EFFECT OF HEATING TEMPERATURE DURING SEMI-SOLID PROCESSING ON STRUCTURE OF X210CR12 STEEL

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Abstract
Semi-solid processing is an unconventional technique, which can be used to produce intricate components by forming and also to remove the sharp-edged carbides. However, the resulting microstructure after semi-solid processing consists of polyhedral austenite grains and lamellar ledeburite network. The network can be fragmented by applying an appropriate deformation sequence during cooling. X210Cr12 tool was experimentally processed by a combination of semi-solid processing and subsequent thermomechanical treatment. The heating temperature was varied from 1200°C to 1280°C. The obtained microstructures consisted of recrystallized grains of the M-A constituent and fine chromium precipitates without sharp-edged carbides with hardness higher than 800 HV10.

Keywords: semi-solid processing, carbide network, heating temperature, X210Cr12

1 Introduction

Semi-solid processing can be used to manufacture a wide range of products of various materials [1, 2]. Once this technology gained a foothold in the field of aluminium and magnesium alloys, the research effort refocused on Fe-based materials [3-6]. For thixoforming to be successful, the workpiece microstructure must contain solid spheroids in the liquid matrix. Such a material exhibits thixotropic behaviour when under shear forces [3, 7, 8]. Steels upon semi-solid processing often contain polyhedral austenite grains embedded in a eutectic network [9-11]. This network is brittle but under appropriate conditions and thermomechanical treatment parameters it can be broken up and redistributed.

Owing to the high temperature used, this process is able to eliminate sharp-edged chromium carbides. These carbides exist in high-chromium tool steels produced by conventional metallurgical routes. In most cases, they are M_7C_3 carbides [12]. Carbides in tool steels which remain stable even after heat treatment do improve wear resistance, corrosion resistance and creep resistance but they also reduce toughness [13-16].

2 Experimental programme

The dependence of liquid fraction on temperature governs the rheological behaviour of the material as well as its microstructural evolution [1]. The heating temperature is therefore one of the important parameters of semi-solid processing.

Upon cooling from the semi-solid state, high chromium tool steels contain brittle lamellar networks which are impossible to remove by conventional heat treatment routes. One of the

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effective methods for eliminating such networks is thermomechanical treatment which can break them up and redistribute the resulting fragmented carbides.

2.1 Experimental material and methods

The experimental material was X210Cr12 steel, a typical representative of steels which contain sharp-edged chromium carbides. With its chemical composition and a wide freezing range, this steel is suitable for semi-solid processing (**Table 1**), [17].

Table 1 Chemical composition of X210Cr12 steel [wt.]

C	Cr	Mn	Si	Ni	P	S
1.8	11	0.2	0.2	0.5	0.03	0.035

It has been developed for applications in punching machines and presses, mainly for heavy-duty punches and highly-complex progressive and combination tools [18]. For this experiment, it was obtained in the form of annealed bars. Its microstructure contained large sharp-edged primary chromium carbides and very fine cementite embedded in a ferritic matrix.

Optical (OM) and scanning electron microscopes (SEM) were employed for microstructure observation (Tescan VEGA 3, Zeiss Crossbeam 340-47-44). The amount of retained austenite was measured by X-ray diffraction phase analysis. The automatic powder diffractometer AXS Bruker D8 Discover with a position-sensitive area HI-STAR detector and a cobalt X-ray source ($\lambda_{K\alpha}$ = 0.1790307 nm) was employed.

2.2 Determination of suitable processing parameters

The first step was to map the relationship between the heating temperature, the liquid fraction and the extent of dissolution of primary chromium carbides. As part of this effort, an approximate calculation using the JMatPro program was carried out [19].

It was found that up to 758°C the material retains a stable ferrite-cementite microstructure. It begins to melt at 1225°C and the melting is completed at 1373°C. Chromium carbides dissolve at 1255°C (**Fig. 1**).

