

Integration of Press-Hardening Technology into Processing of Advanced High Strength Steels

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Abstract. Development of high strength or even ultra-high strength steels is mainly driven by the automotive industry which strives to reduce the weight of individual parts, fuel consumption, and CO₂ emissions. Another important factor is the passenger safety which will improve by the use of these materials. In order to achieve the required mechanical properties, it is necessary to use suitable heat treatment in addition to an appropriate alloying strategy. The main problem of these treatments is the isothermal holding time. These holding times are technologically demanding which is why industry seeks new possibilities to integrate new processing methods directly into the production process. One option for making high-strength sheet metals is press-hardening which delivers high dimensional accuracy and a small spring-back effect. In order to test the use of AHSS steels for this technology, a material-technological modelling was chosen. Material-technological models based on data obtained directly from a real press-hardening process were examined on two experimental steels, CMnSi TRIP and 42SiCr. Variants with isothermal holding and continuous cooling profiles were tested. It was found that by integrating the Q&P process (quenching and partitioning) into press hardening, the 42SiCr steel can develop strengths of over 1800 MPa with a total elongation of about 10%. The CMnSi TRIP steel with lower carbon content and without chromium achieved a tensile strength of 1160 MPa with a total elongation of 10%.

Introduction

High-strength steels are promising materials for applications in the automotive industry. As they typically contain a multiphase microstructure and exhibit numerous strengthening mechanisms, they can attain a wide range of mechanical properties [1, 2]. Chemical composition is another of their advantages, being very cost effective and comprising relatively few alloying elements. Their mechanical properties are obtained, for the most part, by means of appropriate heat treatment or thermomechanical processing sequences.

With their good combination of strength and ductility, TRIP steels fall into this group as well [3-5]. They are treated using intercritical annealing which involves isothermal holding in the bainitic transformation region. At this stage, bainite forms and retained austenite becomes stable. Stability of retained austenite (RA) is governed by the carbon content and by the RA morphology and distribution [6]. Higher strength levels are obtained in martensitic steels by Q&P processing. It comprises isothermal holding between the M_s and M_f temperatures; and leads to a mixture of martensite and foil-like retained austenite between martensite needles [7]. Strengths of more than 2000 MPa combined with up to 10% elongation are obtained.

Given their favourable properties and ability to absorb crash energy, these materials could be used for making body-in-white safety components. One of the processes by which such high-strength components can be manufactured is press-hardening. It enables sheets of hardenable materials to be worked using lower forming forces and to have the springback effect reduced [8, 9]. Therefore, processing of these steels without isothermal holding needs to be tested or post-forming heat treatment must be added.

Experimental Programme

For this experiment, several heat treatment routes were proposed. They were based on press-hardening and applied to two experimental steels. One of them was CMnSi TRIP steel, a typical TRIP steel, and the other was 42SiCr, one of the steels for Q&P processing. The proposed sequences reflected press hardening in a tool at RT and heat treatment. The purpose was to determine and describe, firstly, the effect of varying heat treatment parameters on microstructure and mechanical properties and, secondly, the suitability of these steels for press-hardening.

Experimental Materials. CMnSi TRIP is a low-alloy steel with 0.2% carbon, whose only alloying elements are manganese and silicon (Table 1). This chemistry was chosen for stability of retained austenite, solid solution strengthening, and to prevent carbide precipitation during bainite formation [4]. Specimens for heat treatment were made by waterjet cutting from a soft-annealed sheet of 1.5 mm thickness. Its microstructure consisted of ferrite and pearlite; the hardness was 180 HV10. Characteristics of phase transformations were calculated using the JMatPro software (Release 9.0, Sente Software Ltd., 2016). The M_s temperature was found to be 370°C and the M_f was 257°C.

42SiCr had a higher carbon content than CMnSi: 0.43%. It also contained chromium which greatly strengthens solid solution and improves hardenability (Table 1). The initial microstructure of the sheet of this steel consisted of pearlite and a small amount of ferrite. Its hardness was 290 HV10. Owing to the higher carbon level, the M_s was 290°C and the M_f temperature was 178°C.

