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Modification of metastable microstructure of CPM15V steel by heat exposure after treatment in semi-solid state

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ABSTRACT

Processing in the semi-solid state allows the benefits of the process of forming and casting to be combined. In addition to obtaining complicated shapes, unusual forms of structures with exceptional properties can also be formed. A special processing procedure in the semi-solid state for very small parts has been developed, which is called mini-thixoforming, is able to handle CPM15V steel powder. From the original ferrite matrix with primary chromium–vanadium carbides – a mixed structure was obtained by processing consisting of metastable austenite, rod-shaped chromium–vanadium carbides and the original chromium–vanadium carbides. Compared to the initial state (micro hardness approx. HV10 330), this structure achieved, as a result of the relatively high rate of cooling in the form, a hardness of approx. 730 HV10. Due to the fact that this is a metastable structure, experimental heating to temperatures 400, 500, 600, 700, 800 °C for 1 h was performed. With exposure at temperatures 400 and 500 °C there was a slight decrease in hardness of approx. 20 points, heat treatment at 600 °C achieved hardness of 960 HV10. This state corresponds to an equivalent value of compressive strength of approx. 2880 MPa, Further increase in temperature leads to a continuous decrease in hardness due to decomposition of the metastable matrix. Thermal exposure at 700 °C, resulted in hardness of 585 HV10. After exposure to 800 °C there was a significant decrease of hardness to 425 HV10.

1. Introduction

Development of new ceramic, plastic and non-ferrous metallic materials is typically motivated by pressure on price or by a need for better mechanical properties or degradability. Last but not least is the need to achieve the final shape of the product as effectively as possible. In many cases, steels are still irreplaceable even against the competition of currently available materials and processing technologies. The competitiveness of this group of materials is enhanced by new types of steels and by innovative processing methods that continue to push back the frontiers of application of traditional materials. One such method is the unconventional semi-solid processing of powder steel. One of the main strengths of this process known as thixoforming is its potential to create new microstructure constituents which could not form during conventional forming or casting process [1–7]. Consequently, the final product may, if appropriate material and processing parameters are used, exhibit better mechanical properties than products made by conventional processes. Another strength of the thixoforming process is its ability to produce intricate final shapes in a single forming operation, thus avoiding extensive machining. In addition, processing small volumes of material offers the benefits of rapid heating, solidification and cooling. A new mini-thixoforming process was developed to reap these benefits [8–11]. Mini-thixoforming allows very small components to be manufactured [9]. In this study, mini-thixoforming was used for processing a difficult-to-machine powder steel. The purpose of this investigation was to obtain not only the intricately-shape final product, but also microstructures that can be expected to possess good mechanical properties and high wear resistance. Since the microstructures created in this manner contain a high volume fraction of metastable austenite, the experiment was designed to explore their thermal stability and map the stages of decomposition of individual microstructure constituents.

2. Experimental

Semi-solid processing was performed in experimental mini-thixoforming equipment, developed for that purpose, combines high-frequency induction heating and resistance heating. The feedstock in this device is heated in the mould, unlike

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Table 1
Chemical composition of CPM 15V powder steel in wt.%.

C	Cr	V	Mo	Mn	Si
3.40	5.25	14.50	1.3	0.5	0.9

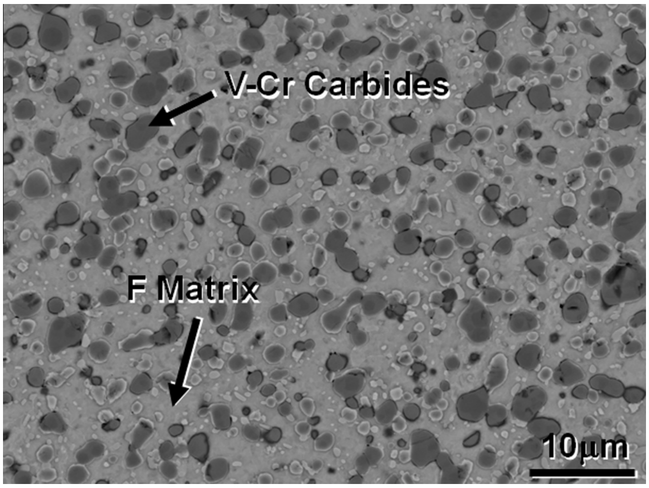

Fig. 1. Initial microstructure of CPM15V steel.

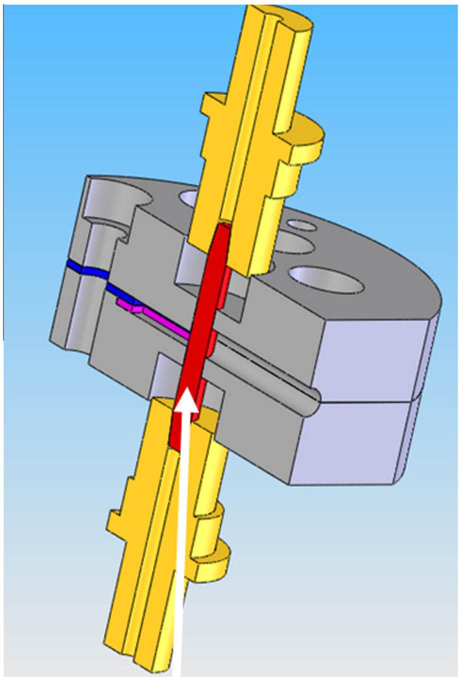

Fig. 2. Tool for mini-thixoforming, cross-section.

