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Combination of press-hardening and isothermal holding in the treatment of high-strength steels

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Abstract. Today, high-strength parts for the automotive industry are mainly produced by the press-hardening technology. In order to reduce costs, savings in production and optimal materials are sought. One option involves the use of high strength steels of various chemical compositions. Two high strength steels were studied in the present experiment. The first one was CMnSi steel, a typical low-alloy TRIP steel with a carbon content of 0.2 %; alloyed with manganese and silicon. The second one was 42SiCr steel, a member of the group of martensitic steels, with a carbon content of 0.42 %. In addition to manganese and silicon, this steel is also alloyed with chromium. The CMnSi steel has not proved to be very sensitive to changes in process parameters, achieving an ultimate tensile strength of more than 950 MPa and an elongation of over 10%. 42SiCr steel was found to respond to both heating temperature and deformation, showing different mechanical properties. With the right combination of process parameters, an ultimate tensile strength of over 2100 MPa was achieved.

1. Introduction

Press-hardening, a thermomechanical treatment method which combines conventional hot forming and cold pressing, has been evolving rapidly in recent years [1]. Using this technique, high-quality automotive parts can be produced and treated to strengths over 1500 MPa [1-3]. These include parts such as front bumper, tail bumper, A-pillar, B-pillar, C-pillar, roof frame, floor frame, door panel, and door anti-beam [2-4]. At the same time, new materials are sought and developed with a view to reduced weight, less emissions and improved passenger safety. The first materials used for press hardening operations were boron steels similar to the 22MnB5 grade [1, 5]. Grades such as USIBOR1500, Docol Boron 02 and B1500HS followed suit. Several companies are in the process of developing new materials with compositions based on Mn-Mo-B, Mn-Cr, Mn-Cr-B, Mn-W-Ti-B and other concepts [1]. Steels of this kind are known as PH steels (press hardening steels).

Other grades which can be used for this process include advanced high-strength steels in which retained austenite is produced purposefully in order to improve their properties. These are known as TRIP and QP steels [6-9]. When subjected to deformation, these steels exhibit the TRIP effect (transformation induced plasticity). TRIP effect occurs in the course of cold deformation, which includes impact and crash scenarios. In such an event, retained austenite transforms to strain-induced martensite [10, 11]. As a result, these steels can absorb large amounts of crash energy, which makes them good candidates for safety components for cars. To achieve the desired mechanical properties to these steels, special heat treatment routes are needed which involve isothermal holding. Using appropriate treatment parameters, strengths up to 1100 MPa and elongations of more than 30% can be achieved in TRIP steels. In QP steels, these values can reach 2000 MPa and 10–14%, respectively. However, to be able to obtain these properties in these steels, one needs to test and understand their behaviour during press hardening and, where relevant, during isothermal holding.

2. Experimental Programme

Two high-strength steels have been selected for the present experiments (table 1). One of them was a TRIP steel which contained 0.2% C, manganese and silicon. These alloy additions are typical of this group of steels. The other was a martensitic steel from the class of materials intended for Q&P processing. It contained more than 0.4% C, manganese, silicon, and chromium at a level of 1.33%, the purpose of which was to provide solid solution strengthening and better hardenability. The semi-product for the experiments was 1.8 mm sheets with untreated surfaces.

The initial structure of TRIP steel contained ferrite and pearlite and had a hardness of 190 HV10. Its ultimate strength and elongation were 627 MPa and 26%, respectively. The QP steel in initial state had a pearlitic microstructure with a small amount of proeutectoid ferrite. Its hardness was 222 HV10, ultimate strength was 668 MPa and the elongation level was 25%.

Their phase transformation temperatures were determined using a Bähr dilatometer; on specimens which were 5 mm in diameter and 10 mm in length. The A_{c3} temperature was 909°C in the TRIP steel and 844°C in the QP steel. The M_s was determined at a cooling rate of 30°C/s. In the TRIP steel, it was 387°C. In the QP steel, it was 305°C.

Table 1. Chemical compositions of experimental steels (wt. %).

	C	Mn	Si	Al	Nb	P	S	Ni
TRIP steel	0.21	1.4	1.8	0.006	0.002	0.007	0.005	0.07
QP steel	0.42	0.68	1.96	0.008	0.07	0.01	0.01	0.07

2.1. Sequences for simulating press hardening operations

Testing the use of new materials directly in production can prove difficult both economically and technologically. One of alternatives to such attempts involves testing new material processing techniques in the laboratory and under conditions closely approaching the real-world process. Based on this reasoning, this study was carried out using a thermomechanical simulator, for which process sequences can be constructed from data measured in real production.

