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Effect of Cooling Rate on the Microstructure and Mechanical Properties of Low Carbon Steel

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Abstract

This paper reports the effect of cooling rate on the microstructure and mechanical -properties of a kind of low carbon steel microalloyed with V and Nb content (0,01%and0,0164%) after hot deformation by using real forging experiments. The results show that cooling rate has a significant effect on the microstructure, yield strength, tensile strength and impact energy of the P285NH steel. The accelerated air cooling with 1,48 ºC/s cooling rate yielded to the formation of mixed structure with acicular ferrite and bainitic ferrite which resulted higher tensile strength and lower toughness. In this case, the normalization step was needed to obtain higher toughness which customer's demand.

Keywords: hot forging, cooling rate, accelerated air cooling, direct cooling, microalloyed steel

1 INTRODUCTION

Hot forging is a classic and also widely diffused industrial process. Every year in Europe, millions of tons of steel parts are produced by hot forging processes [1]. In metal forging process the quality and performance of the forged product is heavily dependent on various parameters such as grain size, austenization temperature and cooling rate after hot forging. The cooling rate after finishing deformation stage has a significant effect on the mechanical properties establishing final microstructure which controls the mechanical properties. Higher cooling rates give rise to a decrease of ferrite amount and an increase pearlite amount causing high strength, hardness, dislocation density, and fine phases because it suppresses the atomic diffusion. But it causes a decrease impact toughness. On the other hand, slow cooling results soft, coarse and less dislocated phases like polygonal ferrite and less amount of pearlite resulting higher toughness [2]. The size and percentage distribution of ferrite and pearlite within the microstructure play an important role on the final mechanical properties [3]. Required strength levels can be provided via controlled evolution of microstructure and substructure by governing of cooling rate.

In conventional hot forging processes, forged parts are cooled to room temperature in large boxes putting on top of each other. This kind of cooling is called batch cooling (BC) and followed by normalization step. This procedure wastes the thermal energy available in the hot forged parts, hence requiring their reheating for subsequent normalizing [4]. Low alloy steel can attain acceptable properties for many applications following hot forging either via cooling freely in air, or through direct quenching [5]. Direct cooling processes allow to eliminate reheating and normalization step [6]. In comparison to conventionally processed quenched and normalized steels, direct-cooled low alloy steels offer the potential for significant cost savings [7].

This is a part of an industrial project. A hot forging company wants to guarantee the yield strength and ultimate tensile strength at room temperature as well as impact test at -20 ºC for a pressured vessel component. The present investigation was aimed to process optimization for the component. Basically, the effect of cooling rate after hot forging on the microstructure and mechanical properties of low carbon steel P285NH was studied. The different mechanical properties like yield strength, ultimate tensile strength, impact strength and hardness obtained were correlated with microstructure using high magnification optical microscope. At the same time, the continuous cooling transformation (CCT) diagram was calculated using the JMatPro (Sente Software Ltd., Guildford, UK) software [8]. This package was also used to monitor the evolution of potential phases. Finally, the correlation between the experimental and numerical studies was discussed.

2 MATERIAL AND METHODS

The material used in the study was low-carbon microalloyed steel grade P285NH (Tab. 1). The material was received in as-hot rolled condition with reduction ratio 17:1.

1. Table: Chemical composition of microalloyed steel P285NH used in the study

C	Si	Mn	P	S	Cr	Mo	Ni	V	Al	Cu	Sn	Nb
0,10	0,20	1,08	0,009	0,002	0,13	0,01	0,07	0,01	0,025	0,04	0,003	0,0164

