OPTIMIZATION OF HEAT TREATMENT OF CLOSED-DIE FORGINGS OF 2.5% MN STEEL

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Abstract

The forging industry seeks ways to improve mechanical properties of forged parts without using costly alloyed steels or complicated and time-consuming post-forge heat treatment. One of the available options is Q&P processing (Quenching and Partitioning) of advanced high-strength martensitic steels. The Q&P process is characterized by rapid cooling from the soaking temperature to a quenching temperature which is between the M_s and the M_f, and subsequent reheating to and holding at a partitioning temperature. Strength levels of more than 2000 MPa and elongation above 10 % can be obtained. Since the quench needs to be interrupted between the M_s and the M_f, new alloying strategies are being developed in order to depress the M_f below 100°C. With such steels, plain quenchants could be used, including boiling water.

Using material-technological modelling, several heat treatment routes involving various cooling profiles were tested on three high-strength 2.5 % Mn steels with different Ni and Mo levels. The data for constructing the first model were acquired from a real-world treatment of a forged part. Quenching the forged part in boiling water and subsequent partitioning led to a strength of 2130 MPa and elongation of 12 %. Metallographic examination and measurement of mechanical properties were carried out on the experimental steels after the treatments.

Keywords: Closed-die forgings, Q&P process, retained austenite, material-technological modelling

1. INTRODUCTION

The current trend in the forging industry is to achieve good mechanical properties in products at minimized costs. The costs can be reduced by avoiding materials with high-priced alloying strategies, as well as time-consuming post-process heat treatment of closed-die forgings. One way to impart high strength and ductility to a material is the Q&P process (Quenching and Partitioning) which leads to strengths in excess of 2000 MPa and elongation levels of about 10 % [1]. It is characterized by rapid cooling from the austenite region to a temperature between the M_s and M_f temperatures, during which martensite forms whereas some austenite remains untransformed. During subsequent isothermal holding, retained austenite becomes stabilised thanks to carbon which migrates from super-saturated martensite to austenite. According to current knowledge, this retained austenite exists primarily in the form of thin foils between martensite laths or plates [2, 3]. Stabilization of retained austenite depends mainly on the cooling rate and on the M_s and M_f having been depressed by well-chosen alloying elements [4]. This paper focuses on the effects of cooling rate on microstructural evolution and mechanical properties in high-strength steels.

2. EXPERIMENTAL PROGRAMME

Three steels were newly designed for this experiment using the JMatPro software. Their special chemistries led to depressed M_s and M_f (**Table 1**). The key was the increased manganese level: 2.5 %. Other alloying elements included silicon, chromium and molybdenum. The purpose of silicon was to prevent carbides from forming, to facilitate the super-saturation of martensite with carbon and to provide solid solution strengthening. Chromium improves hardenability and strengthens solid solution. Molybdenum was added to depress the M_s

and M_f and improve the stability of martensite. It also shifts the start of austenite decomposition towards higher temperatures. Nickel was added in a small amount. It makes austenite more stable during cooling, improves hardenability and provides solid solution strengthening. Carbon content was the same in all steels: between 0.42 and 0.43 %.

Table 1 Chemical compositions of experimental steels [wt. %]

	C	Mn	Si	P	S	Cu	Cr	Ni	Al	Mo	Nb	M_s [°C]	M_f [°C]
AHSS-2	0.428	2.48	2.03	0.005	0.003	0.07	1.46	0.08	0.004	0.16	0.03	214	83
AHSS-3	0.419	2.45	2.09	0.005	0.002	0.06	1.34	0.56	0.005	0.04	0.03	209	78
AHSS-4	0.426	2.46	1.99	0.005	0.002	0.06	1.33	0.56	0.005	0.15	0.03	204	73

