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Fabrication of functionally graded materials by introducing wolframium carbide dispersed particles during centrifugal casting and examination of FGM's structure

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Abstract

The paper describes procedures developed for disperse powders introduction into metal melts. We propose to fabricate functionally graded materials by introducing WC particles into liquid metal during mould filling in centrifugal casting machine. A number of experimental studies have been conducted, samples with different WC content have been fabricated and their structure has been examined. The research has revealed that WC particles were distributed unevenly along the width of the samples with the highest concentration in the outer zone of the cylindrical samples. The particles considerably influenced macro- and microstructure causing its grade to decrease from 2 to 9.

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Keywords: wolframium carbide, low-carbon steel, centrifugal casting, functionally graded materials (FGMs).

1. Introduction

Functionally graded materials (FGMs) with preset properties are increasingly used in machines and mechanisms in petrochemical, gas and machine building industries. Efficient design procedures that can ensure predicted interdependence of composition, structure, mechanical and physical properties provide new opportunities and fields for FGM practical application [1].

Introduction of carbide, oxide and nitride dispersed particles during mould filling is one of the methods of FGM fabrication. FGMs can be classified into materials made of fine disperse powders that have been pressed and

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sintered, as well as into materials reinforced with disperse powders (their content doesn't exceed 20 %) that were introduced into a melt at various stages of production [2]. The current paper does not focus on materials made of fine disperse powders since a great number of studies have been dedicated to that subject [3-10]. This study contains a detailed examination of methods used to fabricate so-called dispersedly reinforced materials with disperse powder content of up to 20 %.

2. Method

Experts of the General Metallurgy Department of the South Ural State University developed and patented a new method of FGM production: disperse powder is added to molten while a centrifugal casting mould is being filled [11]. The method is based on difference in density of reinforcing carbides and a reinforced metal. If the density of a thermally-resistant dispersed particle differs from the density of the melt in which it's been introduced, the centrifugal force influencing the particle isn't balanced with the gravity force. Thus, a particle is pushed towards the inner or outer edge of a sample. Once the particle faces the solidification front, the molten metal presses it to the front. Therefore, the particle cannot surface and gets captured by growing dendrites. Particles with a density higher than melt's density (e.g. wolframium carbides, ρ=15,6 g/cm3) are pushed towards the outer zone, meanwhile, particles with lower density (e.g. silicon carbides, ρ=3,2 g/cm3) move towards the inner zone of a sample.

Experimental casting was performed to test the proposed method. Low-carbon steel was used as a reinforced metal (C 0.17–0.24%; Si 0.17–0.37%; Mn 0.35–0.65%; S≤0.040%; P≤0.035) and WC powder was taken for reinforcement Table 1.

Table 1. Amount of carbides in experimental samples

Cast number	1				2			
Sample number	1	2	3	4	5	6	7	8
WC content, g	0	40	80	120	0	120	240	360
WC content, % (mass percentage)	0	0.4	0.8	1.2	0	1.2	2.4	3.6

3. Results

Eight hollow cylindrical samples were fabricated for the study. Their dimension were the following: outer diameter of 140 mm, inner diameter of 55 mm, length of 140 mm. Molten metal was heated up to 1650 ˚C and poured into a rotating mould (1200 rpm) with a graphite core.

Samples for metallographic examinations were cut out from the cylinders (Fig.4). The cylinders were roughly divided into 3 zones Fig. 1: 1 – the outer zone, 2 – ½ of a cylinder width, 3 – the inner zone.

The prepared samples were treated for 10 sec. with the following reagent: 3 ml of HCl; 0.2 g of $CuCl_2 \cdot 2H_2O$; 3 g of $FeCl_2$; 0.1 g of $SnCl_2$; 10 ml of ethanol; 100 ml of water. The samples were examined to find out whether their macrostructure from the outer to the inner zone had changed Fig. 2.

Fig. 1. Fabricated cylinders and cut-out samples: 1 – outer zone, 2- ½ of the width, 3 – inner zone.

