025	0.003

3. Results and discussions

3.1 The effect of different heating and cooling parameters on the alloy grain size

The correlation between the heating temperature and the grain size is: an increase in the grain size is found when increasing the temperature or when varying the chemical composition. Rapid and non-uniform cooling leads to the appearance of a relatively rough structure, as shown in Fig. 3.

In this case, the grain size varies from 0 to 5, according to SR EN ISO 643-2013. The grain size was determined by the oxidation method, and the obtained score was 7.

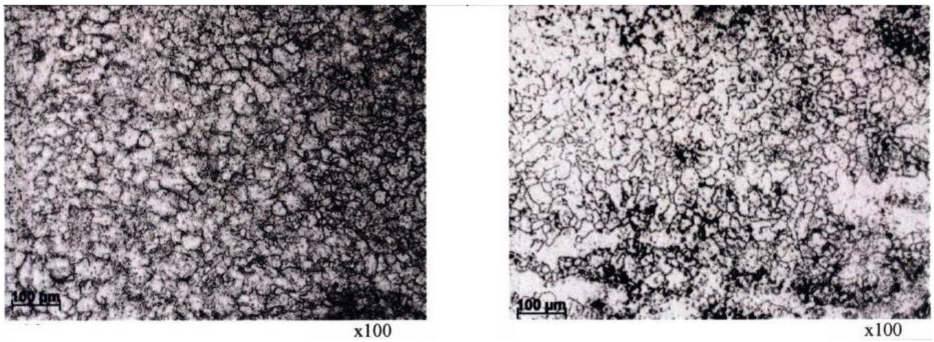

Fig. 3. Size of hereditary grain by the oxidation method

3.2. The effect of different heat treatment parameters on the alloy microstructure and mechanical characteristics

Fig. 4 shows the macroscopic features under two states: a- forged semi-finished product and b - annealed semi-finished product, previously forged. It is to be noticed that after forging, the grain size distribution is relatively rough and inhomogeneous at the base, as compared to the sample submitted to primary heat treatment.

The microscopic analysis performed in the first raw forged section (shown in Fig. 5) reveals the existence of isolated non-metallic inclusions such as sulphides and oxides of small size. These may have a negative effect along the mechanical processing (causing micro-fissures, deformations of the workpiece under mechanical force or processing temperature etc.) and by decreasing the working life of the finished product as a result of premature wear, superficial corrosion of the parts, a.s.o.

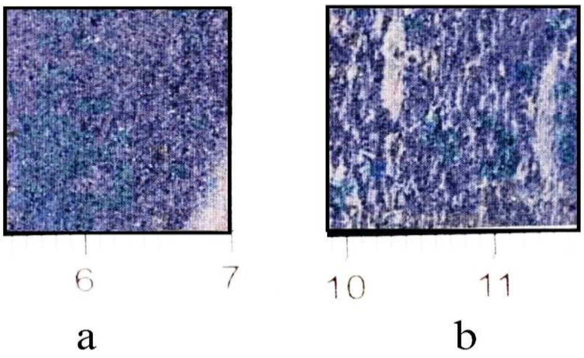

Fig. 4. The macroscopic aspect of the analyzed section

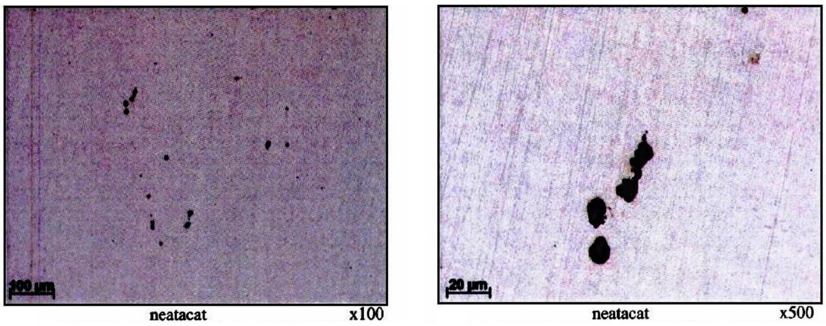

Fig. 5. Isolated metallic inclusions

Several microscopic analyses were performed on the above-mentioned samples, highlighting the following conclusions:

In Fig. 6 the microstructure is made of lamellar and spheroidized perlite, a small proportion of ferrite and bainite. In some areas grains having grain size 1 have been identified. The grain size distribution is relatively inhomogeneous, ranging from 1 to 5, according to SR EN ISO 643-2013. The heat treatment applied after forging was full annealing: heating at 700-820°C, holding time 1 hour/25mm section followed by furnace cooling.