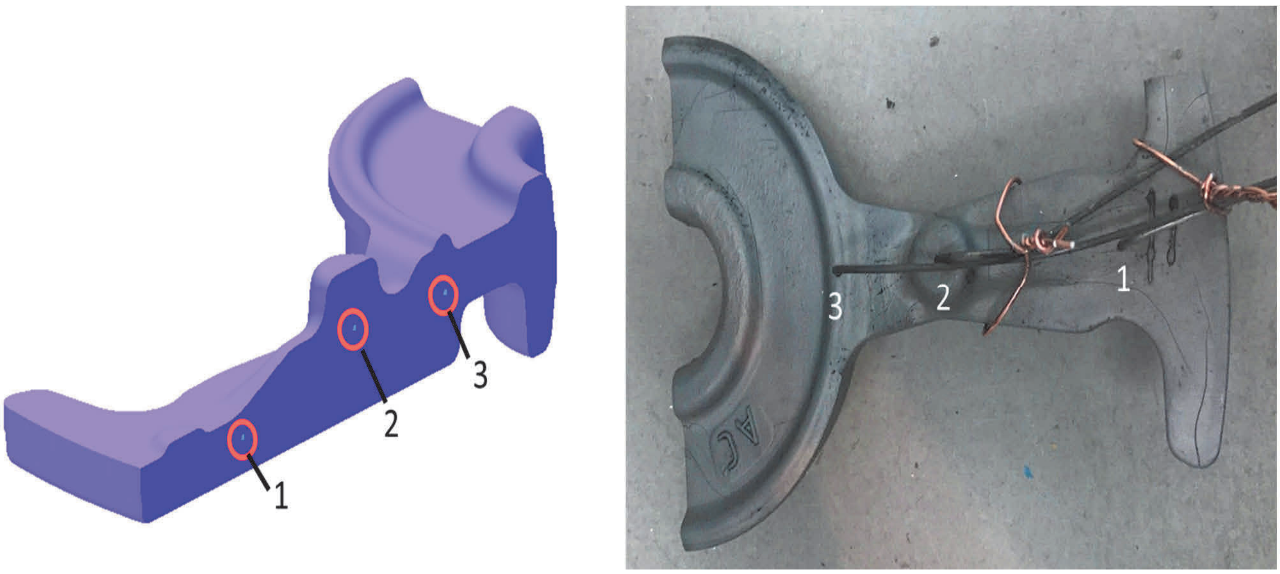

Figure 1 Closed-die forged part of an AHS steel with attached thermocouples

2.1. Development of physical simulation procedure

A test part (**Figure 1**) of the AHSS-3 experimental steel was closed-die forged and heat-treated. Data for designing the physical simulation sequences were measured during the heat treatment. Thermocouples were attached to those locations which cooled the most rapidly and the most slowly. One thermocouple was placed on the surface (no. 1) and two thermocouples were placed in the part's interior (nos. 2 and 3), (**Figure 1**). The heat treatment had the form of a Q&P process. The part was brought a to full-austenite temperature, approx. 880 °C, in a furnace. During subsequent cooling, its temperature had to remain above the M_f. Boiling water (at 100 °C) was therefore chosen as a quenchant. Once the surface of the forged part reached this temperature, the part was removed from the quenchant and tempered in a furnace for 1 hour at 200 °C (**Figure 2**). Another heat treatment route involved cooling to 200 °C in a furnace at this temperature. As the part was held at this temperature, carbon migrated from super-saturated martensite to austenite and stabilized the latter.

Cooling rates in these heat treatment routes were measured by thermocouples and used for planning the physical simulation sequences. The sequences were then carried out in a thermomechanical simulator which enables small amounts of material to be treated in a manner close to the real-world process. As the simulation takes place in laboratory conditions, it delivers time and cost savings.