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

Steel	C	Mn	Si	Al	Nb	P	S	Ni	M_s	M_f
CMnSi	0.21	1.4	1.8	0.006	0.002	0.007	0.005	0.07	370	257
42SiCr	0.43	0.68	1.96	0.008	0.07	0.01	0.01	0.07	298	178

Material-technological modelling of press-hardening process. In order to be able to test press-hardening on these newly-developed high-strength steels, material-technological modelling was employed. Using this technique, thermal and deformation routes which were measured in a real-world forming process can be tested on a chosen material. It is performed in a thermomechanical simulator which uses high-frequency electric resistance heating and offers high heating and cooling rates (up to 200°C/s). The data for developing the model was measured in a real-world process, with the tool either at room temperature or pre-heated to various temperatures. It allowed various cooling profiles to be designed to match the materials' characteristics.

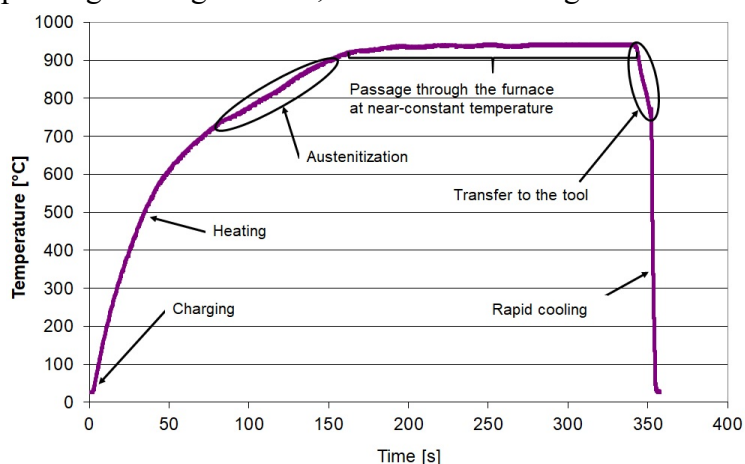


Fig. 1. Material-technological model of the press-hardening process for a thermomechanical simulator, tool at room temperature (RT)

In the first sequence proposed, the tool was at room temperature (Fig. 1). The initial heating to 937°C was followed by soaking for 100 seconds. Then, a 7-second step represented air cooling of the workpiece during transfer to the forming tool. The temperature dropped to 760°C. The next step was a simulation of press-hardening in a tool at room temperature at a cooling rate of 100°C/s (the CMnSi-01 sequence). In other sequences, the impact of cooling rate was tested. The cooling rate was reduced to 12°C/s and 6°C/s (CMnSi-02 and CMnSi-03 sequences, respectively). TRIP steels

are intercritically annealed to obtain a mixture of ferrite, bainite and retained austenite. Therefore, isothermal holding was incorporated into cooling in some sequences. In the first one of these, cooling rate changed at 425°C from 51°C/s to 1.5°C/s (the CMnSi-04 sequence). Then, sequences with isothermal holding at a bainitic transformation temperature for 600 seconds and 900 seconds were used (the CMnSi-05 and 06 sequences, respectively). The purpose of the last sequence was to study the effect of the rate of cooling after isothermal holding at 425°C (the CMnSi-07 sequence).

Table 2. Heat treatment and mechanical properties of the CMnSi TRIP steel

Treatment	Tool temp. [°C]	Holding time [s]	Cooling rate to the tool [°C/s]	Cooling rate from the tool [°C/s]	HV10 [-]	Offset YS ($R_{p0.2}$) [MPa]	UTS (R_m) [MPa]	A ₂₀ [%]	RA [%]
CMnSi-01	RT	-	100	-	241	410	876	17	3
CMnSi-02		-	12	-	225	396	740	19	
CMnSi-03		-	6	-	235	430	787	22	
CMnSi-04	425	-	51	1.5	250	374	844	21	4
CMnSi-05		600	51	1.5	402	676	1160	10	11
CMnSi-06		900	51	1.5	206	316	758	20	6
CMnSi-07		600	51	0.7	213	328	744	19	7

