Materials Science & Engineering A 615 (2014) 61–69

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

# *In-situ* surface hardening of cast iron by surface layer metallurgy

Sebastian F. Fischer [a,*], Stefan Muschna [a], Andreas Bührig-Polaczek [a], Matthias Bünck [b]

[a] *Foundry Institute, RWTH Aachen University, Intzestraße 5, 52072 Aachen, Germany*
[b] *Access e.V., Intzestraße 5, 52072 Aachen, Germany*

ARTICLE INFO

*Article history:*
Received 19 May 2014
Accepted 18 July 2014
Available online 28 July 2014

*Keywords:*
Surface layer metallurgy
Surface hardening
Cast iron
Ledeburite

## ABSTRACT

Abrasive wear is a serious problem in many cast iron castings used in industry. To minimize failure and repair of these components, different strategies exist to improve their surface microhardness thus enhancing their wear resistance. However, most of these methods lead to very brittle and/or expensive castings. In the current work a new method for surface hardening is presented which utilizes surface layer metallurgy to generate *in-situ* a boron-enriched white cast iron surface layer with a high microhardness on a gray cast iron casting. To do this, sand molds are coated with a ferroboron suspension and cast with a cast iron melt. After solidification, a 100–900 μm thick layer of boron-enriched ledeburite is formed on the surface of the casting which produces an increase in the average microhardness from 284 $HV_{0.1} \pm 52$ $HV_{0.1}$ to 505 $HV_{0.1} \pm 87$ $HV_{0.1}$. Analyses of the samples' core reveal a typical cast iron microstructure which leads to the conclusion that the coating mainly affects the castings' surface. By varying the grain size of the ferroboron powder in the coatings, it is shown that a powder size $\leq 100$ μm is most suitable to create a boron-enriched ledeburite surface layer possessing high hardness values.

## 1. Introduction

Abrasive wear occurs in many cast iron castings used for industrial parts such as drive shafts, camshafts, pulleys, machine slide-ways, and components for agricultural machinery. This abrasive wear leads to a progressive loss of material from the component's surface. Worn components have to be repaired or replaced in order to re-establish the manufacturing productivity of the affected machine. All failures and repairs of these parts should be kept to a minimum since, in many cases, the costs of maintenance and machine breakdown are extremely high [1–4]. Due to abrasion, the improvement of cast iron castings' and cast iron materials' surface microhardness is an ongoing process to increase their wear properties [5–7].

Different strategies exist for improving the abrasive wear of a cast iron component. These include alloying, chilling, heating and cooling using induction, flame, laser and electron beam techniques, or using mechanical processes [8].

One of the most widely used casting material for applications subject to abrasive wear is high-alloyed white cast iron [9]. Due to their high chromium content (10–40 wt%), white cast iron alloys solidify according to the metastable Fe–$Fe_3C$ diagram. Here, in the case of the common hypereutectic composition, carbides (mainly in the form of $M_7C_3$, where M includes Fe and Cr) are precipitated as both primary as well as eutectic phases increasing the materials' hardness. In the as-cast state, the carbides are most often embedded in an austenitic matrix, which can be transformed via heat treatment to ferrite, pearlite, bainite or martensite [4,10]. However, the outstanding high microhardness is accompanied by the brittleness and high production costs in relation to gray cast iron [1,3,4,11–15].

In contrast to white cast iron, chilled gray cast iron provides lower production costs and a much higher resistance to impact loading combined with good wear behavior [1,7,14]. To produce chilled gray cast irons, the melt is alloyed with a low percentage of Cr (e.g. 0.6 wt% [1,14]) and the casting is chilled by applying a high cooling rate to its surface, e.g. by using permanent molds or chills in parts of the sand mold which promote solidification according to the metastable Fe–$Fe_3C$ phase diagram [1,2,14]. Another process route for the production of chill cast iron includes surface remelting, e.g. by laser, gas tungsten arc welding (GTAW) or plasma arc welding (PAW). Following the remelting of a comparatively small area, the base material acts as a chill, leading to an undercooling of the surface layer's liquid and thus to a metastable microstructure [14,16,17].

However, according to İpek et al. boronizing (also called boriding) is a more effective treatment than chilling to improve

---

[*] Corresponding author. Tel.: +49 241 80 96790.
*E-mail addresses:* s.fischer@gi.rwth-aachen.de (S.F. Fischer), smuschna@yahoo.de (S. Muschna), sekretariat@gi.rwth-aachen.de (A. Bührig-Polaczek), m.buenck@access-techcenter.de (M. Bünck).

http://dx.doi.org/10.1016/j.msea.2014.07.062
0921-5093/© 2014 Elsevier B.V. All rights reserved.

**Table 1**
The chemical composition of the inoculated EN-GJL-250 and the ferroboron powder (wt%). Only main elements are given.

| Alloy | C | Si | Mn | P | S | Cr | Ti | B | CE [%] |
|---|---|---|---|---|---|---|---|---|---|
| EN-GJL-250 | 3.19 | 1.97 | 0.61 | 0.07 | 0.03 | 0.069 | 0.020 | 0.0013 | 3.9 |
| FeB powder | max. 0.5 | max. 1 | n/a | max. 0.1 | max. 0.01 | n/a | n/a | 18–22 | – |