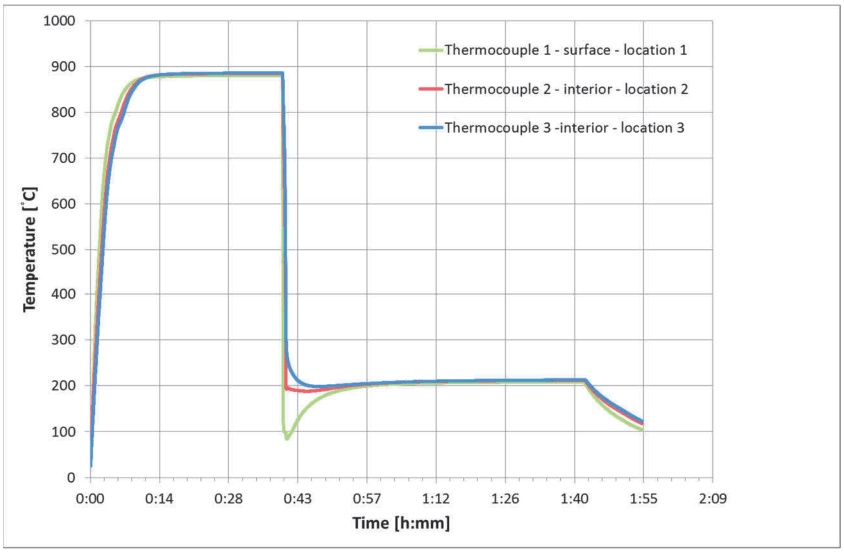

Figure 2 Thermal profiles of Q&P processing and quenching in boiling water for several locations of closed-die forged part

2.2. Physical simulation of cooling of forged part

Three physical simulation sequences involving heat treatment with different cooling rates were carried out on specimens of each experimental steel. The rationale for this arrangement was that stability of retained austenite depends on not only the quenching temperature (QT) in the Q&P process but also on cooling rate. The sequences were constructed using the cooling curves measured on the real-world forged part. These curves described cooling of the part's surface and interior in boiling water and in the furnace (**Figure 3**). The physical simulation sequences involving various cooling rates (boiling water, furnace) for the forged part's surface and in its interior were applied to the other two steels in order to explore the effects of treatment on microstructural evolution and mechanical properties. Thus, the impact of chemical composition was characterized and the fitness of the AHSS-2 and AHSS-4 steels for the Q&P process was ascertained. Comparison between physical simulation and the treatment of a real-world forged part was obtained for the same material by applying these sequences to the AHSS-3 steel.

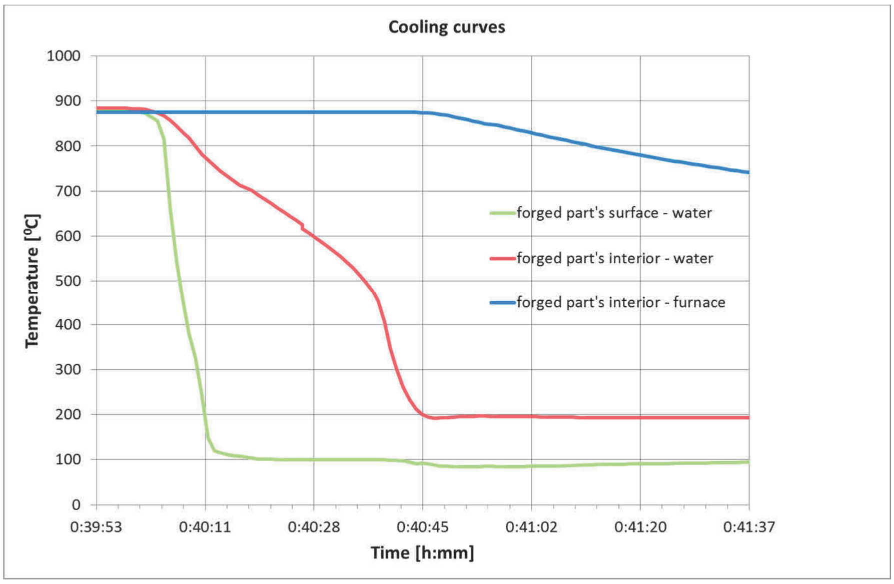

Figure 3 Cooling curves of the forged part's surface and interior in boiling water and in a furnace

In the first sequence, i.e. physical simulation of quenching of forged part surface in boiling water, the cooling rate was 64 °C / s. The cooling step was followed by reheating to the partitioning temperature (PT) of 200 °C and holding for one hour, during which retained austenite became stabilized in the martensitic matrix. The second sequence related to location 3 in the forged part's interior. The cooling rate was 13 °C / s. After cooling, the specimen was reheated to the partitioning temperature of 200 °C and held for one hour. The third sequence was physical simulation of slow cooling of the interior of the forged part in a furnace at a rate of approx. 1.3 °C / s. The specimen cooled for 2 hours in a furnace at 200 °C.

