INFLUENCE OF HOLDING TIME IN THE DIE ON STRUCTURE DEVELOPMENT OF LOW-ALLOYED TRIP STEELS

Hana JIRKOVÁ, Jiří VRTÁČEK, Michal PEKOVIĆ, Štěpán JENÍČEK, Adam STEHLÍK, Karolína BURDOVÁ

University of West Bohemia, RTI - Regional Technological Institute, Pilsen, Czech Republic, EU,
hstankov@rti.zcu.cz[a], vrtacekj@rti.zcu.cz[b], pekovicm@rti.zcu.cz[c], jeniceks@rti.zcu.cz[d], stehlika@rti.zcu.cz[e], kburdova@rti.zcu.cz[f]

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Abstract

Press hardening is a modern forming technology for the production of shaped sheet parts. Its use has been growing in recent years because of its high production accuracy, reduced spring back effect and lower forming forces. This technology is also suitable for high strength TRIP steels (transformation induced plasticity). However, with dies at room temperature, undesirably high cooling rates are obtained, leading to the formation of martensitic structures with a low ferrite content. These structures possess high strength but low ductility. It is therefore important to interrupt the press hardening operation at the right time or even carry out additional heat treatment in a furnace.

Two low-alloy TRIP steels with a carbon content of 0.2 % and different niobium levels were selected for this experiment. At the first stage, the sheets were press-hardened between dies of a hydraulic press. The holding time was varied from 0 to 10 s and the sheet temperature after removal from the dies was measured with a thermal imaging camera. At the second stage, press hardening in a flat press hardening tool was followed by isothermal holding in a furnace. Mixed structures of martensite, bainite, proeutectoid ferrite and retained austenite were obtained when parameters were chosen properly.

Keywords: TRIP steel, multiphase structure, press hardening

1. INTRODUCTION

One of the available options, when it comes to reducing the weight and fuel consumption of vehicles to improve safety of passengers [1-3], is the use of car body parts of high-strength steels. In such a case, reduced emissions are an additional and today's highly relevant benefit.

Sheet parts for the car body are mostly produced by press hardening. It is a modern forming method which is suitable for a variety of steels, including high-strength martensitic steels for high-precision parts with low springback [2-4]. Since a variety of mechanical properties are required across the car body, these parts are also made of a wide range of materials. In the materials for the passenger compartment, high ultimate strength is required, which calls for martensitic steels with ultimate strengths of 1500 MPa and higher [5]. On the other hand, the demands on toughness are low in this part of the structure. By contrast, the car's crumple zones require high-ductility and crash-energy-absorbing materials. TRIP steels are a choice which meets these conditions [5]. When cold-deformed, these steels exhibit strain-induced plasticity (the TRIP effect) manifested by absorption of energy and by transformation of retained austenite to martensite [6-8]. The difficulty with these steels is their treatment which should produce a multiphase microstructure consisting of ferrite, bainite, a small amount of martensite and retained austenite. In order to achieve this goal, the rate of cooling in press hardening tools should be reduced, or the workpiece should be removed from the tools, which are at room temperature, before it cools below the M_s. The workpiece can then be held at a certain temperature to ensure that retained austenite becomes stable and that an amount of bainite forms. Hence, several processing parameters need to be optimised to obtain the desired multiphase microstructure with an optimal distribution of structure constituents [9,10].

2. EXPERIMENTS

In multiphase TRIP steels, the rate of cooling through the ferritic and pearlitic transformation regions is of major importance. The cooling rate must be sufficient to prevent the formation of pearlite, which is undesirable in TRIP steels, as it uses up carbon at the expense of stabilisation of retained austenite. Yet, cooling must be interrupted above the M_s, to ensure that the amount of newly-formed martensite is not excessive because martensite provides high strength but reduces ductility. In the press hardening of sheet products using tools at room temperature, the workpiece must be removed from the tooling early for either isothermal treatment in a furnace or slow and controlled cooling. It will produce the appropriate multiphase structure with the desired mechanical properties and high elongation. In this study, appropriate press hardening times in dies at room temperature were sought experimentally for two multiphase TRIP steels.

Both steels belonged to a class of low-alloy multiphase steels. They were CMnSi and CMnSiNb steels containing 0.2 % carbon, and additions of manganese and silicon (**Table 1**). The reason for choosing steels with manganese and silicon was that these elements enhance the stability of retained austenite and solid solution strengthening [6,7]. CMnSiNb also contained niobium which contributes to recrystallisation, appropriate grain size development, transformation behaviour and the desired characteristics of retained austenite [8,11,12].