Table 3. Heat treatment and mechanical properties of 42SiCr steel

Treatment	Tool temperature [°C]	Cooling rate [°C/s]	PT/Pt [°C/s]	HV10 [-]	Offset yield strength ($R_{p0.2}$) [MPa]	UTS (R_m) [MPa]	A ₂₀ [%]	RA [%]
42SiCr-01	RT	100	-	653	1420	1906	1	4
42SiCr-02	200	100	air cooling from 200°C	614	1462	2057	5	
42SiCr-03	200	100	250/600	575	1130	1850	10	14
42SiCr-04	200	50	250/600	545	1248	1802	9	11
42SiCr-05	200	10	250/600	482	935	1642	4	
42SiCr-06	200	100	250/800	569	1420	1798	8	
42SiCr-07	200	100	250/400	573	1472	1844	9	
42SiCr-08	200	100	230/600	600	1488	1919	8	
42SiCr-09	200	100	270/600	565	1337	1722	7	

The first sequence applied to 42SiCr steel represented cooling of sheet metal in a tool at room temperature (the 42SiCr-01 sequence) (Table 3). Other sequences simulated the typical processing of this steel, the Q&P process. In the second sequence, the cooling rate changed below 200°C (the 42SiCr-02 sequence). In the next sequence, cooling stopped at 200°C and was followed by reheating to a partitioning temperature of 250°C and holding for 600 seconds (the 42SiCr-03 sequence), while the cooling rate prior to placement in the tool was kept at 100°C/s. Lower cooling rates of 50°C/s and 10°C/s were tested as well (42SiCr-04 and 05). The time at the partitioning temperature plays a role in the stability of retained austenite. For this reason, sequences with holding times of 800 s and 400 s were used (42SiCr-06 and 07). The last sequences introduced change partitioning temperatures: 230°C and 270°C (42SiCr-08 and 09).

Methods of evaluation. Microstructures were examined by optical (OM) and scanning electron microscopy (SEM). Tescan VEGA 3 and Zeiss EVO MA 25 scanning electron microscopes were employed. The amount of retained austenite was measured by X-ray diffraction. The automatic powder diffractometer AXS Bruker D8 Discover with a HI-STAR position-sensitive area detector

and a cobalt X-ray source ($\lambda K\alpha = 0.1790307 \text{ nm}$) was employed for this measurement. Measurements were taken in the centres of metallographic sections at diffraction angles in the interval of $25 \div 110^\circ 2\theta$. Mechanical properties were measured by HV10 hardness testing and tensile testing.

Results and Discussion

The sequence which represented press-hardening in a tool at RT at a cooling rate of 100°C/s caused the CMnSi TRIP steel to develop a ferritic microstructure with martensite and 3% of retained austenite (Fig. 2). The hardness was 241 HV10. The ultimate strength was 876 MPa and elongation reached 17% (Table 2). After the cooling rate had been decreased from 100°C/s to 6°C/s , neither substantial differences in microstructure nor pearlite formation were detected (Fig. 3). The ultimate strength decreased by 100 MPa and the elongation level was 22%.

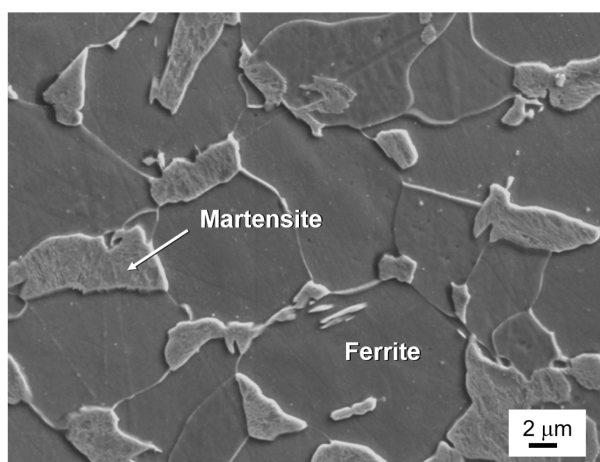


Fig. 2. CMnSi-02 schedule – press-hardening at a rate of 100°C/s in a tool at RT, ferritic-martensitic microstructure, SEM