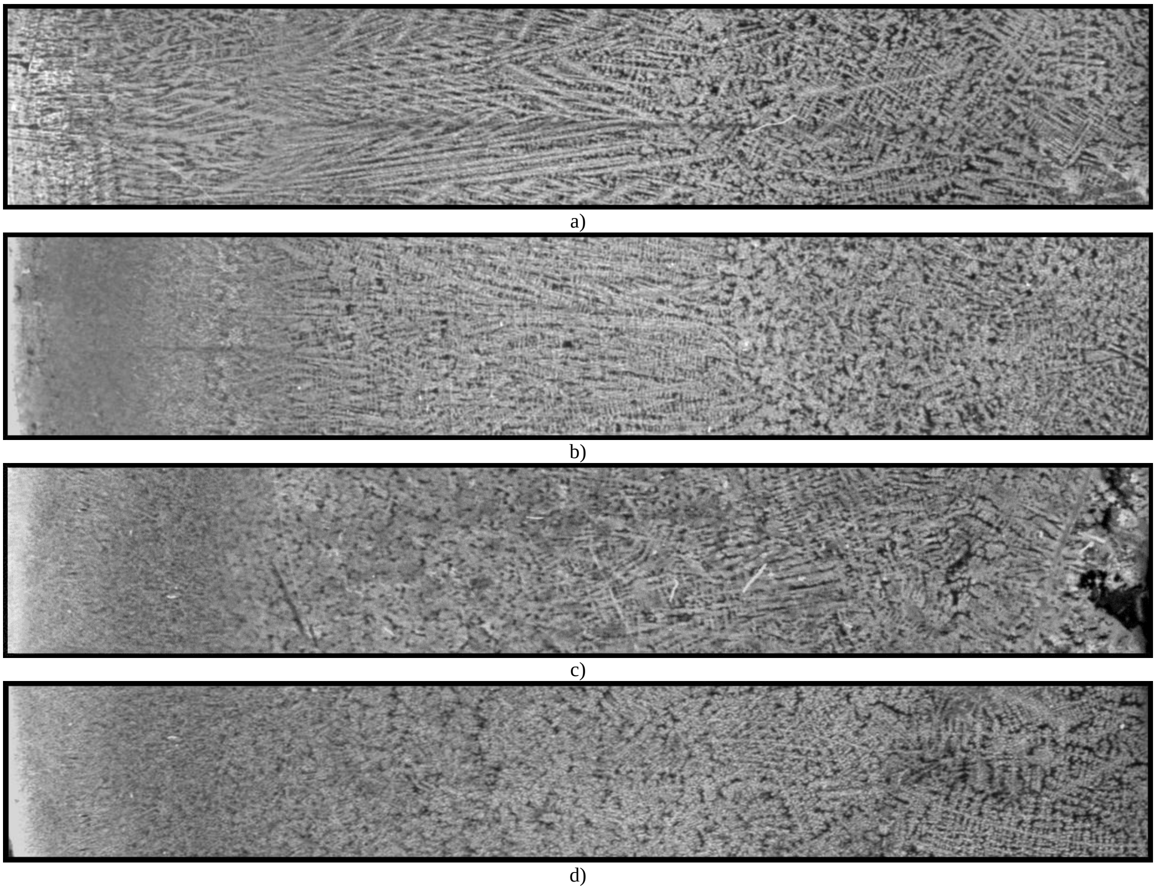

Fig. 2. Macrostructure from the outer to the inner zone: A – sample without dispersed particles, B – 120 g of WC added, C – 240 g of WC added, D – 360 g of WC added.

Macrostructure analysis of samples without reinforcing agents showed that the structure of polished cross-sections was uneven and coarse and the length of crystals was considerable. 3/5 of the samples were composed of dendrites, monad axils were easily distinguished and twofold axels were thin and densely positioned at the outer edge, grew thicker and got less dense to the inner edge. 2/5 of the samples' width (at the inner edge) were composed of non-oriented equiaxed crystals. Thus, we may suggest that 3/5 of the samples' width was composed of fringe crystals because, firstly, the heat was directed towards the outer edge and then solidification conditions changed.

Macrostructural analysis of reinforced samples showed that, despite different reinforcing agent concentration, the outer zone of the examined samples was composed of fine equiaxel grains with dendrites positioned at an angle to each other. It is easy to distinguish clusters of dendrite crystals that are uniform in size and are positioned at angles to each other. The width of the zone composed of equiaxel grains depend on disperse powder concentration: it occupies ¼ of the sample #4 (120 g of WC), ½ of the sample #7 (240 g of WC) and ¾ of the sample #8 (360 g of WC).

To examine changes in microstructure, the samples were ground, polished and treated for 10 seconds with nitric acid (HNO3), 4 % in ethanol. Their microstructure was inspected under Axio Observer. Z1m microscope with 100x-200x zoom.

Introduction of the reinforcing agent considerably influenced the samples' structure: the higher concentration of the agent, the more intense microatomization took place. Changes in grain grade were calculated by measuring the lengths of circle chords and are presented by the table 2.