The steels were supplied in the form of 1.8 mm cold-rolled sheet. They were produced by cutting up ingots and hot rolling the resulting segments to 5.8 mm thickness. After grinding and descaling, the semi-finished products were cold rolled to the final thickness of 1.8 mm. Before the actual experimental heat treatment, the sheets were annealed at 900 °C for 30 minutes. Blanks 100 mm in length were cut from the sheet stock.

The annealed microstructure consisted of ferrite and lamellar pearlite. No effect of niobium was manifested in hardness: both steels showed values of 180 -1 90 HV10. Neither was it apparent in phase transformation calculations performed using JMatPro software. The M_s temperature of CMnSi steel was calculated as 360 °C and that of CMnSiNb was 370 °C (**Table 1**).

Table 1 Chemical composition of experimental steels (wt. %), phase transformation temperatures (°C) and mechanical properties of annealed sheet blanks

Steel	C	Si	Mn	P	S	Cr	Nb	M_s (°C)	M_f (°C)	A_{c1} (°C)	A_{c3} (°C)	HV10 [-]	$R_{p0.2}$ (MPa)	R_m (MPa)	A_{20mm} (%)
CMnSi	0.20	1.74	1.41	0.008	0.003	0.12	0.001	360	246	734	862	190	422	635	27
CMnSiNb	0.21	1.77	1.44	0.008	0.003	0.11	0.06	370	257	734	861	180	427	627	26

2.1. Determination of appropriate press hardening time

The experimental programme was conducted in two stages. In the first one, the effects of press hardening times between flat dies of a hydraulic press were explored. The goal was to correlate the time between dies and the sheet temperature and microstructural evolution. Soaking at 950 °C took 100 seconds. The blank was then removed from the furnace, transferred and placed between dies, which took 5 seconds. It was then held between closed dies for 1, 3, 5, 7 and 10 seconds. Once the dies had opened, the temperature of the entire surface of the blank was measured with a thermal imaging camera. It was important to find the dwell time, upon which the blank temperature drops below the M_s. Final cooling to room temperature took place in the air.

In the second stage, actual press hardening tooling was installed on the press. After reviewing the results of the first stage of experiments, only three press hardening times were chosen for the second stage: 3, 5 and 10 seconds. In this case, a longer pause was required for handling the blank and placing it into the tool cavity: seconds. The 3 and 5-second press hardening operations were immediately followed by holding at 425 °C in a furnace for 20 minutes. The goal of these sequences was to explore the effect of the press hardening time on microstructural evolution and to test the complete treatment route for multiphase TRIP steels.

2.2. Materials characterization

The post-treatment microstructures of the sheets were examined using Olympus optical microscope (OM) and scanning electron microscopes Zeiss EVO MA (SEM). Hardness was measured on the materials using the HV10 scale. Room-temperature tensile tests at 0.003 s^{-1} were performed on miniature specimens with 1.2 mm × 2 mm and 5 mm gauge section and length, respectively. Temperatures were measured with FLIR SC 7550 thermal imaging camera at a resolution of 320 points × 256 points.

3. RESULTS AND DISCUSSION

In the first stage of experiments, which involved flat dies installed on a hydraulic press, the relationship between the press hardening time and microstructural evolution was studied. The measured temperature of the blanks being placed into the press was 890 °C. After the sequence with a 1-second press hardening time, the CMnSi microstructure was a mixture of bainite and martensite and a small amount of free ferrite (**Figure 1a**). Its hardness was 360 HV10. When removed from the dies, the sheet had a temperature of 595 °C. After longer press hardening times, the temperatures of the blanks were lower, understandably. After 5 seconds, the temperature was 330 °C; and after 10 seconds it was a mere 207 °C, which is below the M_s. With decreasing temperatures, the resulting fraction of martensite was increasing (**Figures 1b, c**).

