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Interrelation between macroscopic, microscopic and chemical dilution in hardfacing alloys

J.N. Lemke *, L. Rovatti, M. Colombo, M. Vedani

Politecnico di Milano, Dipartimento di Meccanica, Via Giuseppe La Masa 1, 20156 Milano, Italy

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ABSTRACT

A common way to extend service life of steel tools under heavy duty service conditions is the use of hardfacing coatings. Coating an economically feasible base material like carbon steel with a hardfacing alloy by any processes based on welding, casting or cladding improves significantly its wear resistance. All these processes involve high heat inputs in order to partially melt the substrate material to create a sound bonding between the substrate and the wear resistant alloy. The intermixing and the elemental diffusion from the hardfacing material into the substrate and vice versa cause a change in microstructure, hardness and wear properties of the diluted alloy. It is not trivial to categorize the amount of dilution and its effects on material properties since composition and microstructure change discontinuously, especially in casting processes, due to different diffusion rates of elements and due to phase transitions. This paper presents a simplified model to correlate the amount of dilution in hardfacing alloys after a casting process considering several reference parameters. Three coefficients are derived to describe the degree of dilution based on crucible casting experiments and are numerically correlated by linear regressions. They specify distinct issues about macroscopic and microscopic dilution, as well as changes in chemical composition. The model is then applied to a spin casting case study which can be taken as a reference example for industrial hardfacing processes where dilution effects are clearly observable.

1. Introduction

In hardfacing technologies, high C and Cr steel alloys have a wide range of use, with main fields of application as thick coatings for tools for instance in the polymer extrusion field or in mining and processing industry [1]. Much of these tools require a high wear and corrosion resistance to counterbalance the hardness of ores or the severe chemical conditions encountered in some polymer extrusion units [2,3]. Nevertheless, it is still unclear how to predict the endurance of such hardfaced tools, because wear phenomena are very complex and there are many concurrent approaches for evaluating the wear performance of materials [4].

In previous studies, the mechanical and wear properties of iron based hardfacing alloys have been characterized. Kotecki and Ogborn analysed the influence of C content in hardfacing steels on microstructure and abrasion resistance [5]. Further studies dealt with the importance of the carbide/boride fraction on wear performance and on the impact of primary hard Cr carbides/borides [6–9]. Kirchgaßner et al. analysed the behaviour of hardfacing iron based alloys under abrasion and impact, considering also the effects of welding [10].

* Corresponding author.
E-mail addresses: Jannisnicolas.lemke@polimi.it (J.N. Lemke), ludovica.rovatti@polimi.it (L. Rovatti), marco1.colombo@polimi.it (M. Colombo), maurizio.vedani@polimi.it (M. Vedani).

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One of the main issues with hardfacing alloys is to predict their performance after the deposition onto a substrate material. In order to create a good bonding between the hardfacing layer and the substrate, interdiffusion is required. Interstitial elements like C and B diffuse rapidly through the coating–substrate steel interface, mainly from the C-rich hardfacing layer toward the substrate. The enrichment of C and B in the substrate decreases its melting point, which favours its partial melting and causes an intermixing of elements with the hardfacing alloy. On the other hand, the hardfacing alloy results in locally depleted C and B after processing and the wear properties can be significantly reduced [11]. Regarding the phase formation in the hypoeutectic region of Fe–C–B alloys, the work of Lentz et al. is worth reading [12].

Karabelchtchikova et al. numerically modelled C diffusion in steel and Eghlimi et al. derived a model to estimate dilution and its effects on the microstructure of super duplex stainless steel [13,14]. A detailed characterization of the effects of alloy dilution is not trivial, since the decrease of properties does not change linearly with the degree of intermixing, but it depends on the formation of distinct phases during solidification. On the contrary, it has been shown that the hardness and wear resistance for a hypereutectic Fe-based alloy can be preserved quite well up to a certain level of dilution (loss of C and carbide former elements), till a transition to a hypoeutectic microstructure occurs due to extensive C and B depletion [15–17].

Precisely identifying the level of alloy dilution could supply a useful perception of the change in material properties as well as a more precise estimation of these effects on hardfacing production processes and on the final performance of a part. A number of papers have been published recently to characterize the effects of dilution. A proper example is the work of Valsecchi et al. who studied the importance of dilution phenomena in cladding of turbine blade parts [18]. Research dealing with dilution effects in direct crucible castings of white iron alloys have been performed and terminology has been derived to describe and distinguish processes from “cast bonding” under vacuum conditions to steel crucible castings in air, termed “kiln casting” by T. Lucey et al. [19,20].

A detailed analysis of the chemical composition along hardfacing layer thickness and in the substrate close to the interface requires special techniques, particularly when focussing on low-atomic number elements, like C and B. There are several techniques to quantitatively measure material compositions such as X-ray fluorescence spectroscopy (XRF), inductively coupled plasma optical emission spectroscopy (ICP-OES) or combustion methods [21]. Another option is to support experimental analyses by numerical models predicting the diffusion of light elements, but this task still requires a lot of expertise and time to develop a precise model. In this regard, Borgenstam et al. discussed about modelling of diffusional transformations in alloys using DICTRA software [22].

