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Rationalizing surface hardening of laser glazed grey cast iron via an integrated experimental and computational approach

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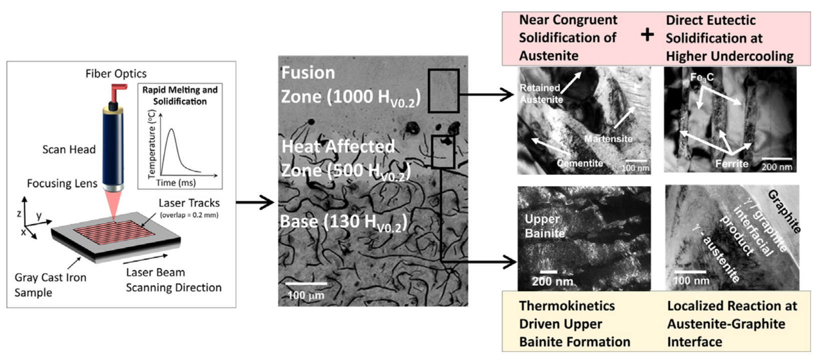
HIGHLIGHTS

- Depths of fusion and heat-affected zones in laser glazed cast iron computationally predicted and experimentally verified.
- Rapid melting and solidification in fusion zone completely dissolved graphite.
- Site-specific transmission electron microscopy revealed unusual sequences of liquid-solid and solid state phase transitions.
- Fusion zone underwent either congruent solidification or direct eutectic decomposition.
- Conversion of graphite into cementite and fine scale martensite in fusion zone made it extremely hard and wear resistant.

GRAPHICAL ABSTRACT



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ABSTRACT

Grey cast iron, a widely used inexpensive alloy, typically exhibits inferior and spatially inconsistent hardness and wear behavior. Using laser glazing, the surface of grey cast iron has been uniformly hardened to 1000 $H_{V0.2}$, an eight-fold increase from the base alloy. This paper clearly demonstrates that the exceptional increase in the surface hardness is the consequence of complex multi-scale graded microstructures, resulting from novel far-from equilibrium phase transformation pathways, occurring during laser surface melting followed by inherent rapid solidification and solid-state cooling. The fusion zone of this graded layer exhibits complete dissolution of graphite flakes in the liquid which undergoes two distinct types of solidification: a) congruent solidification of austenitic dendrites, supersaturated with carbon and b) direct eutectic solidification of austenite + cementite lamellae. In the heat-affected zone, the pearlite matrix transforms into austenite without significant dissolution of graphite flakes during solid-state heating. These experimentally observed far-from equilibrium phase transformation pathways are rationalized based on the local temperatures and very high heating and cooling rates, predicted

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using thermo-kinetic models. Coupling multi-physics computational modelling with detailed multi-scale microstructure characterization, provided novel insights into these phase transformation pathways, and the potential for exploiting them in surface-engineering as well as more broadly during additive manufacturing.

1. Introduction

Cast iron (CI) is a unique material in which cooling rates during solidification and in the solid state result in substantially different microstructures, due to the availability of two competing solidification and multiple solid state phase transformation modes. One of the solidification modes results in the formation of the thermodynamically equilibrium graphitic phase, while the other produces the metastable cementite phase (stable for an extended period at ambient temperature). Work done earlier on laser processing of CI has shown how the solidification mode changes from the equilibrium graphite to the metastable cementite formation depending on the cooling rates imposed during solidification [1–4]. These investigations focused on improvements in the tribological properties such as resistance to erosion and wear of laser- processed grey CI. Chen et al. [2] also showed the preponderance of austenite dendrites (subsequently transformed into ferrite and cementite) in the fusion zone (FZ) of such laser processed material. While describing the sequence of transformations under equilibrium thermodynamic conditions of hypo-eutectic grey CI, Hume-Rothery and Raynor [5] have indicated that the formation of primary dendrites of austenite is followed by the nucleation and growth of eutectic cells of austenite and graphite in the interdendritic regions. The growth of graphite flakes, which tend to extend along their close packed basal plane, is severely restricted by the presence of pre-existing austenite dendrites. The size of graphite flakes, therefore, decreases with an increase in the volume fraction of primary austenite dendrites. Apart from the competition between grey CI and white CI solidification with respect to two primary variables, namely, the alloy composition and the cooling rate, several other interesting issues such as asymmetric and coupled growth of austenite - graphite and austenite - cementite eutectics and transition from a coarse to a fine structure have been reviewed and discussed by Minkoff [6] in terms of thermodynamics and kinetics of the formation of graphite and cementite phases.