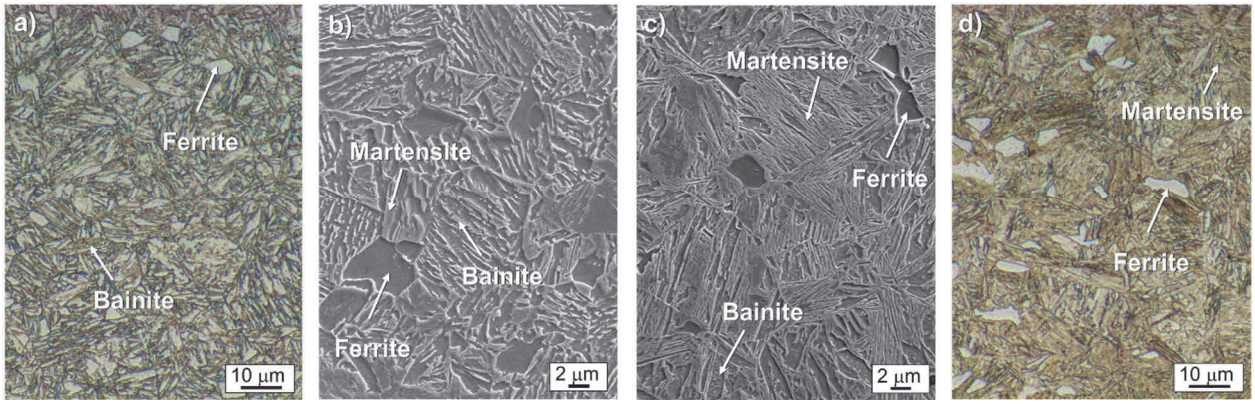

Figure 1 Microstructure of CMnSi steel after press hardening times: a) 1 s (OM), b) 3 s (SEM), c) 7 s (SEM), d) 10 s (OM)

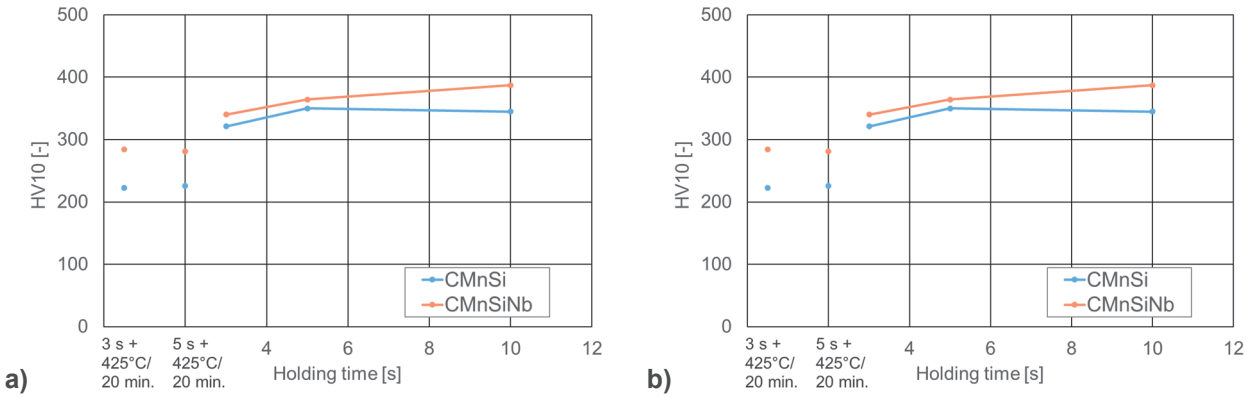

Figure 2 Hardness number HV10 vs. press hardening time (a); Hardness number HV10 after sequences with various press hardening times and with isothermal holding (b)

Martensite began to form along prior austenite grain boundaries. Its increasing amounts were reflected in the increasing hardness: after the sequence with a 10-second press hardening time, it reached 489 HV10 (**Figure 2a**). Martensite then dominated, the only other phase was a small amount of free ferrite (**Figure 1d**).

A similar trend was found in the Nb-microalloyed CMnSiNb steel. After the sequence with a one-second press hardening time, the microstructure was a mixture of bainite, martensite and proeutectoid ferrite. Its hardness was 357 HV10 (**Figure 3a**). In this material, too, longer press hardening times led to a reduction in the amount of bainite in favour of martensite (**Figures 3b-d**), which led to the higher hardness of up to 468 HV10 after the sequence with a ten-second press hardening time (**Figure 2b**).