All specimens treated according to these sequences were then examined and tested: metallographic observation was carried out using light and scanning electron microscopes and mechanical testing was performed. The retained austenite fraction was measured using X-ray diffraction (**Table 2**).

Table 2 Physical simulation sequences and resultant mechanical properties

					Physical simulation				Real-world forged part		
Sequence number/steel	**T_A [°C] / t_A [s]**	**Cooling rate [°C / s]**	**QT [°C]**	**PT [°C / s] / t_{PT} [s]**	**HV10 [-]**	**R_m (UTS) [MPa]**	**A_{5mm} [%]**	**RA [%]**	**HV10 [-]**	**R_m (UTS) [MPa]**	**A_{5mm} [%]**
1 /AHSS2	880/2400	64	100	200/3600	636	2149	10		-	-	-
1 / AHSS3			100	200/3600	637	2114	15		603	2131	12
1 / AHSS4			100	200/3600	630	2102	15		-	-	-
2 / AHSS2		13	100	200/3600	657	2232	4		-	-	-
2 / AHSS3			100	200/3600	669	2250	8		-	-	-
2 / AHSS4			100	200/3600	633	2259	8		-	-	-
3 / AHSS2		1,3	200	200/7200	662	2237	3		-	-	-
3 / AHSS3			200	200/7200	662	2171	3		648	2153	7
3 / AHSS4			200	200/7200	666	2059	4		-	-	-

3. DISCUSSION OF RESULTS

The physical simulation sequences produced in all specimens a martensitic matrix with some retained austenite (**Figure 4 - Figure 8**). Different amounts of retained austenite were obtained with different cooling rates. High cooling rates (simulation of cooling of the forged part's surface in boiling water, sequence 1) led to strengths around 2100 MPa and elongations up to 15 % in all steels (**Table 2**). Large volume fractions of retained austenite in the martensitic matrix were detected by X-ray diffraction analysis. This was confirmed by observation of special two-stage-etched metallographic sections under light microscope (1st etching step: nital, 2nd step: 10% aqueous solution of $Na_2S_2O_5$), (**Figure 5**). Retained austenite was present in a globular form, as well as between martensite needles. Slower cooling (13 °C / s in sequence 2, the simulation of cooling of the forged part’s interior) produced slightly higher (by approx. 100 MPa) strength in all steels than sequence 1. The amount of martensite was larger and hardness was higher by approx. 30 HV10. The increase in strength was accompanied by a drop in elongation (to a mere 4 % in AHSS-2). It can be explained by a lower amount of retained austenite (**Table 2**) and by coarser grain. Lower volume fraction of retained austenite was confirmed by the special etching procedure. The decrease in the amount of globular retained austenite was much sharper than in the inter lath form (**Figure 7**). The slowest cooling (1.3 °C/ s in sequence 3 for cooling in a furnace) led to even lower elongations (3-4 %) in all steels. Strength levels did not increase compared to the preceding sequences (**Table 2**).

Mechanical properties of physical simulation specimens were in agreement with those of the real-world forged part of the AHSS-3 steel. The water-quenched (at 64 °C / s) surface of the forged part had a strength and elongation of 2131 MPa and 12%, respectively (**Table 2**). Slow cooling in a furnace (at 1.3°C/s) produced less retained austenite and a greater amount of martensite. As a result, the ultimate strength was 2153 MPa and elongation was 7 % (**Table 2**).