For the present study, time-temperature profiles, handling times and forming tool temperatures were measured in a real-life press hardening process. Based on this data, physical simulation sequences as shown in figure 1 were developed. These sequences included soaking for 180 seconds. Two soaking temperatures were proposed and used: 860°C and 940°C. The temperature 860°C was below the A_{c3} temperatures of both materials whereas the temperature of 940°C was in a single-phase region. Soaking was followed by cooling which simulated free cooling of a sheet stock while being transferred from the furnace to a tool. The duration of this cooling step was chosen to be 7 s. The sheet forming step was simulated by tensile deformation of the specimen at $\varepsilon = 0{,}15$. In order to explore the effects of strain on microstructural evolution, the deformation was applied at three different temperatures: 680°C, 750°C and 800°C. Deformation was followed by rapid cooling to room temperature at a rate equal to the cooling rate in a closed tool maintained at room temperature. With the goal of improving elongation values, specimens of both steels were treated using additional sequences in which an isothermal hold was integrated in the final cooling phase. In the TRIP steel sequences, which involved deformation at various temperatures, quenching ended at 425°C, followed by holding for 600 seconds. This temperature was above the M_s. Generally, holding at temperatures in this range leads to formation of bainitic structures and to higher amounts of retained austenite. This particular temperature was chosen on the basis of earlier experiments [12, 13].

The same step was added to the sequences for the QP steel. The isothermal temperature was 250°C, which was between the M_s and M_f. The resulting sequence corresponds to Q-P processing, which also stabilises retained austenite and improves toughness in martensitic steels [14, 15].

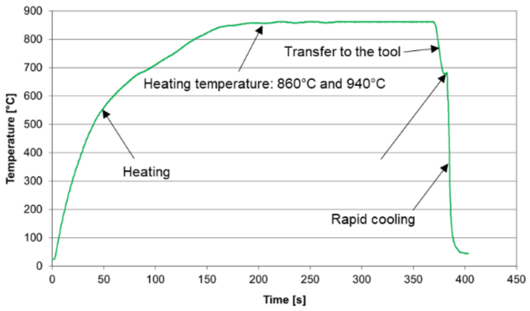

Figure 1. Schematic illustration of a press-hardening sequence.

Microstructures of the specimens were examined in metallographic sections made in the rolling direction and prepared by standard techniques. They were documented using an optical microscope (OM) and a scanning electron microscope (SEM). Microstructural features were revealed by etching with Nital. The amount of retained austenite was measured by means of XRD in the automatic powder diffractometer AXS Bruker D8 Discover with a position-sensitive area HI-STAR detector and a cobalt X-ray source (λKα = 0.1790307 nm). Mechanical properties were evaluated using measurement of HV10 hardness and tensile testing.

3. Results and Discussion

3.1. Press hardening simulations without isothermal holding

In the TRIP steel, press hardening with both soaking temperatures without an isothermal step produced a martensitic-ferritic microstructure with a small amount of retained austenite and a hardness between 282 and 290 HV10 (table 2, figure 2a-c). Deformation at 680°C failed to promote formation of pearlite (figure 2a). No bainite was found, although its presence is quite common in TRIP steels. The amount of retained austenite was very small, 3-4%. It was a result of the absence of isothermal holding in the bainitic transformation region. This step promotes bainite formation and stabilises retained austenite. The resulting large amounts of martensite led to high strengths, from 860 to 946 MPa, but the elongation levels were low: 9-13% (table 2).

Table 2. Parameters of press hardening sequences without isothermal holding; mechanical properties of specimens.

Heating temp. [°C]	Def. temp. [°C]	TRIP steel					QP steel				
		$R_{p0.2}$ [MPa]	UTS [MPa]	A_{20} [%]	HV10 [-]	RA [%]	$R_{p0.2}$ [MPa]	UTS [MPa]	A_{20} [%]	HV10 [-]	RA [%]
860	680	480	933	12.2	282	4	647	1222	5.2	320	5
	750	456	885	13.1	282	4	616	1323	3.7	410	6
	800	464	942	8.9	284	3	665	1487	3.6	451	6
940	680	480	861	11.1	274	3	1454	2150	1.5	673	5
	750	471	909	10.8	281	4	1441	2068	1.5	661	3
	800	464	946	10.8	290	4	1413	2103	1.8	663	4

Soaking and deformation temperatures had a notable impact on the second steel (table 2). The sequence which involved the lower soaking temperature, 860°C (which was below the A_{c3}), and the lowest deformation temperature, 680°C, produced not only martensite and ferrite but also pearlite (figure 2d). Hardness was 320 HV10 and ultimate strength and elongation were 1222 MPa and 5%, respectively. Sequences with higher deformation temperatures, 750°C and 800°C eliminated pearlite from the microstructure. The microstructure then consisted of martensite, ferrite and a small amount of retained austenite (figure 2e). The presence of a larger volume fraction of martensite led to higher hardness of more than 400 HV10. Ultimate strength was higher as well: 1323 MPa and 1487 MPa for deformation temperatures of 750°C and 800°C. Elongation levels were around 6% (table 2). The volume fraction of retained austenite was 5-6%.