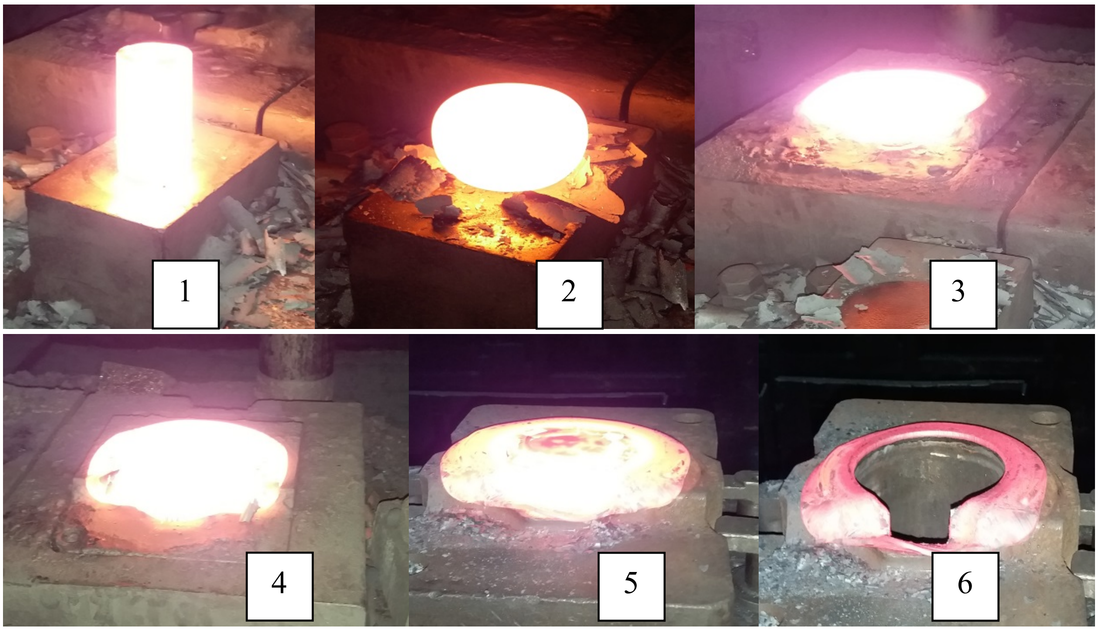
The specimens were cut out from as-received bars and heated up to 1150-1200◦C in an oxidizing atmosphere (air), soaking up for 10 minutes and cooling down to forge-finish point. After the heating cycle was completed, the ingot was forged on a 1600 - ton mechanical open die and forging operations were completed with 6 steps (Fig. 1). After hot deformation the specimens were subject to accelerated air cooling (AAC) without mist by cooling of separate forged parts on the conveyor to evaluate the effect of controlled cooling against batch cooling (BC) inside the heap of forged parts in a box which is most common traditional cooling way in hot forging industry. For comparative studies, samples subjected to normalization process for both BC and AAC. After normalization, samples cooled by batch cooling, named respectively BC-N and AAC-N. For normalization, samples were heated up in four steps (780 oC, 865 oC, 870 oC, 930 oC) for 8-hours. Samples were removed from the furnace at avr.870 oC, waited for 10 min and transferred to air batch for cooling down to room temperature.

In order to control the cooling rates of specimens precisely and to pursue the homogenous microstructure during cooling, pyrometer measurements were maintained for tracing the actual forging temperature and the cooling rates were calculated by measuring the temperature of specimens after exiting of furnace. The temperature of the billets during deformation was also recorded by the same pyrometer. Table 2 shows 4-different thermomechanical states used for investigation of the effects of forging parameters.

2.Table: Four different thermomechanical states used for investigation on the effects of forging parameters

	Cooling rate, ºC/s
Batch Cooling (BC)	0,373
Batch Cooling (BC) + Normalization (BC-N)	0,373 + 0,21
Accelerated Air Cooling (AAC)	1,48
Accelerateded Air Cooling + Normalization (AAC-N)	1,48 + 0,226

The part is manufactured as a pressured vessel component for a company (Fig.2) and according to the standards required by the company the yield strength must be above 245 (N/mm2), the tensile strength must be in the range of 390 - 510 (N/mm2) and the impact energy must be above 40 joules at -20°C.



1. Figure: Forging steps

2. Figure: Final part after finishing operations

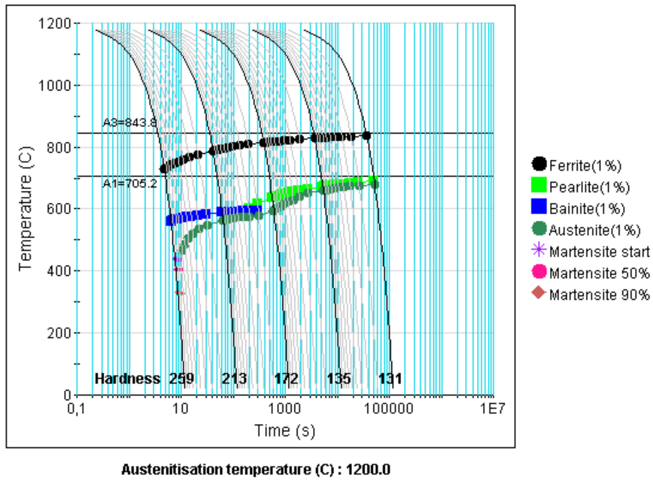
Tensile tests were performed on a Universal tensile-testing machine (INSTRON 1195), at a crosshead speed of 20 mm/min. Yield strength (YS), Ultimate tensile strength (UTS) and Elongation to failure (%El) were measured. The Charpy tests were carried out at -20°C temperature. Rockwell B indentation experiments were performed to determine the effects of heat treatment conditions on the mechanical properties. Samples for metallographic analysis were prepared by mechanically grinding and polishing. Etching of samples was performed by nital solution. Metallography analysis was performed using scanning electron microscopy (SEM) method. Grain size was measured by means of Clemex professional edition image analyzer software.