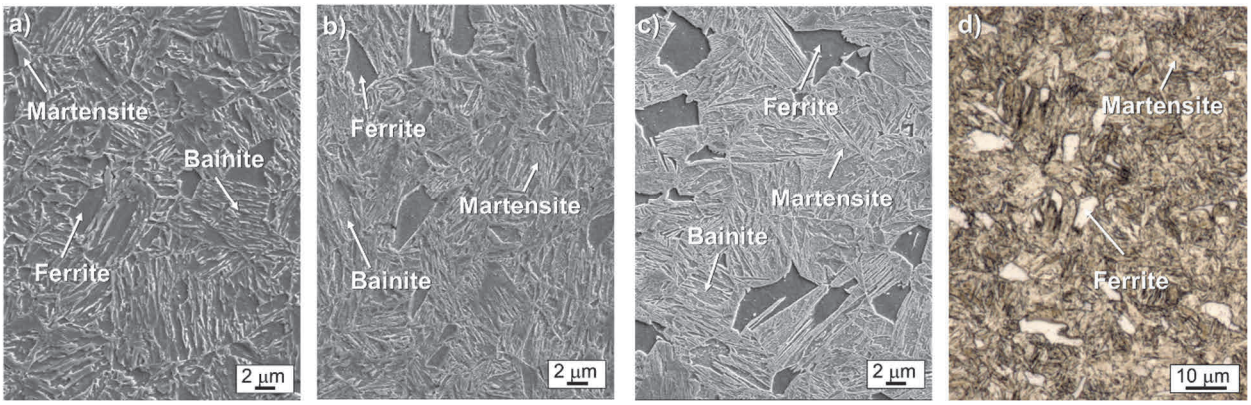

Figure 3 Microstructure of CMnSiNb steel after press hardening times: a) 1 s (OM), b) 3 s (SEM), c) 7 s (SEM), d) 10 s (OM)

Table 2 Heat treatment parameters and mechanical properties

Steel	Press hardening time (s)	Furnace temperature (°C)	Holding time in furnace (min)	HV10 (-)	$R_{p0.2}$ (MPa)	R_m (MPa)	A_{5mm} (%)
CMnSi	3	-	-	321	611	1116	12
	3	425	20	222	385	779	38.2
	5	-	-	350	616	1164	17
	5	425	20	225	369	785	35.2
	10	-	-	345	590	1117	17.5
CMnSiNb	3	-	-	340	988	1387	21
	3	425	20	281	556	865	33.8
	5	-	-	364	662	1236	13.3
	5	425	20	284	739	1027	28.2
	10	-	-	387	595	1135	17.2

Press hardening of CMnSi in a special tool for five and three seconds produced a ferritic-martensitic structure with hardness levels of 350-321 HV10 (**Figure 4a**). Thanks to a large amount of martensite, the ultimate strength was higher than 1160 MPa. A large ferrite fraction contributed to higher elongation: 12 - 17 % (**Table 2**). Additional microstructural changes only became apparent after isothermal holding, which followed the press hardening step. Short press hardening and holding at 425 °C in a furnace for 20 minutes led to a ferritic-bainitic structure with a small fraction of martensite (**Figure 4b**). This change in microstructure led to a drop in hardness to 222 HV10. As the press hardening time was short, the temperature has not decreased below the M_s; holding in the furnace then stabilised retained austenite thanks to enrichment with carbon, and also led to bainite formation. After this sequence, the ultimate strength was below 800 MPa, but elongation was appreciably higher: above 35 % (**Table 2**). For comparison, a sequence with a press hardening time of 10 s was performed as well. The blank reached the M_s during press hardening. Its microstructure consisted of martensite and ferrite and had a hardness of 345 HV10 (**Figure 4c**). Its ultimate strength was 1117 MPa and its elongation reached 17.5 % (**Table 2**).