Table 2. Results of dendrites cross-section examination

Zone of examination	Inner zone		½ of width		Outer zone	
Sample number	Dendrite cross-section, μm	Grain grade	Dendrite cross-section, μm	Grain grade	Dendrite cross-section, μm	Grain grade
1	156	2	60.9	5	48.6	5–6
2	39.9	6	30.3	7	18.5	8
3	25.2	7	23.5	7	15.9	8–9
4	28.5	7	23.9	7–8	12.9	9
5	38.7	6	34.2	6–7	23.6	8
6	39.3	6	35.3	6–7	20.2	8
7	30.3	7	22.3	7–8	17.9	8
8	25.5	7	19.6	8	15.5	9

Dispersed particles distribution was inspected under JEOL JSM–6460 LV scanning electron microscope. It showed that WC particles were fixed in the microstructure of the solidified samples #2, #3, #4, #6, #7 and #8. WC grains of the samples were considerably smaller in size (0.1-0.94 μm) than initial particles of WC powder (4-65 μm) Fig.3.

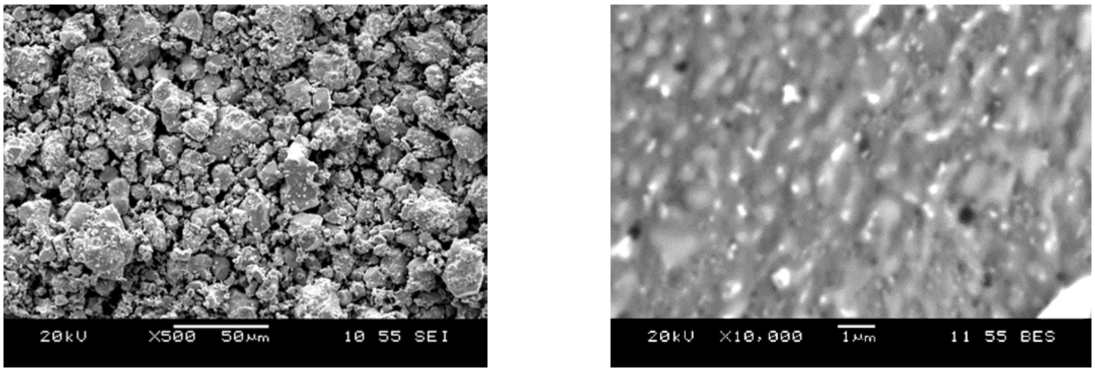

Fig. 3. WC grains: a – before experimental study (x500), b – in fabricated samples (x10000).

WC concentration in uneven along the samples' width with the highest rate at the outer edge, a lower rate in the central zone and almost zero concentration at the inner edge.

Uneven distribution is characteristic to all the other samples reinforced with WC. WC concentration distribution was thoroughly examined in accordance with the following method: different cross-sections of a sample were examined with the same zoom and the number of particles per square micron (p/μm2) was counted. The "table 3" present WC concentration distribution along the samples' width.

Table 3. WC concentration distribution along the cross-section

Sample number	Dispersed particles concentration distribution		
	Inner zone, p/μm^2	½ of sample's width, p/μm^2	Outer zone, p/μm^2
1	0	0	0
2	0	0	0.4
3	0	0	0.6
4	0	0	2.5
5	0	0	0
6	0	0	2.8
7	0.5	2.6	5.1
8	3.4	3.5	5.1

4. Discussion

Files The developed method of FGM fabrication in based on difference in density between introduced carbides and a metal. Our anticipations about particles distribution have been indirectly supported by the following facts:

- a change in grain grade depending on the quantity of introduced particles;
- a significant difference in samples' microstructure from the outer to inner edge.

Our anticipations have been directly proved by examination performed with an electron microscope. As a result, data on WC concentration from the outer to the inner edge of the samples has been accumulated "Table 3". The fact that particles concentration is different at the outer and the inner edge of the samples proves our hypothesis that particles' distribution depends on their density.

It's worth noting that there is a certain WC "saturation point" for a material fabricated in accordance with the proposed method. This conclusion resulted from examination of the samples #7 and #8 that had been fabricated with different WC content, but showed the same rate of WC concentration at the outer edge. If the number of introduced particles increases, their distribution becomes limited: in the sample #8, WC concentration rates are almost equal in the inner and central zones.

Since dispersed particles influence mechanical properties of the reinforced material and they are distributed unevenly over the volume of the samples, we can claim that the fabricated material is functionally graded. It's worth saying that the proposed method is a promising way of FGM production since the number of carbides, oxides, nitrides and other compounds is plentiful and there are several thousands of steel grades that can be reinforced with dispersed particles. It's possible to fabricate materials with different preset properties varying along the width depending on steel composition, dispersability and particles density. Thus, a fabricated FGM will have a continuous structure without an easily distinguished interface which, otherwise, becomes a stress point.

However, the abundance of reinforcing particles/reinforced metal combinations requires additional examination of particles/metal reaction rates, particles dissolution rates, particles wetting with metal and etc.

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