With the JMatPro program, CCT chart was obtained by introducing a given composition, austenisation temperature and grain size into the program where the austenite grain size was taken as 33 µm. Obtained chart is shown in Fig. 2. JMatPro also incorporated a capability to calculate transformations involving ferrite, pearlite and bainite in steels closely based on the model of Kirkaldy [9].

3 RESULTS

The CCT curves of the P285NH alloy are given in Figure 3. As it is seen that while A3 is 843,3 oC, A1 is 705,2 oC. Table 3 shows the calculated phase percentages and HRB hardness values after complete cooling to ambient temperature. As it is seen that BC and AAC yielded almost same hardness, respectively 82 and 83 HRB. The normalizing process gives raise to increase in ferrite amount and decrease the hardness. After normalization, no matter how batch cooling or accelerated air cooling, microstructure showed almost same ferrite and pearlite fractions with lower grain size. The austenite to ferrite transformation, cooling rate and different ferrite morphologies are important because by controlling of these parameters, the mechanical properties of steel are improved.

CCT



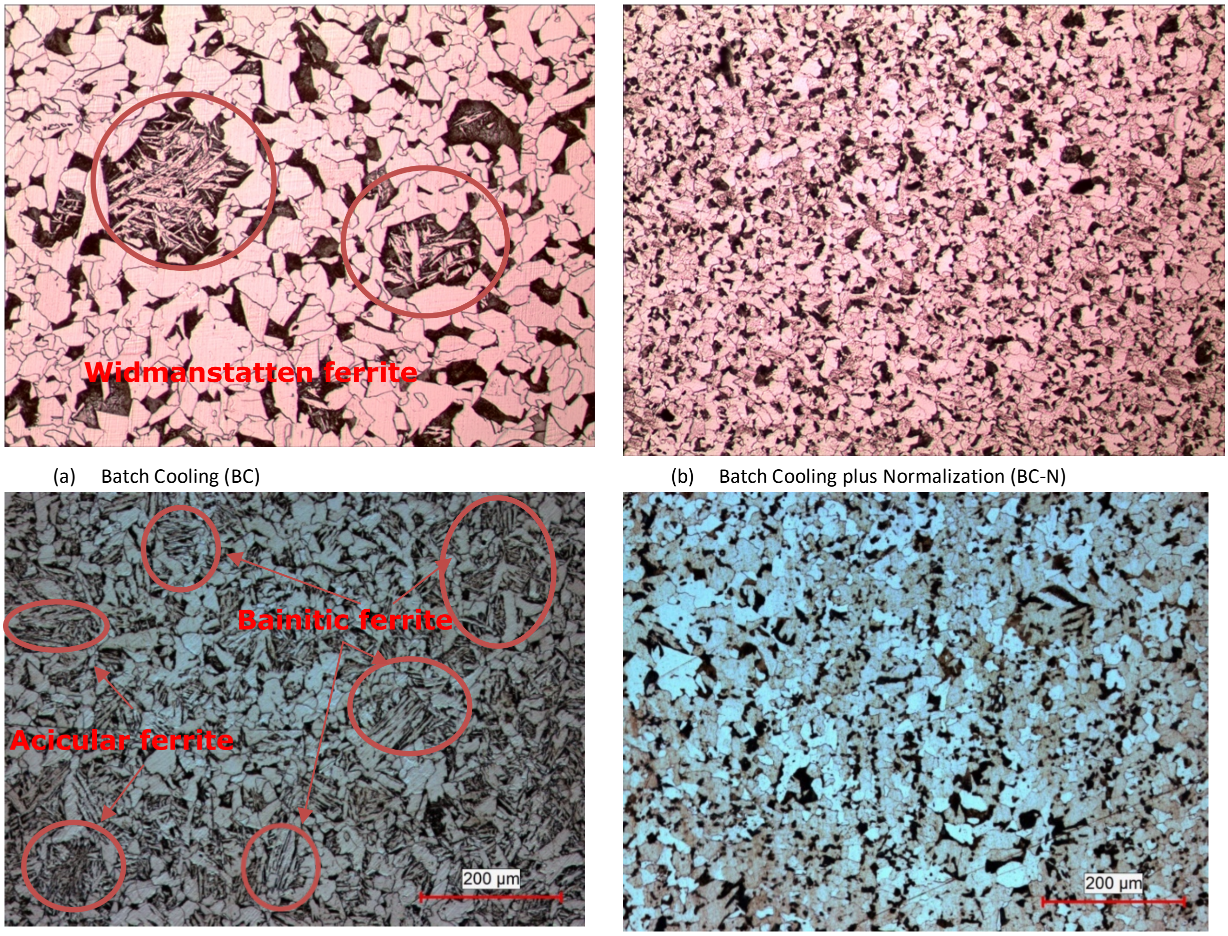
3. Figure: CCT diagram for P285NH steel by JMat-Pro analysis