Post solidification, solid-state phase transformations in CI are also quite diverse. The extent of partitioning of substitutional alloying elements between the growing phases can have a strong influence on the phase equilibria and hence the microstructure. As the diffusion rates of carbon and substitutional solutes are significantly different, there are possibilities of equilibrium partitioning with respect to carbon while incomplete partitioning of substitutional solutes under rapid cooling. Both thermodynamic and kinetic parameters of the relevant transformation processes are altered under such para-equilibrium conditions [7]. Zackay and Aaronson [8] and Cahn and Hagel [9] compared eutectoid transformations of a ternary Fe-M-C system under an equilibrium and an incompletely partitioned (with respect to M, a substitutional alloy element) conditions to highlight the changes in the relative stability of the competing phases and in the sequence of phase transformations.

The undercooling imposed during the solidification process has a strong role to play in the microstructure developed in CI. Stephanescu [10] in a critical review of the development of CI microstructure has emphasized that during solidification of a hypoeutectic cast iron, as primary austenite dendrites grow, C and Si are partitioned into the inter-dendritic liquid phase causing constitutional undercooling to a large extent. This promotes graphite nucleation followed by the growth of graphite in different morphologies such as spherical or lamellar. The selection of the morphology of graphite is primarily dictated by the competition between the rate of growth of graphite on $(10\bar{1}0)$ or (0001) face of the graphite prism [11]. The grey CI versus white CI solidification mode is also dependent on the imposed undercooling. In the binary iron-carbon system the equilibrium temperature for the (austenite + graphite) eutectic is 1153 °C, while the metastable (austenite + cementite) eutectic is at 1148 °C. The growth rate of the latter eutectic rapidly exceeds that of the former at a temperature below 1140 °C [6]. The transitions from grey CI to white CI and from white cast iron to grey CI have been explained on the basis of the growth rates of the two competing eutectic reactions [12, 13]. A higher cooling rate, which can impose the necessary undercooling, therefore, promotes white cast iron formation.

Surface melting of CI by laser processing has earlier demonstrated that the microstructure of the rapidly melted and solidified surface layer can be altered significantly. The grey CI structure can be converted into the white CI structure at the laser treated surface [1, 2, 4]. Such a change in the microstructure was found to improve the hardness, wear resistance, coefficient of friction, and corrosion resistance substantially [1–4, 6, 14]. The surface modification of CI by high energy beams such as laser beam and electron beam has demonstrated improved performance of several automotive components [15].

Despite the extensive work on surface modification of CI and the prospect of its applications in improving several engineering components, a detailed microstructural study at different length-scales aiming at the identification of the phase transformation sequence has not been reported so far. In the present work, a hypoeutectic grey CI was subjected to a laser surface treatment with varying power density and a constant interaction time. Different phase transformations during the laser melting and subsequent solidification processes were identified from the observed microstructures at various depths. An attempt has been made to rationalize the observations in terms of the phase transformation pathways governed by metastable phase equilibria in this system.

2. Experimental methods

2.1. Laser surface treatment

CI coupons of dimensions 50 mm × 25 mm × 10 mm were used for laser processing experiments in the current work. The composition and hardness of these coupons have been presented in Table 1. A clearance of 10 mm was maintained on each side of the top surface of the samples to avoid/minimize the edge effects during laser surface melting (Fig. 1(a)). The edge effects have been reported to cause a non-uniform thermal diffusion from the edges of the sample compared to the inner surface [16, 17]. This is attributed to the additional sample surface adjacent to the edges which provides a considerable contribution during heat transfer. The laser surface melting process was carried out using a continuous wave Nd:YAG laser (wavelength of 1064 nm). The laser beam diameter on the sample surface was 0.6 mm and the beam had Gaussian energy distribution (Fig. 1(a)). Furthermore, the laser

Table 1
Composition and hardness of grey cast iron employed in the current work.

Element	Carbon	Silicon	Manganese	Phosphorous (max)	Sulphur (max)
			Chemical composition		
wt%	3.5	2.5	0.45	0.12	0.07
			Rockwell B hardness		
			72 ± 2		