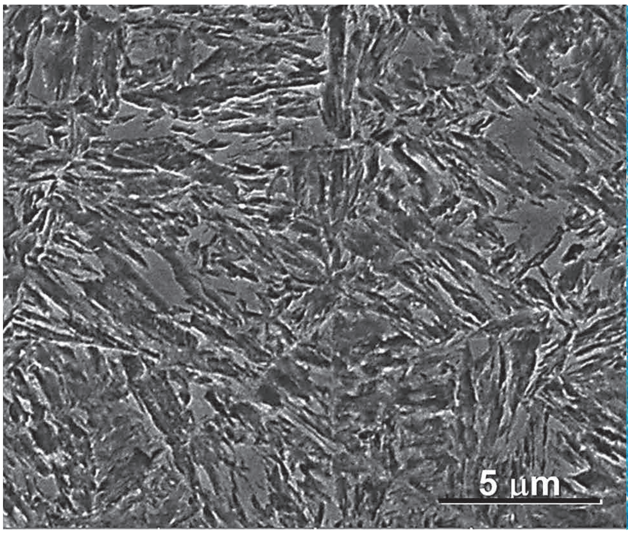

Figure 4 AHSS-2 steel - martensitic-austenitic microstructure, cooling rate of 64 °C / s, scanning electron micrograph (SEM)

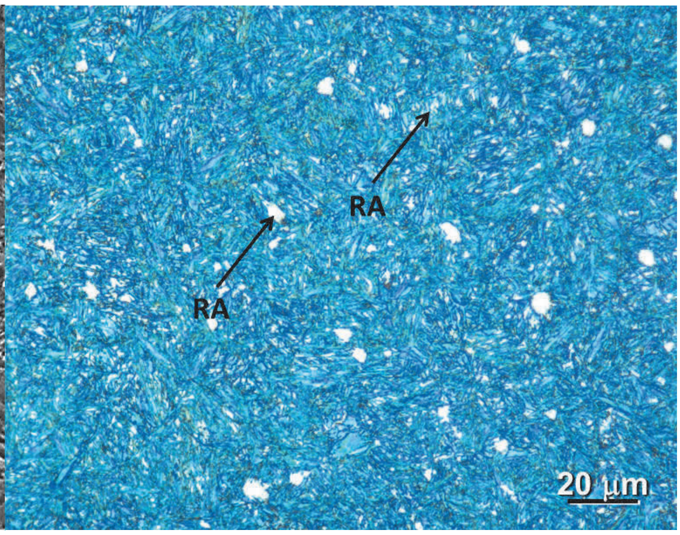

Figure 5 AHSS-2 steel - martensitic-austenitic microstructure, cooling rate of 64 °C / s, colour etch, light micrograph (LM)

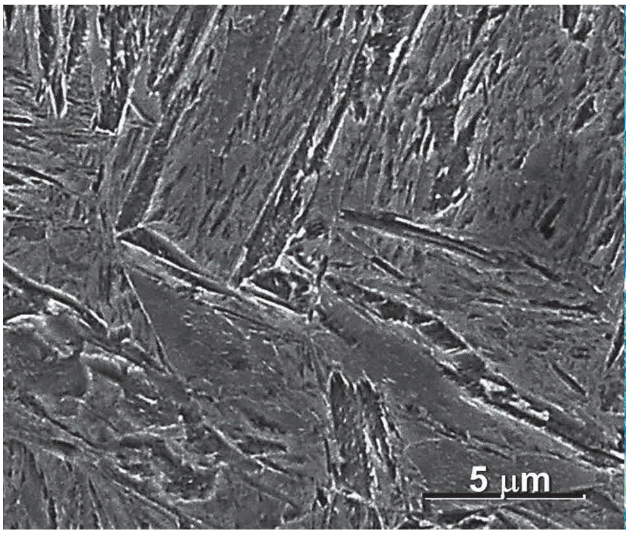

Figure 6 AHSS-4 steel - martensitic-austenitic microstructure, cooling rate of 13 °C / s, SEM