The metallographical observations (Fig.4) confirmed JmatPro analysis that AAC results large amount of bainite plus acicular ferrite while BC results coarse polygonal ferrite and very small amounts of pearlite with a few widmastaten ferrite island. The normalizing heat treatment changes the original microstructures (Fig. 4 b and d) to an equiaxed fine ferrite microstructure for both AAC and BC.

Jmatpro analysis cannot obtain acicular ferrite. It is known that ACICULAR ferrite (AF) is formed in the same temperature range as bainitic ferrite (BF) (approximately 400 °C to 600 °C) by the same type of transformation mechanism. It is very hard to distinct the AF and BF. A change from bainite to acicular ferrite can be achieved by simple control of the nucleation sites. In the case of bainite, the ferrite nucleates at the austenite grain boundaries and forms packets of parallel plates with similar crystallographic orientations, whereas acicular ferrite nucleates intragranularly at nonmetallic particles, as it can be seen in Fig. 4, schematically [10-13]. Thus, Díaz-Fuentes et al. (2003) recommended that structures of parallel ferrite plates inside the austenite grain should be named intragranularly nucleated bainite and that only chaotically arranged ferrite plates nucleating at point sites should be classified as acicular ferrite [14].

3.Table: Calculated Phase Percentages by JmatPro and Hardness Values and grain sizes determined by experimentally

	JmatPro analysis			Experimentally determined	
	Ferrite, wt-%	Pearlite, wt-%	Bainite, wt-%	Hardness, HRB	Grain size,
Batch Cooling (BC)	71.9	28.1	-	82	30,26
Batch Cooling + Normalization, BC-N	85.35	14.65	-	69	16,95
Accelerated Air Cooling, AAC	58.35	13.06	28.09	83	25,34
Accelerated Air Cooling + Normalization, AAC-N	83.84	16.16	-	66	18,45



(a) Batch Cooling (BC)

(b) Batch Cooling plus Normalization (BC-N)

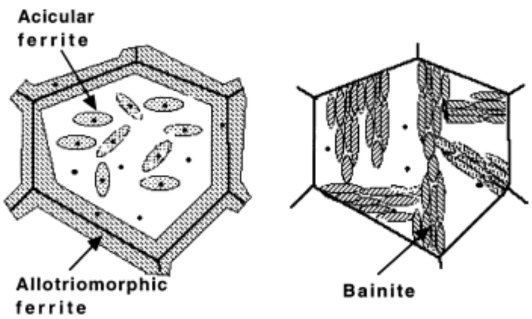
(c) Accelerated Air Cooling (AAC)

(d) AAC plus Normalization (AAC-N)

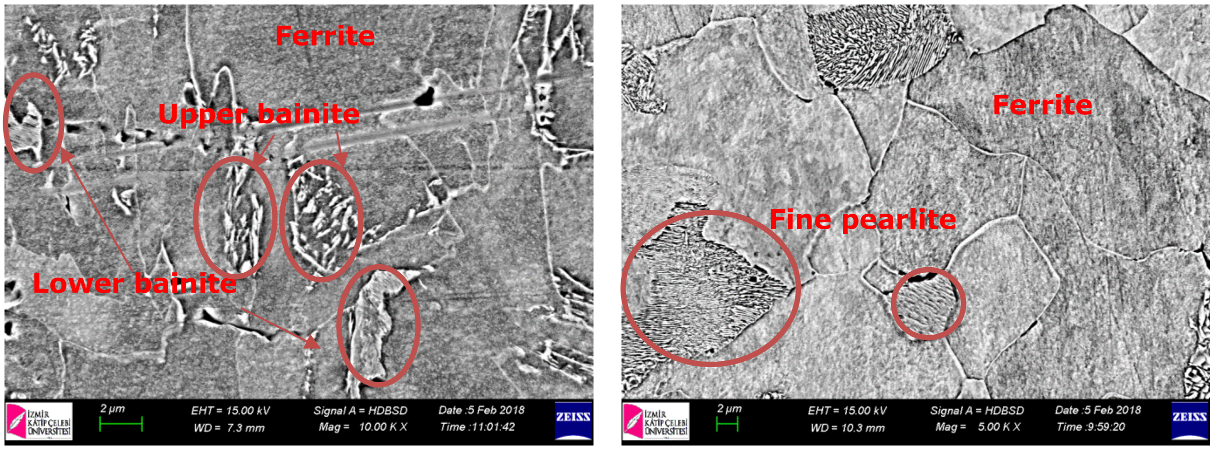
4. Figure: Microstructures from various TMT's