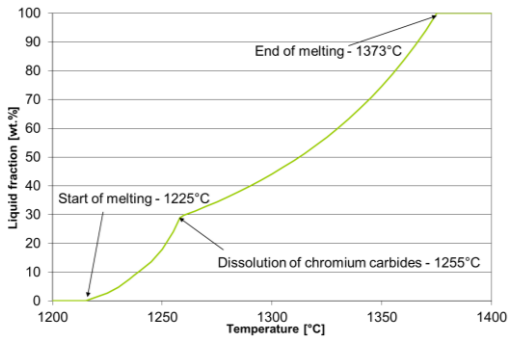

Fig. 1 Liquid fraction vs. temperature – calculation by JMatPro software

2.3 Semi-solid processing and press forming

To facilitate handling of the partially melted workpiece, the tool steel stock was placed into a container of SJ355 low-carbon steel whose solidus temperature was appreciably higher than that

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of the tool steel. The container had a diameter of 30 mm, wall thickness of 6 mm and length of 55 mm. Heating into the semi-solid state took place in an air furnace. In order to break up the lamellar ledeburite network, redistribute its fragments and facilitate recrystallization, the enclosed workpiece was open-die-forged between flat dies of a hydraulic press. The objective of the experimental programme was to test various heating temperatures, from those below the solidus to those at which the material contains 30% liquid phase (**Table 2**).

Table 2 Semi-solid processing and press forming parameters and results

Treat.	Heating temp. [°C]	Time at temperature [minutes]	Forming temperature [°C]	Time at temperature [minutes]	Number of forming steps [-]	HV10 [-]	Retained austenite [%]
1	1200	15	1080	1.5	4	848	13
2	1220	15			4	803	15
3	1220	60			5	836	10
4	1240	15			5	864	17
5	1240	60			5	855	11
6	1250	15			5	836	10
7	1265	15			5	881	12
8	1280	15			5	866	8
9	1240	1.5	quenched in water after holding at heating temperature			371	78
10	1240	15	1080	1.5	water quenching	388	71

The first step of each experimental sequence involved heating to the heating temperature and holding for 15 or 60 minutes. The second step was water quenching for 3 seconds. This step led to rapid solidification. It had been found earlier that the cooling rate governed the fineness of the lamellar network [10, 20]. The third step involved reheating in a furnace to the forming temperature of 1080°C and holding for 1.5 minutes. The next step was press forging using four or five blows. Alternately, upsetting and drawing out blows were applied. After forging, the workpieces were quenched in water.

The first sequences involved temperatures below the solidus: 1200°C and 1220°C (sequences 1 and 2). The effect of extending the time at temperature from 15 to 60 minutes was explored in sequence 3. After the heating step in these sequences, the microstructure consisted of austenite and undissolved M_7C_3 chromium carbides.

The heating temperature of 1240°C was combined with 15-minute holding time (sequence 4), as well as 60-minute holding time (sequence 5). According to the calculations, the material should contain 10% liquid phase at this temperature but the chromium carbides should not be fully dissolved yet. Other temperatures used in the experimental sequences were 1250°C (sequence 6), 1265 °C (sequence 7) and 1280°C (sequence 8).

The behaviour and microstructural condition of the material after heating into the semi-solid state without forming were figmapped with the sequence that involved the heating temperature of 1240°C and subsequent water quenching (sequence 9). In order to assess the effects of reheating to 1080°C, sequence 10 did not include forming operations and the specimen was quenched in water after reheating to the forging temperature.

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3 Results and discussion

Sequences with heating temperatures below the solidus temperature, i.e. 1200°C (sequence 1) and 1220°C (sequences 2 and 3), led to microstructures with very fine recrystallized austenite grains, most of which eventually decomposed into martensite. The result was the M-A constituent (**Fig. 2**). The size of these grain was less than 0.5 μm. Some of the austenitic grains did not recrystallize fully, causing grain coarsening. (**Fig. 3**). Since the heating temperature was relatively low, the primary chromium carbides have not dissolved. The material did not melt during heating, and therefore no lamellar network has formed. Very fine secondary chromium carbide precipitates were present in the matrix. Hardness values were very high: between 804 and 848 HV10 (**Table 2**). Even the extension of the time at temperature from 15 minutes to 60 minutes has not led to a change in the type of microstructure.