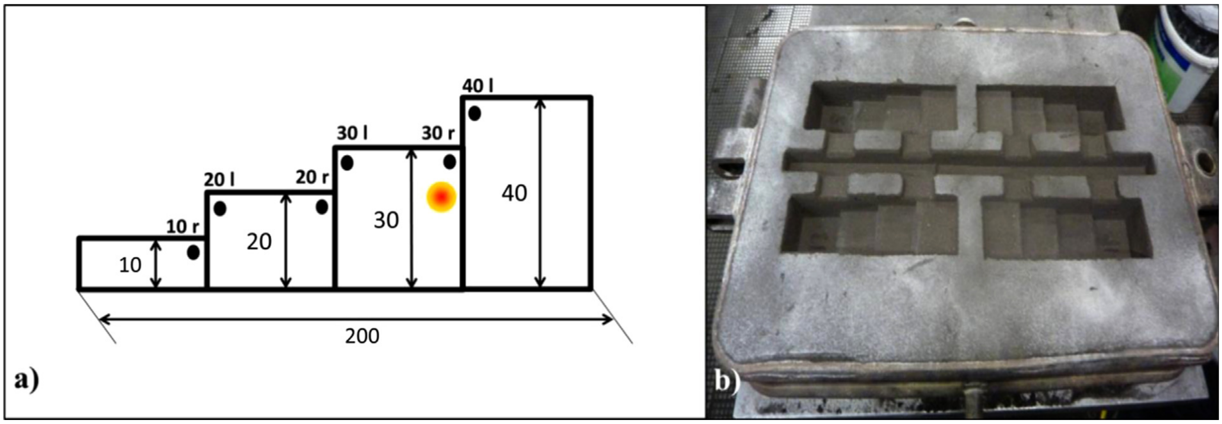

**Fig. 1.** (a) Schematic illustration of the employed step wedge (width = 50 mm) depicting the dimensions, the last point of solidification and the positions of the hardness measurements. (b) Mold drag with runner and gates.

**Table 2**
Experimental design.

| Test run | Grain size of ferroboron [μm] | Content of ferroboron in suspension [g] |
|---|---|---|
| 1 | 100–200 | 40 |
| 2 | 100–200 | 60 |
| 3 | ≤ 100 | 40 |
| 4 | ≤ 100 | 60 |

**Table 3**
Results of the thermal analyses with $T_l$ = liquidus temperature, $T_{leut}$ = low and $T_{heut}$ = high stable eutectic temperature, $T_w$ = metastable eutectic temperature, and $T_{eof}$ = temperature at the end of freezing.

| Curve | $T_l$ [°C] | $T_{leut}$ [°C] | $T_{heut}$ [°C] | $T_w$ [°C] | $T_{eof}$ [°C] |
|---|---|---|---|---|---|
| Tellurium cup | 1185 | – | – | 1109 | 1091 |
| Base melt | 1179 | 1151 | 1154 | – | 1115 |

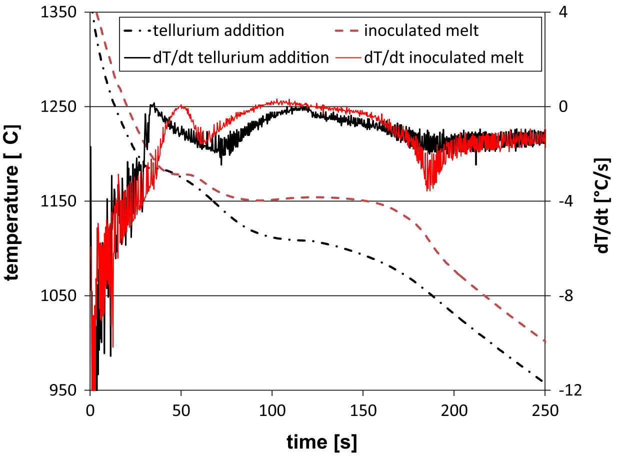

**Fig. 2.** Thermal analyses of the melt with the aid of QuiK-Cups. One cup contained tellurium (dark lines) to suppress the solidification according to the stable Fe–C system.

the surface microhardness and tribological properties of gray cast iron subjected to dry adhesive and abrasive wear conditions [2]. The boronizing process makes use of the chemical or electrochemical reactions between the boron source and the cast component, whereat boron atoms diffuse into the metal lattice at the surface and form borides with the atoms of the substrate [5,18]. The solubility of boron in iron is very low (0.0004 wt% below 700 °C) leading to the formation of borides. Depending on the boronizing process employed, borides are formed if boron is added to ferrous alloys in the solid state at high temperatures over certain periods of time [11,19]. Due to the resulting smooth surfaces and the relatively modest equipment, the pack boronizing method is mainly used. According to this method, the casting is packed with a powdery boron source in a heat resistant box or an inert atmosphere and is annealed for 1–8 h at 800–1000 °C [7,18,20,21]. With increased boronizing duration and temperature, the thickness of the boronized layer is increased [7]. The resulting borides, featuring the properties of special ceramics together with those of metals, exhibit high melting points, metallic resistivity and high hardness values, even higher than carbides if they are combined with the same element [5,15,19].

Even the abrasive wear can be substantially increased by borides. However, the resulting thin layer is very brittle for industrial applications and the boronizing process requires extensive amounts of energy, thus making this casting treatment expensive. Due to the great need for wear-resistant components having low unit costs, new production methods have to be developed to realize gray cast iron components possessing high abrasive wear-resistant surfaces [7].

An ambitious way of generating a composite with high surface hardness, consisting of a high wear-resistant material at its surface and an impact resistant low cost core material, is to employ one step, *in-situ* production techniques. *In-situ* techniques involve a chemical reaction at the surface of the casting which mainly occurs within liquid-based routes and leads to the formation of phases supporting the wear resistance of the component [22,23]. Most of the existing *in-situ* processes involve particle