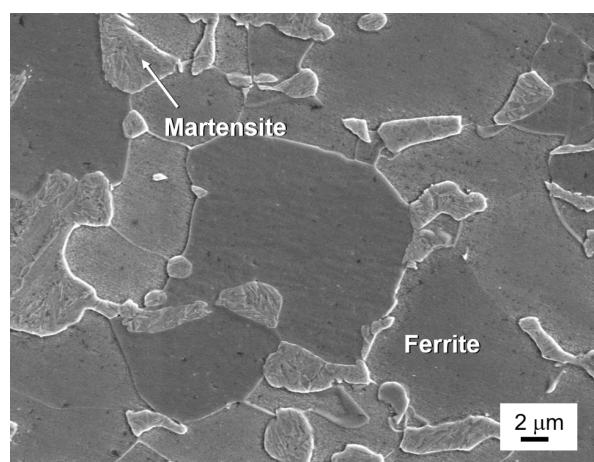


Fig. 3. CMnSi-03 schedule – press-hardening at a rate of 6°C/s in a tool at RT, ferritic-martensitic microstructure, SEM

The sequence which comprised holding at 425°C for 600 s promoted formation of bainite. The resulting microstructure was a mixture of martensite, bainite and a small amount of free ferrite (Fig. 4). The isothermal hold contributed to stability of retained austenite (RA). The amount of RA was 11%. The reduced volume of ferrite and the increase in the amount of hardening microstructure were reflected in a notable increase in UTS to 1160 MPa and in reduced elongation: 10%. Neither an extended holding time of 900 seconds, nor a reduced cooling rate after isothermal holding have further stabilised retained austenite whose amount therefore decreased to 6% and 7%, respectively. In both these schedules, the resulting ultimate strength was in the 744–758 MPa interval. The elongation levels were about 20%.

After the 42SiCr steel, which had a higher carbon level and contained chromium, was processed according to the first schedule which represented press-hardening in a tool at RT, its microstructure consisted of a majority of martensite and a small amount of bainite. The volume fraction of retained austenite was a mere 4%. Hardness was 653 HV10. The ultimate strength was 1906 MPa and elongation reached 1%. Elongation did not increase even after the rate of cooling below 200°C had been reduced in the 02 sequence. Improved elongation was obtained by incorporating the Q&P process into cooling. Elongation increased to 10% and high ultimate strength remained: 1850 MPa. As in previous cases, the microstructure was martensitic and contained a small amount of bainite. However, the fraction of retained austenite increased to 14% (Fig. 5).

After the cooling above 200°C had been slowed down from 100°C to 50°C/s , a small amount of free ferrite formed (Fig. 6). As a consequence, hardness decreased slightly from 575 HV10 to 545 HV10, as did the ultimate strength whose value was 1802 MPa. Elongation was 9%. Yet another reduction in the cooling rate to 10°C/s led to an increased proportion of ferrite, to even lower mechanical properties, and to no increase in elongation (Fig. 7).

Extended holding time at the partitioning temperature, from 600 s to 800 s, resulted in reduced ultimate strength of 1798 MPa and elongation of 8%. Reducing the partitioning temperature from 250°C to 230°C caused the ultimate strength to increase from 1850 MPa to 1919 MPa, whereas elongation slightly decreased to 8%. By contrast, increasing the partitioning temperature to 270°C has led to a lower ultimate strength, 1722 MPa, and no change in elongation. In this case, the microstructure was very similar to the others. It consisted of martensite with a small amount of bainite, no free ferrite and no visible precipitates.

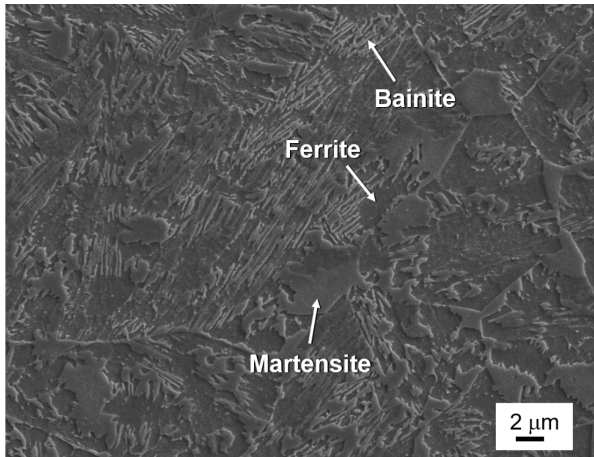


Fig. 4. Sequence CMnSi-05 – holding at 425°C for 600 s, martensitic-bainitic structure with ferrite and retained austenite, SEM