Sequences with a soaking temperature of 940°C, which lies in the austenite region, led to higher mechanical properties. In all cases, martensite dominated in the resulting microstructure, being complemented by very small amounts of ferrite and retained austenite (table 2, figure 2f). Since most ferrite had been eliminated the ultimate strength was much higher. The ultimate strength exceeded 2000 MPa and hardness was higher than 660 HV10. The microstructure consisted of fresh martensite, and therefore elongation was very low, less than 2%.

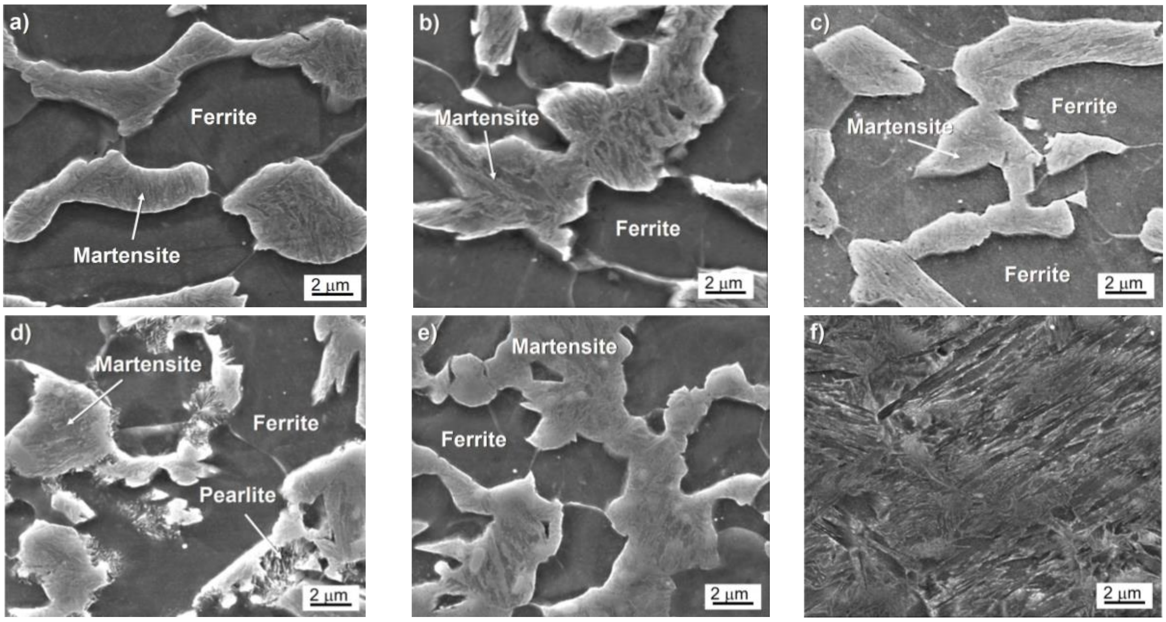

Figure 2. Microstructures produced by press-hardening sequences without isothermal holding: a) TRIP steel: 860°C – 680°C, b) TRIP steel: 860°C – 800°C, c) TRIP steel: 940°C – 800°C, d) QP steel: 860°C – 680°C, e) QP steel: 860°C – 800°C, f) QP steel: 940°C – 800°C.

3.2. Effects of an isothermal hold inserted in the cooling between the forming temperature and RT

With a view to improving elongation levels in both experimental materials, physical simulation sequence were developed and tested which included an isothermal step applied in the course of cooling to room temperature (table 3, figure 3a,b). For TRIP steel, this involved sequences with soaking temperatures of 860°C as well as 940°C. In sequences involving soaking at 860°C, two deformation temperatures were tested: 680°C and 800°C. The specimens were held at 425°C for 600 seconds. In all cases, this produced a small amount of bainite (figure 3a) and to a larger amount of retained austenite, approx. 7%. Though minor, this change in the microstructural composition resulted in higher elongation, by approximately 5%, i.e. to values of 17 and 19% (table 3). The ultimate strength was approx. 100 MPa lower than in the relevant reference case. The isothermal step was also reflected in the nature of fracture surfaces. In the earlier cases, there were brittle fracture with cleavages. Now the fracture was ductile and showed dimples (figure 3c, d).

For QP steel, the isothermal hold was only incorporated in the sequence with a soaking temperature of 940°C (table 3). The purpose of the isothermal step was to facilitate partitioning of carbon between super-saturated martensite and retained austenite. The temperature and time were 250°C and 600 seconds. Tempered martensite and about 9% retained austenite (figure 3b) were the result of this sequence. This hold at the partitioning temperature led to a notably higher elongation, 8%, and lower ultimate strength, 1885 MPa (table 3). In this case, too, isothermal holding influenced the nature of fracture surfaces. The mixed fracture changed to ductile fracture with dimples without signs of brittle failure (figure 3 e,f).