Therefore, it is seen from Fig. 5-c that accelerated air cooling with 1,48 oC/s cooling rate leads to formation of bainitic structure with some acicular ferrite and polygonal ferrite.

It was expected that accelerated air cooling would yield to acicular ferrite formation and it would give a good toughness [15-18]. Nevertheless, it was not possible to produce pure acicular ferrite with applied cooling rate in this study. Mechanical properties showed (Table 4) that bainite plus acicular ferrite formation in the microstructure cause increase in tensile and yield strength with a consequent decrease in ductility values.



5. Figure: Schematic illustration of the mechanism by which the presence of allotriomorphic ferrite at the austenite grain surfaces induce a transition from a bainitic to acicular ferrite microstructure



(a) Accelerated Air Cooling (AAC) (b) Accelerated Air Cooling plus Normalization (AAC-N)

6. Figure: AAC microstructures by SEM with higher magnification

Finally, a spectacular strength increase along with a marked decrease in impact strength is observed in AAC specimens. Accelerated air cooling resulted in a mixture of bainitic and acicular ferritic structures and pearlitic transformation was substantially suppressed by the prior occurrence of the equilibrium. Moreover BC resulted both lower yield&tensile strength and lower impact energy comparison to AAC. However, it was expected that lower strength should correspond higher toughness. It is concluded that this lower impact energy arised from widmanstatten ferrite in BC part. It is known that continues cooling yields the transformation structure, respectively; grain boundary ferrite, polygonal ferrite, widmanstatten ferrite, acicular ferrite, upper bainite, lower bainite and martensite Observation of the mechanical property of materials with different ferrite microstructure has shown that widmanstatten ferrite, upper bainite, grain boundary ferrite is detrimental to toughness, whereas acicular ferrite improves it [19].

According to customer standard of the pressured vessel component, the impact energy must be above 40 joules at -20°C, the yield strength must be above 245 (N/mm2) and the tensile strength must be in the range of 390 - 510 (N/mm2). All samples provided yield strength and impact energy criteria. But both BC and AAC resulted above the limit of tensile strength and their standard deviation was highest. The only normalization processes provided the customer's all parameters. The charpy energy increased dramatically, at least 4 or 5 times with normalization. Finally, the change of mechanical properties reflects microstructural changes, confirming a strong structure sensitivity of toughness. The highest toughness exhibits the fine ferrite-pearlite structure.

4. Table: Mechanical properties

TMT's	Yield Strenght (MPa)	Std.Dev.	Ultimate Strenght, MPa	Std.Dev.	Impact Energy, Joule	Std.Dev.
Batch Cooling (BC)	358	3,4	516,6	5,9	55,2	38
Batch Cooling + Normalization, BC-N	319,3	1,2	459,7	1,85	250,6	5,8
Accelerated Air Cooling, AAC	371,3	13,8	541,6	3,7	62,8	45
Accelerated Air Cooling + Normalization, FC-N	317,5	13,8	454,9	5,2	243,1	10,8

4 CONCLUSION

We studied the effect of batch cooling (BC) and accelerated air cooling (AAC) on microstructural properties and mechanical properties of P285NH microalloyed steel which is used for a pressured vessel component. This part is conventionally produced by hot forging, batch quenching and normalization steps, respectively. It is known that the hot forging followed by controlled cooling can eliminate the normalization step establishing beneficial microstructure such as acicular ferrite which is associated with beneficial combination of strength and toughness. But we didn't reach to get acicular ferrite, we could get mixed structure with mainly bainite and acicular ferrite, therefore it yielded high ultimate strength which is out of limit for the part. It is concluded that it is not possible to produce this part with P285NH microalloyed steel without normalization after cooled BC or AAC which applied in this study. It is suggested that either the part should be produced with normalization step or the cooling rate which yield to pure acicular ferrite should be determined.

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