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Analysis of the influence of the gas velocity, particle size and nucleation temperature on the thermal history and microstructure development in the tool steel during atomization

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ABSTRACT

The paper deals with the analysis of the influence of the nitrogen gas velocity, particle size and nucleation temperature on the microstructure development in the tool steel of ledeburite type Ch12MF4 in the process of atomization. Three main types of solidification microstructures were identified using microscopic analysis in rapidly solidified powder particles: dendritic, cellular (grain-refined) and compound, representing the mixture of dendritic and cellular microstructures. It can be supposed that the transition from initially dendritic to compound and cellular or grain-refined microstructure occurs by the mechanism of thermally induced fragmentation of dendrites during quasi-isothermal period of solidification if additionally the recalescence temperature is sufficiently high. The microstructures documented the procedure of dendrites fragmentation and following spheroidization of dendrite fragments in rapidly solidified powder particles from the Ch12MF4 alloy are presented.

Applying developed mathematical model of cooling and solidification of a single spherical droplet in atomization process, the influence of nitrogen gas velocity and other parameters as nucleation temperature on the thermal history of a droplet with various diameters during atomization is studied. Based on the comparison of results of mathematical modeling and microstructural observations, the thermophysical conditions for the transition from dendritic to cellular (grain-refined) microstructure development in the rapidly solidified powder particles from the Ch12MF4 steel are predicted.

1. Introduction

Gas atomization of molten alloys belongs to the technologies applied with many benefits for production of large scale of metallic materials. During gas atomization, a molten stream is disintegrated by the impact of a high velocity gas flow into quasi-spherical droplets of different sizes [1,2]. Solidification of solid phase in the liquid particles starts by nucleation at a certain temperature below the liquidus temperature. Rapid non-equilibrium solidification of an undercooled droplet is accomplished non-isothermally in several stages. After nucleation, the phase of recalescence or quasi-adiabatic period of rapid solidification occurs. During this period, the temperature of the droplet rapidly increases due to the latent heat release. In the next period of quasi-isothermal plateau, the temperature of the droplet remains almost constant as the latent heat released and the heat extracted from the droplet to the atomizing gas per unit time are approximately equal. The final stage of solidification represents the cooling of the solidified particle. The size of rapidly solidified (RS) powder particles exploited for production of compacts from high-alloyed alloys achieves tens to hundreds of micrometers.

Pressure, velocity and temperature conditions in the atomizing cone are very different. In this reason, various microstructures can develop in single particles during their rapid solidification. For example, in RS powder particles from the iron, cobalt and nickel based alloys, several types of primary solidification microstructures have been observed [3–15]. However, the thermophysical conditions and mechanisms of the development of different types of primary structures in RS powder particles from iron based alloys have been not sufficiently recorded and explained. According to the morphology of primary phases in the RS powder particles from alloys of hypoeutectic type, three main kinds of microstructures obviously occur: dendritic, cellular and compound.

Moreover, the phenomenon of grain refinement during rapid solidification of highly undercooled melt has been observed in several metallic systems. For explanation of the structural changes

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during solidification of the undercooled single-phase solid-solution alloys, grain-refinement models of dendrite fragmentation were developed [16–19].

The paper deals with the solidification of the hypoeutectic tool steel of ledeburite type Ch12MF4 in the process of gas atomization. The quasi-equilibrium solidification of hypoeutectic steels of ledeburite type during conventional casting starts by formation of austenite followed by eutectic reactions resulting in the development of different types of hard carbides located in interdendritic regions [11,20–22]. In order to suppress the liquation processes and to enhance mechanical, technological and utility properties, these steels are produced at present mainly by techniques of powder metallurgy.

Different types of microstructures developed in the RS powder particles from the Ch12MF4 tool steel in the process of nitrogen gas atomization have been documented in [23]. The mechanism of austenite dendrites fragmentation was also presented together with the semi-quantitative thermophysical model of microstructure evolution in RS powder particles from the Ch12MF4 steel. The main aim of this work is to complete and extend the developed model taking into account relevant microstructural and technological parameters influencing formation of the final microstructures in RS powder particles from investigated steel.

Table 1
Volumetric density of crystal nuclei for analyzed diameters of RS powder particles.