Table 3. Effects of isothermal step during cooling to RT on mechanical properties of TRIP steel.

Steel	Heating temp. [°C]	Def. temp. [°C]	Hold [°C/s]	$R_{p0.2}$ [MPa]	UTS [MPa]	A_{20} [%]	HV10 [-]	RA [%]
TRIP steel	860	680	425/600	408	800	18.6	254	6
		800		383	830	17.2	250	7
	940	800		362	750	19	244	6
QP steel	940	800	250/600	1085	1885	8.3	598	9

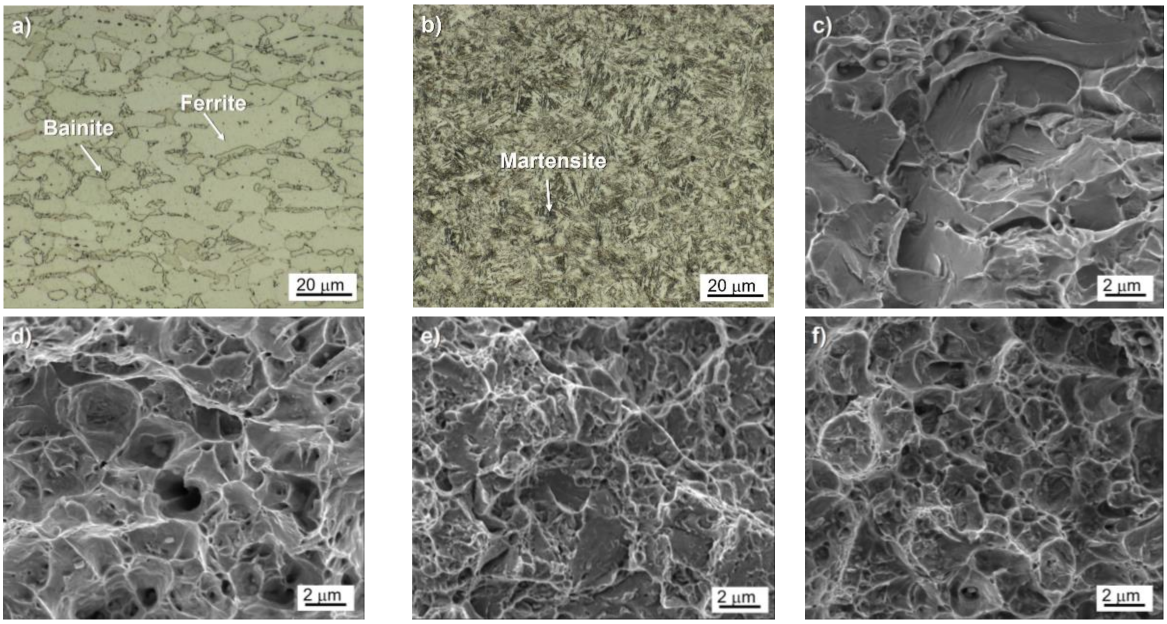

Figure 3. Microstructures produced by press-hardening sequences with isothermal holding: a) TRIP steel: 940°C – 800°C, b) QP steel: 940°C – 800°C; Fracture surfaces - c) TRIP steel: 940°C – 750°C (no isothermal hold), d) TRIP steel: 940°C – 800°C (with isothermal hold), e) QP steel: 940°C – 800°C (no isothermal hold), f) QP steel: 940°C – 800°C (with isothermal hold).

4. Conclusions

Sequences which simulated press hardening were carried out on two high-strength steels with different levels of carbon and alloying elements. Various soaking temperatures and deformation temperatures were used. In TRIP steel, which contained 0.2%, microstructure was not affected by changes in soaking and deformation temperatures to any appreciable extent. In all cases, the resulting microstructures were of ferritic-martensitic type and contained a small amount of retained austenite. Ultimate strengths were between 860 and 940 MPa, with elongations of more than 12%. Where isothermal holding was applied in the bainitic transformation region, bainite formed slightly more readily and a higher amount of retained austenite was stabilised. As a result, elongation increased to 19%.

In QP steel, changes in both soaking and deformation temperatures had a considerable impact on mechanical properties. To obtain the highest possible mechanical properties, soaking had to be performed at 940°C, which eliminated ferrite. Then, ultimate tensile strengths above 2000 MPa and elongation levels of 2% were achieved. Elongation was then improved by incorporating an isothermal step, resulting essentially in a Q&P process. Consequently elongation rose to 8% while the ultimate strength was 1885 MPa.

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