In this research paper a model has been derived to evaluate and predict trends in hardfacing processes by quantifying the changes caused by dilution with easy to perform and inexpensive methods. Three coefficients for the degree of dilution (DOD) are introduced which correlate macroscopic, microscopic and chemical analysis observations in castings. For the development of the model, a well understood and described alloy very similar to the Fe–C–B–Cr–Mo alloy analysed by Rovatti et al. and a simple Fe–C–B were selected [16]. In that research the authors simulated dilution effects on the hardfacing alloy by mixing it with Fe powders to produce diluted compositions in the different regions of the phase diagram (hypereutectic, near eutectic and hypoeutectic) and tracked the change of microstructure and wear characteristics. These results should be considered as a reference for the material characterization of the alloys investigated in this paper. Furthermore, Hugget and Ben-Nisan also studied white cast iron alloys which exhibit similar microstructural phases as the Fe–C–B alloy [23].

2. Experimental procedures

2.1. Materials

The substrate steels and hardfacing alloys compositions investigated are listed in Table 1. C and B are known to promote the formation of equivalent phases, like $Fe_3(C, B)$ and type $M_3(C, B)$ with different alloying elements (here labelled as M) and are therefore considered together [24]. It must be specified that the table reports average values of elements as measured by SEM EDS except for C and B which refer to nominal values. Even though the results are not as precise as those determined by other methods (i.e. mass spectrometry), these compositions will be more consistent with experimental data gathered by EDS of diluted samples. Possible lack of precision is tolerated here since the scope of the work is to analyse differences which are expected to be much higher than the sensitivity of the measurement techniques (e.g. of the order of 0.1 wt.%).

Table 1
Alloy and substrate steel compositions (wt.%).

Alloy Code	C + B	Si	Mn	Cr	Ni	Mo	V	Cu	Fe
Alloy A	2.95	2.06	0.54	0	3.93	0	0	0	Bal.
Alloy B	5.74	1.87	0.4	12.3	4.1	7.36	0.27	1.11	Bal.
Steel C60	0.65[a]	0.4	0.9	0.4	0.4	0.1	0	0	Bal.
Steel 51CrV4	0.6[a]	0.4	1.1	1.2	0	0	0.3	0	Bal.

[a] B is virtually absent from substrate steel compositions.

In alloy A, no significant amount of alloying elements is present except for Ni, which is selected to provide toughness. Alloy B contains a substantial amount of Cr and Mo to improve protection against corrosion and to form even harder phases [25]. Two different substrate steels have been selected to obtain more opportunities to observe dilution effects, in particular to facilitate the detection of intermixing effects by SEM.

2.2. Experimental methods

Typical optical micrographs of undiluted alloys A and B after melting in alumina crucibles (size $30 \times 15 \times 10$ mm) are reported in Fig. 1. It is observed that these alloys feature a microstructure consisting of large amounts of primary carbides/borides with columnar morphology in alloy A and more equiaxed form in alloy B [16]. In a following stage, the alloy powders were blended with different amounts of pure Fe powder to simulate dilution effects, by increasing the nominal amount of iron in 10 wt.% steps, thus creating powder blends with 4 hardfacing alloy to Fe powder weight ratios of: 9:1, 8:2, 7:3 and 6:4. Subsequently they were cast under the same conditions as the undiluted alloys in an alumina crucible. This approach was chosen to simulate microstructures affected by dilution and to create a baseline for determining the carbide/boride amount at known chemical compositions. The samples were then transversally sectioned, prepared for microstructural analyses according to standard metallographic techniques, etched with Nital 3% and Marble reagent and observed under a Leitz Aristomet optical microscope (OM) ($25\times$–$500\times$ magnification) and a scanning electron microscope (SEM) by Zeiss EVO 50, equipped with a “Modula Inca Energy 200” EDS detector.

In a second set of experiments, the alloy powders A and B were placed in steel crucibles and cast under controlled atmosphere. Using EDS line scans from the hardfacing alloy–substrate steel interface to the centre, the homogeneity inside the moulds was investigated for two samples. The scope of these casting experiments was to create a range of samples with different degrees of dilution generated by the direct dissolution of the substrate steel (the crucibles). Therefore several castings were produced under different conditions, by varying the heating time from 15 min up to 35 min and the crucible geometry. Three kinds of casting were produced, referred to as single crucible, double crucible and triple crucible in respect to the number of moulds available for the casting. The crucible designs and their size are shown in Fig. 2.

The multiple crucible designs have been developed for practical reasons, to provide more parameters to investigate with limited number of castings. Moreover, this approach facilitates the production of several samples under identical casting conditions. Each casting in a mould will be referred to as individual samples and is indexed by a code: crucible type–cast alloy–mould number–numeric index. For example D–A–I–1 stands for “double crucible, alloy A, left mould, first sample of this type”.

About thirty samples were produced according to described methods, nineteen have been selected for deeper investigations on microstructure and macroscopic melting of the substrate steel, while in a further selection of eleven castings, additional chemical analyses have been performed. The selection of samples for chemical investigation was based on a visual inspection of the sectioned samples and on evaluation of diluted region, to uniformly cover a large range of interest (as molten substrate volume is used as a parameter to assess the amount of dilution).

2.3. Conceptual approach of the model

Fig. 3 shows a schematic of the diffusional flows expected during casting of a low-melting hardfacing alloy into a steel crucible according to four steps during casting time. In the first stage (Fig. 3a) the alloy melts and it would solidify by a hypereutectic mode after immediate