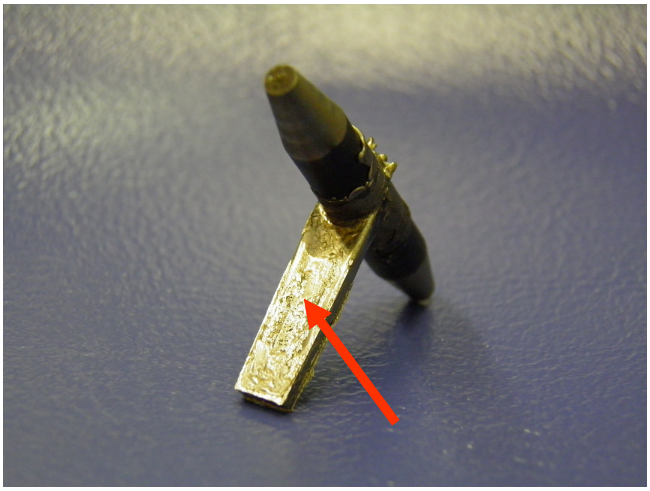

Fig. 3a. Example of product with 5 × 1 mm^2 cross-section, length 12 mm.

the other devices for thixoforming. Further details of the experimental setup are given in [8–13]. By this means, thermal and deformation pathways can be controlled to a high precision even at high heating and cooling rates [9,12,13]. The experimental material was CPM15V powder steel with high levels of carbon, vanadium and chromium (Table 1). This steel with uniform microstructure is intended for applications where the combination of high strength and very high wear resistance is of particular importance. The initial microstructure consisted of ferrite matrix and vanadium–chromium carbides (Fig. 1). The hardness of the initial material was 330 HV10, when a maximum achievable hardness by conventional heat treatment, after quenching and tempering, guaranteed by the producer was 748 HV10 [14].

Feedstocks of 6 mm diameter and 46 mm length were made from the initial experimental material. Processing took place in a titanium mould with a replaceable shape insert (Fig. 2). Various final product shapes can be obtained by using various inserts (Figs. 3a and 3b). Electrical current for heating the feedstock placed in the mould was fed through copper electrodes.

For the purpose of semi-solid processing, the volume fraction of the liquid phase should be between 40% and 60% [1,4–7]. In the CPM15V steel, the temperature window for thixoforming is very narrow: a mere 25 °C. This is why the thermal schedule must be closely controlled during processing. Once this limitation was overcome, a number of unconventionally distributed microstructure constituents could be obtained thanks to high levels of alloying elements.

Calculations using the JmatPro software (materials Property Simulation Package, Version 6.2) were performed for defining the processing temperature: 1308 °C to define 40% of the liquid phase fraction [17]. The temperatures of the solidus and the liquidus 1300 °C resp. 1318 °C where calculated.

The temperature for the experiment was corrected empirically and stated to 1270 °C, which meant 30% fraction of the liquid phase, estimated from the proportion in the microstructure. At this temperature the mould cavity was filled the best (Figs. 3a and 3b). The maximum range of the working temperatures 25 °C was experimented as well [14,15].

Heating from room temperature to the processing temperature took 55 s (Diagram 1). The feedstock in semi-solid state was then compressed and forced into the mould cavity. The maximal axial force used for compression was 6.5–7 kN (Diagram 2). A FEM simulation of velocity and temperature was calculated in Ansys/Flotran v.10.0 software (Figs. 4a and 4b). Complementary Finite Element calculations indicate that the cooling rates are relatively high and the surface of the product is cooled down below the equilibrium solidus temperature during a time of about 0.3 s. The liquid phase remains only in the central region.

Demonstration products of various shapes were obtained (Figs. 3a and 3b).

Modification of microstructure by heat treatment was explored using a 5 × 12 mm^2 segment of the product (Fig. 3a). The specimen was protected by paint Condursal Z1100 for protection against decarburization. The paint contains carbon, which reduces the concentration gradient of carbon atoms in thermally processed material, preventing carbon diffusion to the material surface temperature until 1100 °C is reached. Thermal exposure took place in an atmospheric furnace at 350, 400, 500, 600, 700 and 800 °C. The holding time was 1 h, followed by cooling in still air outside the furnace (Table 2). The resulting microstructure was observed using optical and scanning electron microscopes. Local chemical composition was measured using EDAX analyzer in both unetched and etched surface conditions. Specimens were prepared for observation by etching in V_2A etchant. Mechanical properties were examined by HV10 hardness testing along two parallel lines.

The microstructures of the specimens were studied using the special designed ultra high vacuum scanning low energy electron microscope (UHV-SLEEM). This microscope is equipped with a cathode lens (CLs) mode. The primary electrons are retarded in the electrostatic field created by the CL. The cathode of the CL is created by the negative biased specimen and the anode is formed by the grounded detector located below the pole piece. The CL mode enables us to observe the specimens with arbitrary landing energies and offers several advantages. The advantages are described in detail [16,17]. In this experiment used the energy 500 eV were used in order to obtain the maximum contrast between the phases and extremely high surface sensitivity.

3. Results and discussion

Compared to the initial state (Figs. 1 and 5) semi-solid processing produced a microstructure consisting of the M–A constituent,