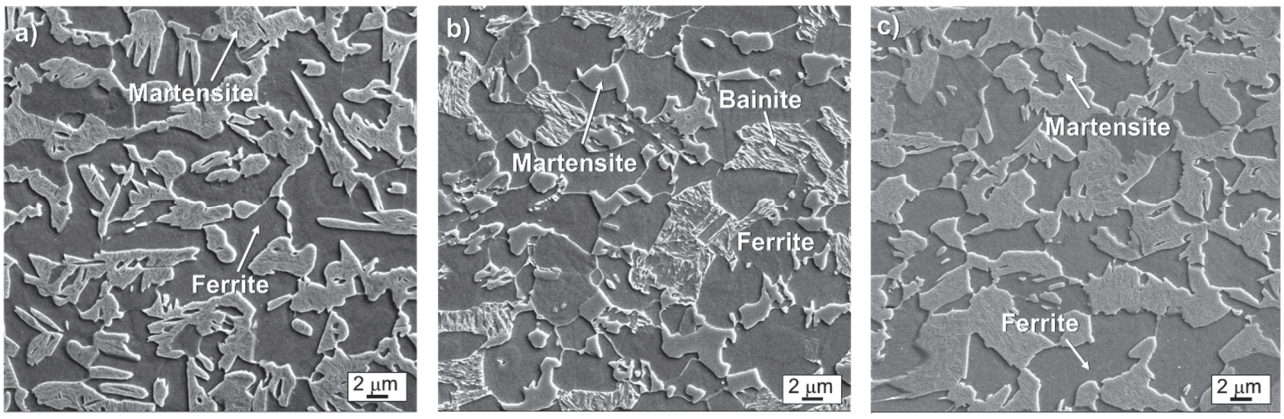

Figure 4 Microstructure of CMnSi steel after sequences with press hardening times: a) 3 s, b) 3 s+425 °C/20 min. c) 10 s

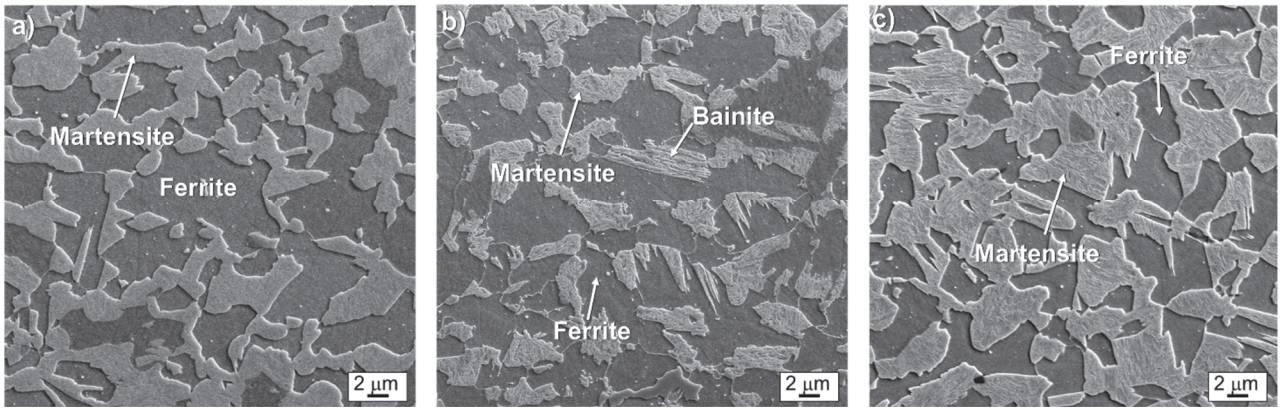

Figure 5 Microstructure of CMnSiNb steel after sequences with press hardening times: a) 3 s, b) 3 s + 425 °C/20 min. c) 10 s

Very similar behaviour was observed in CMnSiNb steel. The press hardening alone produced ferritic-martensitic microstructures, regardless of the dwell time between the dies (**Figure 5a, c**). Hardness levels were slightly higher than in the other steel: 387 through 340 HV10. Microalloying with niobium led to solid solution strengthening. The ultimate strength was between 1236 and 1387 MPa at elongations up to 21 % (**Table 2**). When the press hardening step was followed by holding in a furnace, the resulting microstructure was a mixture of ferrite, martensite and bainite (**Figure 5b**). The martensite fraction was larger than in CMnSi, and the same applied to hardness, 280 HV10, and strength, 865 - 1027 MPa (**Table 2**). Elongation was approximately 30 %.

4. CONCLUSIONS

In the present experimental programme, the effects of press hardening time, either between plain dies or a press hardening tool, on microstructural evolution and mechanical properties of blanks from two TRIP steels has been studied. At five-second and longer press hardening times, a martensitic microstructure with ferrite formed and exhibited high hardness up to 489 HV10. At shorter times, one second and three seconds, the final microstructure was a mixture of martensite, bainite and ferrite. When the press hardening operation in a tool at room temperature was followed by isothermal holding, both steels developed larger amounts of bainite and less martensite. CMnSi steel had ultimate strengths approx. 780 MPa and elongation levels higher than 35 %. In CMnSiNb, microalloying with niobium led to higher ultimate strength, up to 1027 MPa and elongations around 28 %. This experiment demonstrated the viability of press hardening of low-alloy TRIP steels in dies at

room temperature. It also showed that press hardening combined with subsequent holding in a furnace can produce the required mechanical properties.

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