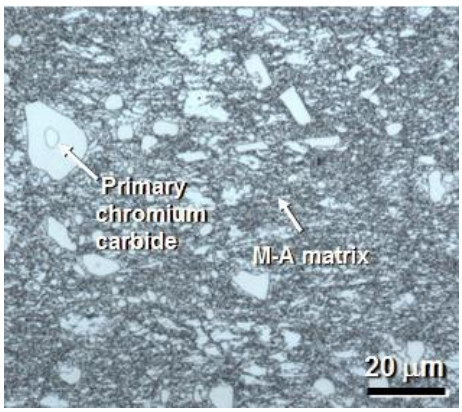

Fig. 2 Sequence 1 – 1200°C – matrix of fine grains of the M-A constituent with undissolved primary chromium carbides and new precipitates of chromium carbides, OM

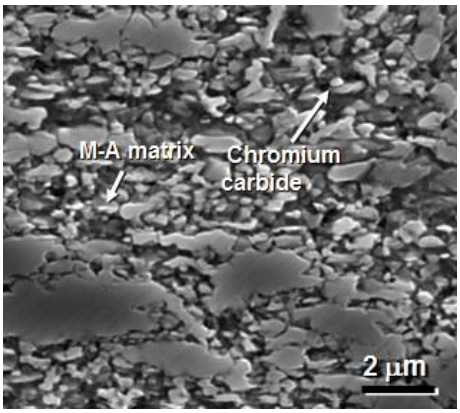

Fig. 3 Sequence 2 – 1220°C – close -up view of the recrystallized matrix with small islands of coarse unrecrystallized austenitic grains, SEM

Using X-ray diffraction analysis, the material was found to contain 10-15% retained austenite. In addition, Cr_7C_3 and Fe_3C carbides were detected. 2D diffraction patterns with smooth and continuous lines indicated that the microstructures were fine-grained. In addition, there was slight preferred orientation (indicated by the varying intensity of diffraction lines along the longitudinal profile).

Another heating temperature was 1240°C which was applied with two holding times: 15 minutes (sequence 4) and 60 minutes (sequence 5). According to the calculations, the material should contain approx. 10% liquid phase at this temperature. This was confirmed by microstructure observation which found a eutectic lamellar network. The network was partially broken up by forging and redistributed within the very fine martensitic matrix with chromium carbide precipitates (**Fig. 4**). As in the previous case, the austenitic grains were very fine: approx. 0.5 μm. Hardness was very high again: 855 to 864 HV10. Longer time at the heating temperature reduced the retained austenite fraction from 17% to 11%. 2D diffraction patterns with smooth and continuous lines again confirmed fine-grained microstructures.

Another sequence had a heating temperature of 1250°C (sequence 6), at which the chromium carbides are almost fully dissolved, according to the calculation. Only a very small amount of

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undissolved large primary chromium carbides was found in the resulting microstructure. Deformation at 1080°C initiated the recrystallization of austenite. During subsequent cooling, austenite transformed to martensite (**Fig. 5**). Hardness was 836 HV10. A further increase of the heating temperature to 1265°C led to no significant change in the microstructure (sequence 7). Hardness rose to 881 HV10, which might be due to complete dissolution of chromium in the solid solution. The volume fraction of retained austenite was 12 %.

Due to high liquid fraction (**Fig. 6**), the largest volume fraction of the ledeburite network was found in the specimen processed with the highest heating temperature, 1280°C (sequence 8). The forging operations failed to remove his network to any significant extent. Hardness was very high: 866 HV10. The lowest fraction of retained austenite was found here: 8%.