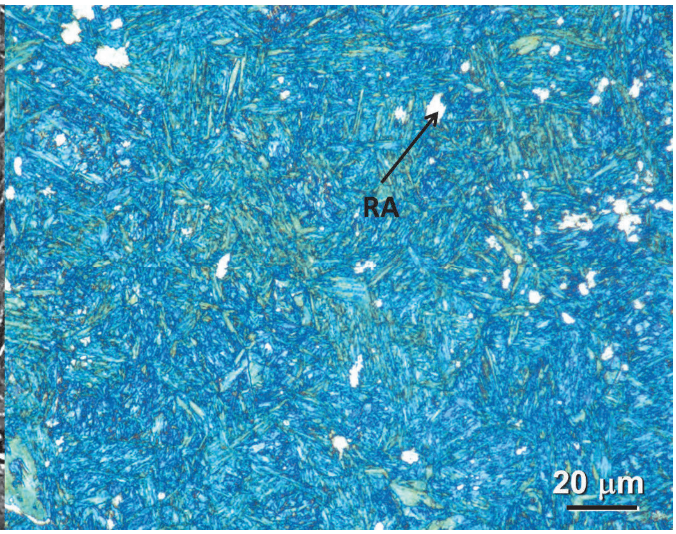

Figure 7 AHSS-4 steel - martensitic-austenitic microstructure, cooling rate 13 °C / s, colour etch, LM

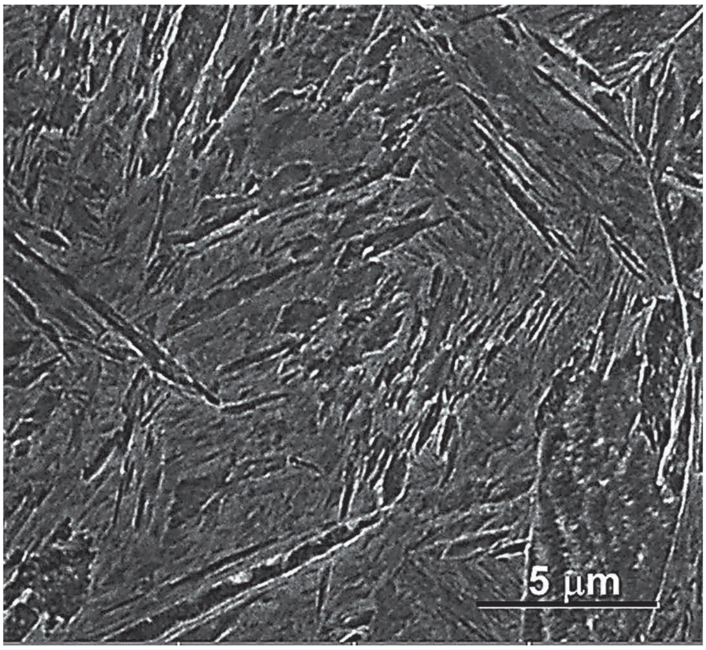

Figure 8 AHSS-3 steel, martensitic-austenitic microstructure, cooling rate of 1.3 °C / s, SEM

4. CONCLUSION

Physical simulation was employed to apply three heat treatment sequences with different cooling profiles and other parameters to three newly-designed high-strength steels alloyed with manganese, silicon and chromium. The input data for constructing these sequences was measured in a real-world process of treatment of a forged part. The cooling rates applied (64 °C / s, 13 °C / s and 1.3 °C / s) had a strong effect on the resultant amount of retained austenite in the martensitic matrix. During the sequence in which the cooling rate was the fastest (representing the forged part's surface), austenite did not transform. A large portion of retained austenite therefore remained in the martensitic matrix thanks to appropriate alloying. The resultant elongation was high, up to 15 %, and the ultimate strength reached approximately 2100 MPa. The sequences, in which cooling was slow (forged part's interior and furnace cooling), led to lower amounts of retained austenite in the martensitic matrix. Consistently with the high volume fraction of martensite, the ultimate strength and hardness were higher than in other cases, approximately 2200 MPa and 660 HV10, respectively. The high strength produced by sequences with slow cooling was associated with lower elongation.

Mechanical properties of specimens of AHSS-3 after physical simulation were in agreement with those of the real-world forged part. The high rate of cooling (64°C/s) of the forged part's surface in boiling water led to a strength of 2131 MPa and elongation of 12 %. Slow cooling in a furnace (1.3 C / s) produced more martensite, a higher strength of 2153 MPa and a lower elongation of 7 %. The comparison between physical simulation and real-world forged part suggests that physical simulation in a laboratory enables a wide range of heat treatment parameters to be tested for optimizing the processing of closed-die forgings.

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