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Feasibility of laser surface treatment of pearlitic and bainitic ductile irons for hot rolls

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ABSTRACT

The effects of laser surface treatment on the microstructure, crackability and stresses generated on laser hardened layers produced in several ductile cast iron materials were investigated. Two kinds of alloys having pearlitic (SGP) and acicular (SGA) matrix microstructures were selected. Hardened layers with thicknesses ranging from 1.5 to 2.5 mm were obtained by means of laser remelting (LSRm) or laser hardening (LSH). Thermal stresses generated upon laser processing have been estimated by a simple thermal model. For energy densities delivered onto the material at above 40 J/mm^2, extensive cracking was developed in SGA and SGP irons due to the contribution of thermal stresses. By lowering the energy density, crack formation was avoided in SGP irons only. At low energy densities, crack formation is controlled by the generation of transformational stresses due to excessive austenite retention. An increase of the surface temperature or the alloying content gave rise to an increase of the retained austenite and the formation of lower bainite at the remelted zone and the heat affected zones, respectively. K_C fracture toughness of Fe_3C carbides embedded in pearlitic and acicular matrixes was measured by means of the nano-indentation technique. Fracture toughness of cementite in SGP irons was slightly higher than in SGA irons, which can help to reduce the crackability of LSH layers.

1. Introduction

Laser surface hardening has been suggested as a potential technique to produce a hard surface that enhances the overall wear resistance of rolls, typically used on high-temperature rolling operations (Heason et al., 2010; Pellizzari and De Flora, 2011). Among the materials employed for rolls, spheroidal graphite (SG) cast irons are commonly used in flat and profile rolls because of their good mechanical properties, together with adequate cost compared with higher-performance and more expensive forged steel or hard high-alloyed rolls (Betts and Baxter, 1990; Gonzalez et al., 2007). Industrial validation of this surface modification technique requires attaining a crack-free surface on the laser-treated roll, while achieving a hardened case in the range between 1 and 2 mm thickness. Economic feasibility of laser surface hardening would imply the utilization of wide laser tracks in order to reduce the number of laser passes on treating the surface roll.

Laser hardening of metallic materials involves rapid heating and cooling of a thin layer on the surface of a bulk material, in order to increase the hardness of this layer compared to the rest of the un-treated material (Ready, 2001). During laser surface remelting (LSRm) and laser surface hardening (LSH) treatments, several liquid-to-solid and solid-to-solid transformations take place in the surface layer being irradiated which promotes the generation of a considerable amount of residual stresses (Major, 2006). Residual stresses arise due to differences in the expansion and contraction ratio of the molten metal, the heat affected zone and the base material (thermal stresses), and volume changes associated with the phase transformation reaction (transformational stresses) (Narazaki et al., 2002). Formation of cracks takes place under certain treatment conditions for which the residual stresses are above the local strength of the laser hardened layer. Previous measurements of the residual stresses induced in bead-on-plate type welds showed that high tensile stress levels developed along the longitudinal direction of the weld line, while residual stresses in the transverse and normal direction were almost negligible (Price et al., 2008).

Considerable research has been conducted on the characterization of the mechanical, wear and microstructure features induced in cast irons after laser hardening. Tan et al. (1990) investigated the wear properties of austempered ductile irons (ADI) after laser processing, and found that wear resistance did not vary despite isothermal transformation temperature employed before laser surface treatment. Roy and Manna (2001) analyzed the effect of LSRm

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and LSH on the adhesive wear resistance of an ADI austempered at 370 °C. These authors observed that LSH produced a martensitic microstructure, while LSRm gave rise to the formation of a predominantly austenite microstructure which was responsible for lower wear resistance after laser hardening of ADI iron. Alabeedi et al. (2009) observed that the erosion resistance of a ferritic ductile iron increased after LSRm treatment due to the formation of a fine microstructure consisting of austenite dendrites with an interdendritic network of carbides. Chen et al. (1988) studied the influence of processing parameters (beam-substrate interaction time and power density) during laser surface modification of nodular cast irons. These authors obtained two different microstructures as a function of the solidification rate of the melted zone. First, a dendritic microstructure with low hardness, and second, a lamellar ferrite plus parallel cementite plates microstructure with high hardness, each microstructure being associated with high and low solidification rates respectively. Formation of a plate-like cementite structure has been discussed previously in the literature by Hume-Rothery (1966), who attributed it to marked supercooling. Chen et al. (1988) suggested that supercooling could be achieved by superheating the melt during laser processing, thus reducing the number of heterogeneous nucleation sites. In another work, Chen et al. (1984) showed that, after laser surface treatment, the ferritic/pearlitic matrix irons and gray cast irons exhibited a marked improvement in wear resistance.

Other techniques have been used for surface hardening of cast irons, based on high-energy electron beams (Suh et al., 1997) or gas tungsten arc welding (Orlowicz and Trytek, 2003). However, except for high-energy electron beam technology, low thickness layers (below 1 mm) were produced by using narrow laser tracks (less than 5 mm). These conditions have been typically employed at laboratory scale, and do not meet requirements for application on an industrial scale on large rolls.