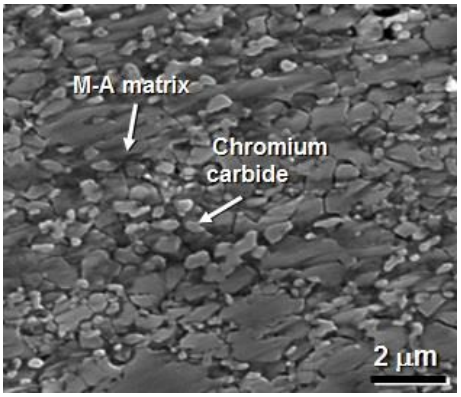

Fig. 4 Sequence 4 – 1240°C – very fine martensitic matrix with 17% retained austenite and secondary chromium carbides, SEM

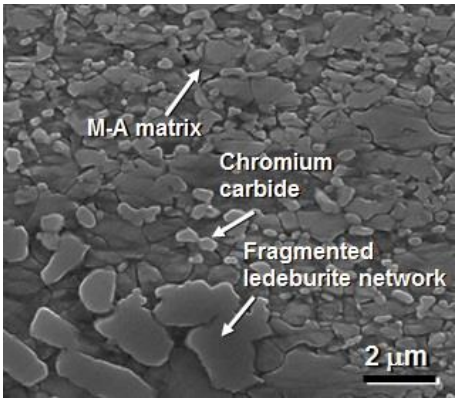

Fig. 5 Sequence 6 – 1250°C – close-up view of fragmented ledeburite network and martensitic islands, SEM

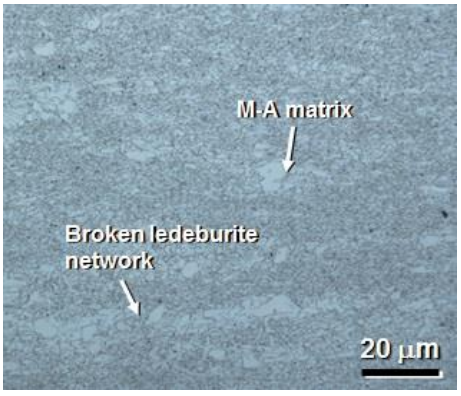

Fig. 6 Sequence 8 – 1280°C – a larger volume fraction of intact ledeburite network, OM

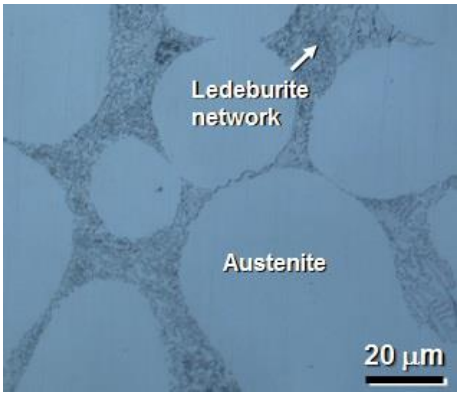

Fig. 7 Sequence 9 – 1240°C – water quenching – polyhedral austenitic grains with ledeburite network, OM

Sequences without deformation led to completely different microstructures. Water quenching immediately after holding at 1240°C (sequence 9) produced a microstructure of polyhedral

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austenite grains and lamellar ledeburite network (**Fig. 7**). This microstructure is a typical product of semi-solid processing. Hardness dropped to 371 HV10. The presence of a large amount of austenite was confirmed by X-ray measurement: 78%. 2D diffraction patterns indicated the onset of coarsening: the longitudinal profile of diffraction lines shows discrete higher-intensity dots and discontinuities. A similar microstructure was obtained with the sequence where water quenching was applied after reheating to the forming temperature of 1080°C. The austenite fraction was lower: 71%.

4 Conclusions

Semi-solid processing with subsequent press forging was carried out on X210Cr12 tool steel. The effects of heating temperatures in the range from 1200°C to 1280°C on dissolution of primary chromium carbides and microstructural evolution were studied. Primary chromium carbides were almost completely dissolved at the heating temperature as low as 1240°C. The microstructure consisted of very fine grains of the M-A constituent, secondary chromium carbide precipitates and partially fragmented lamellar network, and had a hardness of 864 HV10. The volume fraction of retained austenite was 17%. When forming was omitted, the resulting microstructures were those typical of semi-solid-processed materials: large polyhedral austenitic grains and lamellar eutectic network, with hardnesses of around 380 HV10.

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