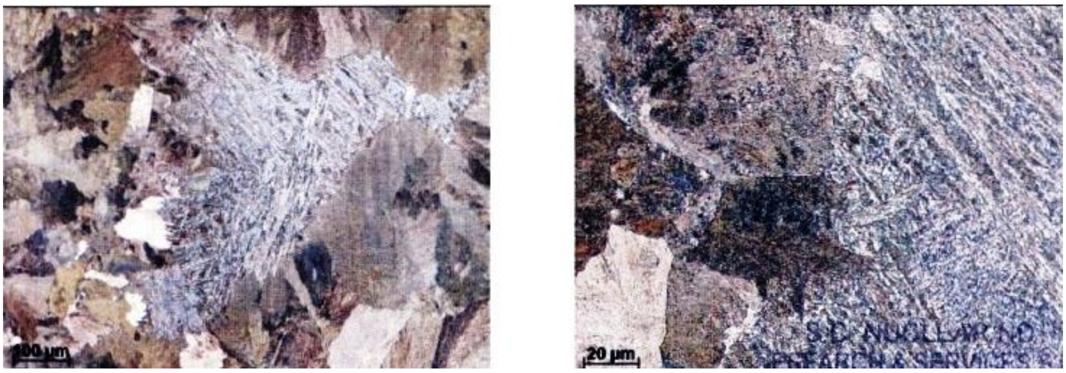

Fig. 6. Microstructure of the analyzed samples - sample Nr. 1 (Nital 2%, ×100 and ×500). Heat treatment applied after forging: full annealing (heating at 700-820°C, holding time 1 hour/25mm section followed by furnace cooling).

In Fig. 7 the microstructure exhibits lamellar and spheroidized perlite, a small proportion of ferrite and bainite. The grain size is slightly inhomogeneous, ranging from 1 to 5, according to SR EN ISO 643-2013. On the inner surface of the forged piece there is a slight decarburization. The heat treatment applied after forging was full annealing: heating at 700-820°C, holding time 1 hour/25mm section followed by furnace cooling.

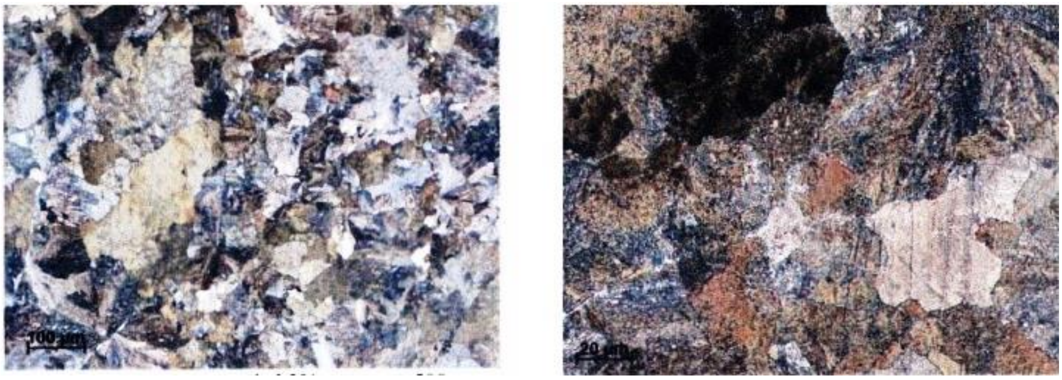

Fig. 7. Microstructure of the analyzed samples - sample Nr. 2 (Nital 2%, ×500). Heat treatment applied after forging: full annealing (heating at 700-820°C, holding time 1 hour/25mm section followed by furnace cooling).

Fig. 8 shows an inhomogeneous microstructure made of lamellar and spheroidized perlite, a small proportion of ferrite and bainite. The structure is characteristic of a forged part, air cooled. In some areas of segregation, large pearlite and bainite grains (grain size 0) were found. The grain size distribution is inhomogeneous, ranging from 0 to 5, according to SR EN ISO 643-2013. Heat treatment applied after forging: normalizing (heating at 820-900°C followed by air cooling).