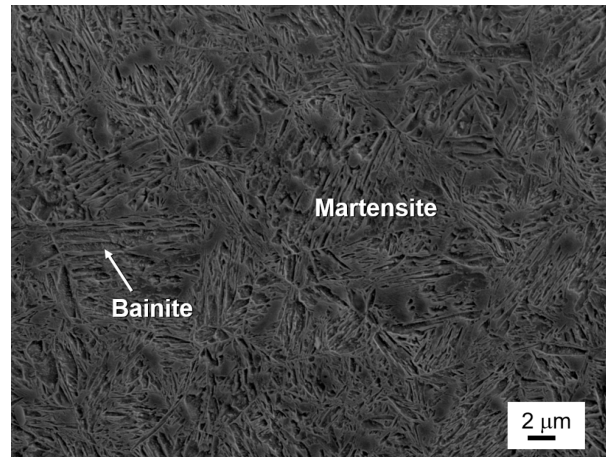


Fig. 5. Sequence 42SiCr-03 – press hardening with Q&P processing – 200°C – 250°C/600 s, martensite with a small amount of bainite, SEM

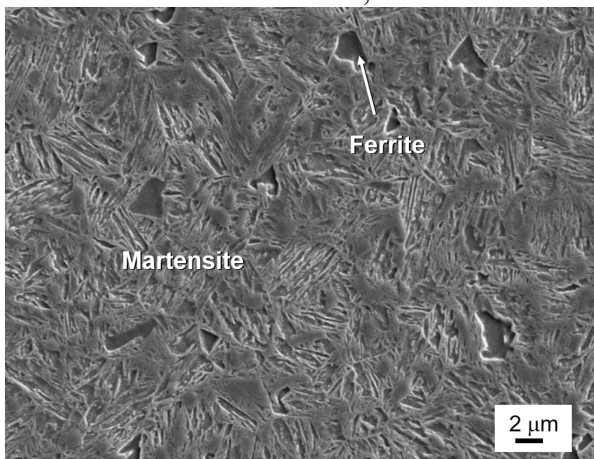


Fig. 6. Sequence 42SiCr-04 – press-hardening with Q&P processing – 50°C/s – 200°C – 250°C/600 s, martensite with small amounts of bainite and ferrite, SEM

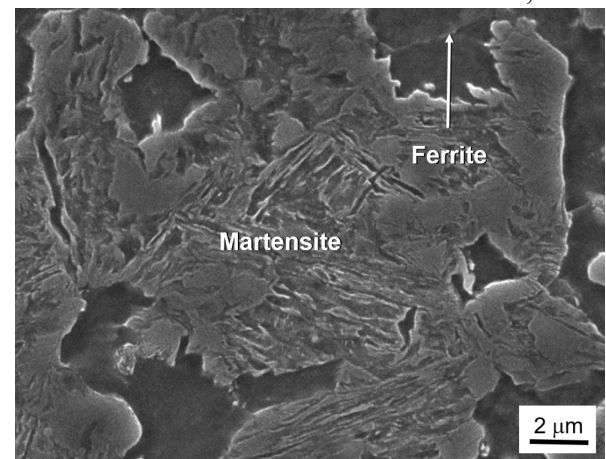


Fig. 7. Sequence 42SiCr-05 – press-hardening with Q&P processing – 10°C/s – 200°C – 250°C/600 s, martensite with ferrite and a small amount of bainite, SEM

Summary

In this experiment, a press-hardening route was tested which had been designed on the basis of data from a real-world forming process. It was applied to two high-strength steels: CMnSi TRIP and 42SiCr.

It was found that in order to obtain the desired mixed microstructure of martensite, bainite, ferrite and retained austenite in the CMnSi TRIP steel, press-hardening must be followed by isothermal annealing at 425°C. By this means, strengths of more than 1100 MPa combined with up to 10% elongation can be obtained.

The incorporation of the Q&P process into the cooling process of the 42SiCr steel, which had a higher level of carbon and chromium, was tested successfully. As a result, it became possible to increase elongation to 10% while the ultimate strength was 1850 MPa.

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