Particle diameter (μm)	Volumetric density of nuclei (mm^3)
40	1,100,000
60	1,400,000
80	790,000
120	370,000
300	190,000
600	180,000

2. Characteristics of the Ch12MF4 steel and RS powder

Material properties and solidification behavior of the Ch12MF4 steel with the chemical composition of 2.37% C, 12.06% Cr, 1.2% Mo, 4.0% V and balance Fe (wt.%) in the quasi-equilibrium conditions were investigated experimentally by differential thermal analysis and also using computational methods in ThermoCalc and JMatPro [24,25]. As it follows from experimental and computational results, the solidification of the Ch12MF4 steel in quasi-equilibrium conditions starts at the liquidus temperature of 1324 °C by crystallization of austenite – solid solution of carbon and alloying elements in iron and it continues by two eutectic reactions. The first eutectic reaction during which the two-phase mixture of austenite and MC carbides develops begins at the temperature T_{E1} = 1253 °C. At the temperature T_{E2} = 1239 °C, the second eutectic reaction starts resulting in the formation of austenite and M_7C_3 carbides. Phase identification was performed by transmission Mössbauer spectrometry and X-ray diffraction analysis [22]. The order of eutectic reactions was determined by computations but it was not experimentally confirmed. The solidification is finished at the solidus temperature of 1225 °C. Thus, the solidification of investigated steel occurs in the temperature interval approximately 100 °C. In the first half of this temperature interval, the alloyed austenite is formed. Afterwards, two different austenite–carbide eutectic mixtures of phases develop.

For microstructural analysis, RS powder particles were screened into nine standard size granulometric fractions ranging from 50 μm to 56 μm up to more than 630 μm. RS powder particles were bounded by electrolytically deposited nickel and metallographically prepared using standard procedures. Methods and experimental techniques of light microscopy and scanning electron microscopy were applied. The analysis of the microstructure in 4500 RS particles (500 particles from each size fraction) confirmed the main results obtained earlier [11,22,23]. From the morphological point of view, three main types of solidification microstructures were identified RS powder particles: dendritic, cellular (grain-refined) and compound, representing the mixture of dendritic and cellular microstructures. It is supposed that the transition from dendritic to compound and cellular (grain-refined) microstructure occurs by the mechanism of thermally induced fragmentation of primary dendrites developed in the initial stage of solidification and following spheroidization of dendrite fragments during the quasi-isothermal period of solidification [23].

3. Numerical simulation of the cooling and solidification of particles in gas atomization

To analyse and predict the conditions for initiation and accomplishment of the process of microstructure transition from

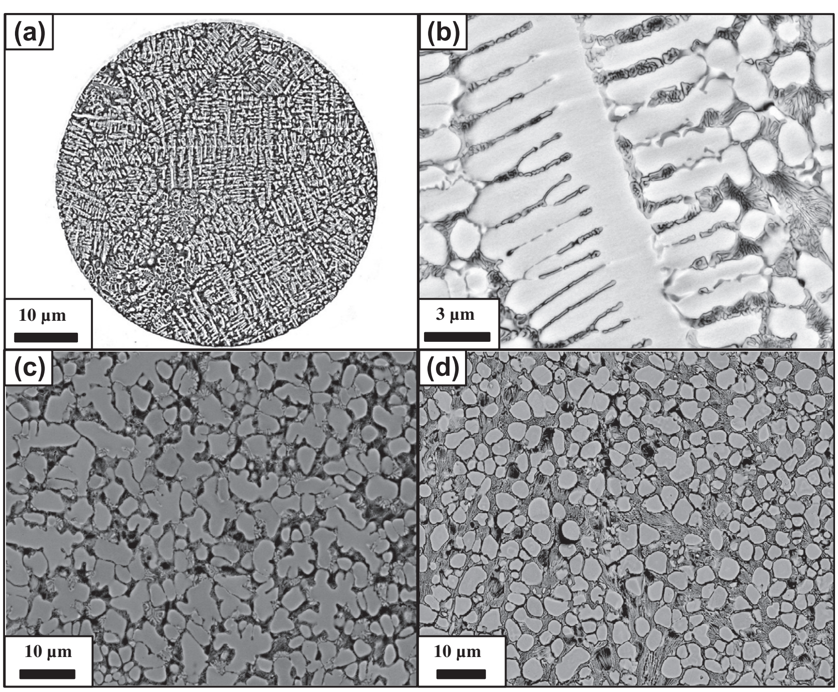

Fig. 1. Thermally induced transition of dendritic microstructure in RS powder particles from the Ch12MF4 steel to the cellular (grain-refined) microstructure: (a) RS particle with dendritic monoblocks of the austenite in austenite–carbide eutectics, (b) fragmentation of secondary austenitic dendrite arms, (c) advanced stage of austenite dendrite fragmentation and spheroidization, and (d) cellular (grain-refined) microstructure developed by spheroidization of austenite dendrite fragments and formed by austenite quasi-globular particles (cells) located in eutectics.

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