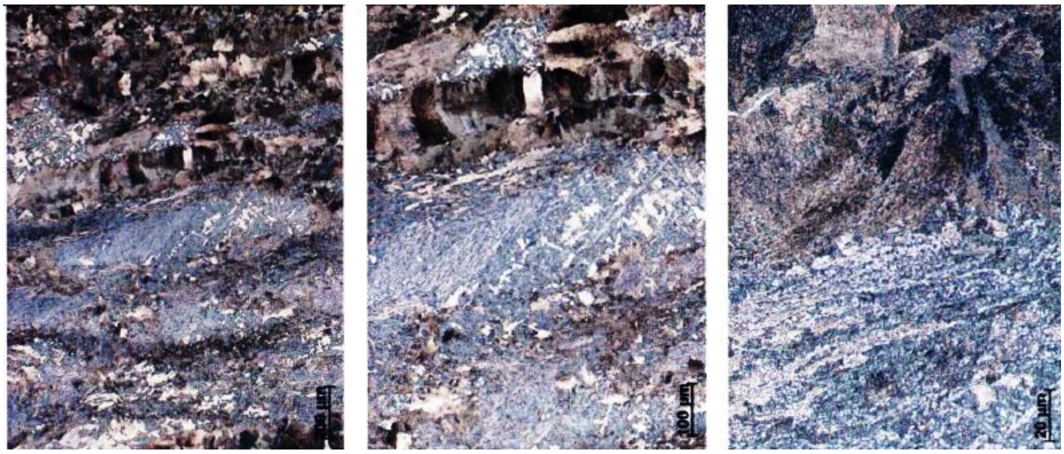

Fig. 8. Microstructure of the analyzed samples - sample Nr. 3 (Nital 2%, ×50 / ×100 / ×500). Heat treatment applied after forging: normalizing (heating at 820-900°C followed by air cooling).

Pearlite is a mechanical mixture of ferrite and cementite. The two phases are simultaneously separated under equilibrium conditions at 727°C from austenite of eutectoid concentration of 0.77% C when slow cooling. According to the microscopic aspect, the lamellar pearlite found in the analyzed samples may be characterized as follows: cementite lamellae are trapped in a mass of ferrite, appearing when slow cooling from temperatures higher than the eutectoid transformation temperature (at the end of the transformation it exhibits a digital finger print feature). On some surfaces, spheroidized perlite in the form of globules in a metallic mass is found. This constituent resulted from spheroidizing annealing (soaking) of the lamellar perlite gives the best machinability. The bainite resulting from carbon supersaturated ferrite "α" and fine globular carbides Fe_xC is formed not only at temperatures close to the kinetic maximum in the alloy TTT diagram (minimum stability of austenite), but also at low temperatures above the M_s point (of the Fe-C diagram), having a relatively acicular structure similar to martensite. The relatively high resistance of bainite is due to the ferrite crystals small sizes, to the carbide precipitates dispersion, to the ferrite network distortions due to carbon supersaturation.

Fig. 9 presents the locations where the VICKERS hardness test was performed on the forged part, according to SR EN ISO 6507-1 / 2006. The HV10 hardness test was performed on three axial lines of the sample and the obtained values are shown in Table 3.

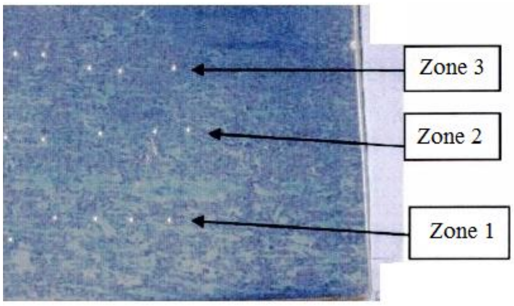

Fig. 9. Hardness test in 3 distinct areas after application of the heat treatment: normalizing (heating at 820-900° C followed by air cooling, holding time 1 hour/25mm section followed by air cooling).

Table 3

Test for VICKERS hardness in three distinct zones

Nr.	**Zone Test**	**VICKERS hardness results**					**HV10**	**Conversion according to SR EN ISO 18265-2014 HRC**
		1	**2**	**3**	**4**	**5**		
1	Zone 1	262	264	262	260	254	**260**	**24**
2	Zone 2	260	254	262	258	262	**259**	**24**
3	Zone 3	256	249	256	256	254	**254**	**23**

Concerning the traction test, a 20 tf - 1033/91 universal mechanical testing machine was used, and the tests were carried out after performing the primary heat treatment on the semi-finished products, according to SR EN ISO 6892-1/2010 _ (method B). The results are shown in Table 4.

Table 4

Tensile testing

Marking	**Direction of sampling**	**Type of specimen**	$R_{p0,2}$ YS (PS) [MPa]	R_m UTS [MPa]	**A** EL [%]	**Z** RA [%]
731 T	Long.	Ø10 mm	512	843	15.4	31.1
Required values			≥ 500	≥ 750	≥ 14	

6. Conclusions

The purpose of the experimental research presented in this paper was to analyses the effect of some primary heat treatments performed on forged raw semi-finished products and to establish the importance of this heat treatment, an evaluation of the final macrostructure and microstructure having been made. One may see that: 1. The variation of the size of the austenitic grain depends on the concentration of the alloying elements and on the heat treatment temperature, and for the steel grade forged at 1150°C a rough structure made of lamellar perlite, bainite and ferrite in small proportions was found.; 2. After the application of the full annealing heat treatment (heating at 700-820°C, holding time 1 hour/25mm section followed by furnace cooling), there is an improved structure of the semi-finished products, favorable to mechanical processing, because this structure makes it no longer prone to cracks or to intergranular damage.; 3. The improvement of the mechanical characteristics depends on the way the free forging and primary heat treatment operations are performed: full annealing (heating at 700-820°C, holding time 1 hour/25mm section followed by furnace cooling), according to AISI4140, after which the characteristics of the semi-finished product perfectly meet the requirements of the quality standards.

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