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Thermal fatigue properties of differently constructed functionally graded materials aimed for refurbishing of pressure-die-casting dies

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ABSTRACT

Different surface layers, constructed on the basis of functionally graded materials using a laser cladding technique, were designed to study the possibility of using them in applications subjected to thermal fatigue. Three different filler materials, varying in terms of the concentrations of alloying elements were used. A graded chemical composition was achieved, varying the concentration of silicon from 0.1 wt.% at surface layer to 1 wt.% in the base material. A specially designed thermal fatigue test was utilized for the assessment of the thermal fatigue resistance of designed surface layers and compared with base tool steel AISI H13. The results of thermal fatigue testing showed that the different concentrations of alloying elements in the surface layers resulted in different thermal fatigue resistances. The thermal fatigue resistance was observed to be approximately 27 times higher in specimens with lower silicon content compared to base material. This was found to be closely correlated with the microhardness and the resistance to softening during annealing.

1. Introduction

High-pressure die casting (HPDC) is a wildly utilized manufacturing process, used for the production of engineered metal parts from different materials, mostly aluminum, copper, and magnesium alloys. The process consists of injecting the molten metal from the die-casting sleeve into the die casting cavity followed by the ejection of the product and the spraying of die surface with the cold lubricant. The stresses on the surface during the cooling phase reach an order of magnitude of 1 GPa as calculated by Klobčar and Tušek [1]. This process is repeated several thousand times and results in the degradation of the die due to four most frequent failure mechanisms, i.e., cracking on sharp edges [2], cleavage cracking, heat checking, wear and erosion [3]. Heat checking is usually the most important life-limiting failure mode in HPDC, causing the degradation of surface of the dies and decrease of the surface quality of the castings.

The thermal fatigue resistance of tool steels is normally studied using a variety of tests. The majority of studies involve the alternating immersion of samples in molten aluminum and water, [1,4,5]. This type of experiments most closely resemble the actual high-pressure die-casting process but lacks repeatability, due to the sticking of the molten aluminum on the sample during testing, is its main weakness. Other authors applied induction heating of samples surface followed by gas cooling [6] or water cooling [7]. Tests with the applied conduction heating of samples, which is followed by water cooling of the tested surface, have also been reported [8].

In order to increase the service time of the casting dies various methods have been proposed in the past, e.g., nitriding [9], PVD/CVD coatings [10,11], and laser surface engineering [12–15]. The study conducted by Lin et al. [16], Salas et al. [11] and Klimek et al. [17] proposed the use of four different layers to achieve an optimum change in the characteristics from metal

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die substrate to working layer. Persson et al. [10] reported that if the surface coating does fail it locally attacks the steel, resulting in subsequent corrosion-pit coalescence. Although these techniques yield good results, other techniques are also applied for the prolongation of the die's service life, e.g., surface welding. When damage occurs, in most cases, dies are repaired by means of grinding out the cracks, which is followed by surface welding [18,19].

The materials used for the construction of dies for HPDC are usually hot-work tool steels, i.e., AISI H11 and H13 or sometimes also maraging steels (AISI MS) with a higher concentration of nickel, which has favorable thermal fatigue resistance characteristics [20].

In the work of [11,16,17,21] the possibility of grading the properties near the surface to maximize the thermal fatigue resistance was mentioned, but the review of the literature revealed only a few works dealing with the use of bulk, functionally graded materials (FGMs) for applications subjected to thermal fatigue [21]. Thus, Syed et al. [22] used a laser-cladding technique to produce bulk FGM by simultaneously depositing Cu powder and Ni wire on a H13 tool-steel substrate. This work was focused on the production of the die surface and an analysis of the distribution of the chemical elements in the graded zone. More recently, Ocylok et al. [23] also produced bulk FGM for die-casting applications, where laser-cladding was used to build up layers of Marlock and Dievar on a H11 substrate. In their work the hardness and the composition profiles for various processing routes are given. In the available literature no work dealing with thermal fatigue resistance, as the main characteristic of bulk FGM for HPDC application, was found. Furthermore there are no laboratory studies indicating the use of differently constructed surfaces with laser cladding that could improve the local surface characteristics of dies and which could consequently lead to the lowering of initial cost of die casting tools by using cheaper base materials. On the other hand, Zhu et al. [24] proposed the use of advanced metallic materials for the parts of dies that are heavily exposed to thermal fatigue, but they did not consider constructing a FGM layer to shield the existing parts.

Therefore, the aim of the present contribution is (i) to design a bulk FGM material for die casting with improved thermal fatigue resistance by employing a non-traditional approach, called laser cladding by wire (LCW), with which superior properties based on fusion bonding can be obtained [25–28], (ii) to characterize the produced material using optical microscopy (OM), scanning electron microscopy (SEM) and microhardness measurements, and (iii) to employ comparative thermal fatigue testing of conventional and various graded materials using a specially designed thermal fatigue test.

Motivated by the results of Delagnes et al. [29] on the role of Si in 5% Cr martensitic-type tool steels which found that Si has a considerable influence on the precipitation of secondary carbides, and consequently, on the fatigue resistance, i.e., the fatigue resistance is increased with a decreasing of Si content that results in a lower volume fraction of small secondary carbides. Thus, in the present study, several FGM surfaces that are similar to tool-steel base material with varying amounts of alloying elements, especially Si and Mo, in surface layer, were designed. Their resistance to thermal fatigue was tested and later characterized.

2. Experimental

2.1. Materials

The wires that were chosen for construction of different FGM's using a laser cladding process had similar amounts of manganese and chromium, but different amounts of carbon, silicon, molybdenum and vanadium. As a reference material and as the base material for all the samples, an AISI H13, chromium-type hot-work tool steel was selected, because of its frequent use as die material in casting industries.

The chemical compositions of the filler and the base materials are given in Table 1. It can be seen from the Table 1 that the contents of Si for all three filler materials are considerably lower (0.16–0.33 wt.%) in comparison to the base material (1.12 wt.%) that can lead to improvement of thermal fatigue resistance. Furthermore, it is worth to mention that the chemical composition of filler material 3 was deliberately selected with increased content of Cr and Si as well as lower value of C in comparison to filler materials 1 and 2. The purpose of this selection (applying filler material 3) was to assess simultaneous influence of Cr and Si which have the opposite effect on carbide size distribution and consequently on thermal fatigue resistance. As already mentioned above, decreasing of Si content decreases the fraction of secondary carbides, while increasing of Cr leads to increased amount and size of $Cr_{23}C_6$ carbides.

2.2. Laser cladding on test samples

The possibility of applying of new designed FGM's for refurbishing purposes in HPDC was tested using pipe-like samples with octagonal-shaped surfaces ($8 \times 24\ mm^2$) on the outer side, as shown in Fig. 1. This would represent a small part of the

Table 1
The chemical composition of the base and filler wire material, given in wt.%.

Designation	C	Si	Mn	Cr	Mo	V	Fe
Base material	0.39	1.12	0.32	5.15	1.35	1.03	Bal.
Filler material 1	0.31	0.16	0.29	4.97	2.91	0.61	Bal.
Filler material 2	0.28	0.25	0.33	4.85	4.05	0.13	Bal.
Filler material 3	0.13	0.33	0.42	6.35	3.72	0.04	Bal.