In the present work, spheroidized graphite pearlitic (SGP) and spheroidized graphite acicular (SGA) cast irons were laser surface treated under different processing conditions in order to produce hardened layers with a thickness of between 1 and 2.5 mm, by using laser track widths larger than 9 mm. Laser surface hardening was carried out by means of two conventional methods, i.e., laser surface remelting (LSRm) and laser surface hardening (LSH). The microstructure obtained after laser treatment was analyzed by taking into account the chemical composition of ductile irons and the laser treatment conditions employed. Measurements of the retained austenite content were also included, and the mechanism explaining the formation of cracks during laser treatment studied. Fracture toughness of eutectic carbides embedded in the as-received pearlitic and acicular materials were determined by means of nanoindentation techniques and compared to prior K_C data of high-alloyed carbides.

2. Experimental procedure

Chemical composition of the pearlitic and acicular SG cast irons studied is shown in Table 1. Si content was lower than in ADI materials (Voigt, 1989) and content of Ni, Cr and Mo alloying elements varied in the range from 1.7 to 3.5%, 0.3% to 1% and 0.3% to 0.6%, respectively. These alloying additions were doubled in SGP1 compared to SGP2. SGP and SGA materials were fabricated by the conventional static cast process followed by normalizing at 850 °C. Rectangular specimens of 150 mm × 50 mm × 50 mm were machined out from the original as-cast SGP and SGA rolls and ground to a smooth surface finish in order to allow adequate absorption of the laser beam.

Table 1
Chemical composition of pearlitic and acicular ductile irons.

Material	C	Si	Mn	P	Cr	Ni	Mo	Cu	V
SGP1	3.26	1.79	0.46	0.047	0.69	2.99	0.47	0.038	0.22
SGP2	3.28	1.74	0.62	0.038	0.31	1.67	0.322	0.09	<0.04
SGA1	3.65	0.92	0.96	<0.017	0.97	3.49	0.58	0.12	<0.04

Laser treatments were performed by using a Nd-YAG Rofin DY 044 power source, with variable power output of up to 4.4 kW. Laser conditions used for LSRm and LSH treatments are listed in Table 2. During laser treatment the output power, P, was varied to achieve the target temperature measured on the specimen's surface, and by means of an integrated temperature control system within the laser head. The value of output power, P, for each selected temperature condition was taken at the steady state after stabilization of the laser beam. In order to achieve larger beam spots, the laser beam was defocused +138 mm, producing spot diameters in the range from 9 to 16 mm. The values of energy density delivered onto the material surface for each laser processing condition are also shown in Table 2. Energy density, E, is calculated as the delivered output power per surface unit and time by using the formula $E = 2P/\pi v r_B$, where v is the transverse speed of the laser beam and r_B is the beam radius. Based on the metallographic analyses, it was concluded that energy densities of 60 J/mm^2 separate the range of LSH and LSRm treatment conditions.

Table 2
Laser conditions used for LSRm and LSH treatments (v = scanning speed, P = output power, T = surface temperature and E = energy density).

Material	T (°C)	v (mm/s)	P (W)	E (J/mm^2)	Treatment
SGP1	1300	2	2550	100.45	LSM
SGP1	1250	2	2500	112.55	
SGA1	1250*	4	3500	71.32	
SGA1	1250*	4	3500	66.87	
SGP1	950	4	2550	57.24	LSH
SGP2	950	10	3490	34.44	
SGP2	1050	10	3830	35.03	
SGP2	950	12	4300	39.95	
SGA1	1050	14	4400	43.02	

* Constant output power.

The values of laser beam-material interaction parameters t_0 and τ, and the thickness of the remelted layers obtained during LSRm and LSH treatments are listed in Table 3. The expressions used to calculate the time (t_0) for heat diffusion over a distance equal to the beam radius, and the beam-specimen interaction time (τ) parameters are given by Li et al. (1986) and Ashby and Easterling (1984), as follows: $t_0 = r_B^2/4\beta$; $\tau = r_B/v$, where β is the thermal diffusivity of ductile irons. Thermal diffusivity can be determined by the $\beta = \lambda/\rho c$, where λ is the thermal conductivity, ρ is the density and c is the specific heat. Data of these parameters for ductile irons employed are listed below in Table 3.

Table 3
Calculated data of interaction time, heat diffusion time, radius-beam and thickness of the melted layer for each laser processing condition.

Material	v (mm/s)	r_B (mm)	t_0 (s)	τ (s)	Thickness of remelted layer (mm)	Treatment
SGP1	2	8.08	0.86	4.04	1.78	LSM
SGP1	2	7.07	0.65	3.53	1.7	
SGA1	4	7.81	0.80	1.95	1.02	
SGA1	4	8.33	0.91	2.08	1.23	
SGP1	4	7.09	0.66	1.77	0.51	LSH
SGP2	10	6.45	0.54	0.64	0.35	
SGP2	10	6.96	0.63	0.70	0.46	
SGP2	12	5.71	0.43	0.47	0.32	
SGA1	14	4.65	0.28	0.33	0.36	