Effect of preheat-treatment during laser hardening on residual stress formation in high-chromium irons

D. M. GUREYEV, V. K. SHUCHOSTANOV, S. V. YAMTCHIKOV
P. N. Lebedev Physical Institute, Academy of Sciences of the USSR, Sadovaya Street 61, Kuibyshev, 443020 K, USSR

The distribution of residual stresses formed on the surface of high-chromium iron with 16% Cr under the influence of cw laser radiation is studied as the function of the initial state of the iron and the laser treatment parameters. It is revealed that on the surface of both cast and heat-treated iron under the influence of the laser action, residual stresses of a tensile nature are formed. The stresses are greatest at the edges of the solidified melt zone and, in the hardened zone, they are greatest in the central part. The distribution pattern of the residual stresses corresponds to the structure phase transformations taking place. The highest level of the residual stresses is in the hardened zone consisting of martensite, austenite and carbides $(Cr,Fe)_7C_3$. It reaches the value of 2140 MPa in the cast iron and 450 MPa in the heat-treated iron. In the latter, a great number of cracks are observed. Their formation is accompanied by a significant relaxation of stresses. Preheating up to 400 °C at the optimum structure of the hardened zone avoids crack formation under laser influence. In this case, the level of residual stress is about 440 MPa, which is comparable with the case of crack-formation with no preheating.

1. Introduction

Nowadays it is generally recognized that the laser treatment is one of the best prospective methods of hardening the working surfaces of machine pieces and tools and increasing of their wear-resistance. There are a number of papers [1–3] devoted to the investigation of processes proceeding in the surface layers under the influence of laser radiation. Nevertheless, a lot of questions are still unanswered. One such question is the problem of the effect of laser treatment parameters on the formation of residual stresses and their distribution in the surface layer. However, there are a number of works [4–8] in which this problem has been investigated mainly for steels after their treatment by pulsed and cw laser radiation.

2. Experimental procedure

The present work was carried out for the purpose of investigation of the distribution pattern of residual stresses on the surface of high-chromium iron with 16% Cr under the influence of cw laser radiation as the function of the initial state of the iron and laser treatment parameters. The blades of shot-flinging devices were used as samples and their surface was only additionally grinded off in the special case mentioned below. The original (cast) blades and those subjected to heat treatment (hardened at 980 °C into oil) were used. Some of the blades subjected to previous heat treatment were also preheated up to 400 °C in a muffle furnace before the laser treatment. A CO_2-laser was used as the source of radiation, the power of which was 600 W. A laser beam was transformed into a strip of the size 11 mm × 1 mm with the equalized power density along the longitudinal direction. The treatment was carried out in the transverse direction and the rate varied in the range from 120–420 mm min^{-1}. This ensured the formation of both a melted zone and a laser-hardened zone at the surface. To avoid the interference of laser tracks, the distance between them was not less than 40 mm.

The residual stresses were measured by X-ray analyses with the help of the "$\sin^2 \Psi$" method [9]. For this purpose, the survey was carried out at four angles $\Psi = 0°$, 10°, 20° and 30°. A chromium K_α-radiation source was used. Lines $(2\,1\,1)_\alpha$ and $(3\,1\,1)_\gamma$ were analysed in the angle range $2\theta = 140°–170°$. A built-in microprocessor chose, of these two lines, the one giving a maximum reflex, depending on the correlation between α- and γ-phases in the structure of the investigated sample. Furthermore, the microprocessor determined the optimum scanning conditions, the angle range sufficient for the calculation of the chosen line, the step and exposure at every point and also calculated the value and the sign of residual stresses. The results of measurements together with the error and all the intermediate data were placed onto the display screen and digital printer.

The residual stresses were measured in the transverse direction to the laser tracks. The X-ray survey in

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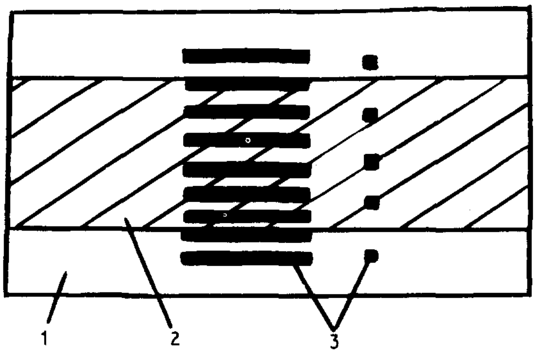


Figure 1 Schematic illustration of residual stress measurement in the transverse direction.

this case was carried out from the areas of the size 1 mm × 1 mm and 20 mm × 1 mm. The scheme of the measurement of residual stresses is given in Fig. 1.

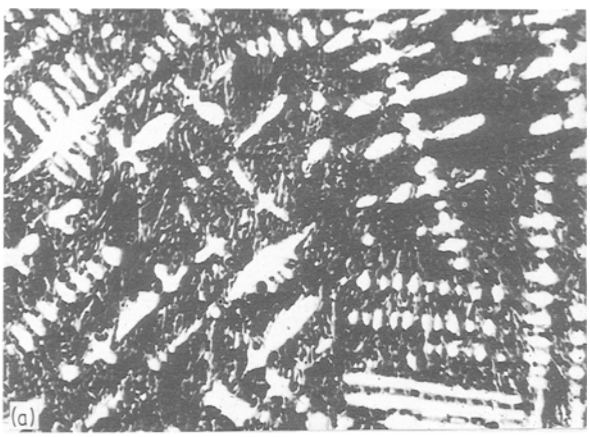
3. Results

Previous investigations of structure phase transformations in the zone of laser effect [10] showed that, in both cast iron and iron subjected to the heat treatment, the zone of solidified melt has the same structure and consists mainly of austenite (Fig. 2a). The hardened zone in the cast iron consists of martensite and coarse eutectic carbides $(Cr, Fe)_7C_3$ (Fig. 2b) and in the heat-treated iron it consists of martensite, austenite, eutectic carbides and re-liberated dispersed carbides $(Cr, Fe)_7C_3$ (Fig. 2c). Out of the calculation of thermal fields, it follows that the maximum hardening effect corresponds to the heating of the surface layer with a thickness of 0.10–0.15 mm up to the temperature 1050–1100 °C [11]. These results formed the basis of the purposeful choice of the laser treatment parameters in the present paper. The residual stresses were measured, on the one hand, at the surface of the zone of maximum hardening of the 0.10–0.15 mm thickness layer subjected to laser hardening at 1050–1100 °C and, on the other hand, at the surface of the solidified melt zone of comparable thickness.

It is discovered that, in high-chromium iron under the influence of the laser effect, residual stresses mainly of the tensile type are formed. Their values and pattern of distribution on the surface of the solidified melt and on the surface of the hardened zone are different. Thus, in cast iron, at the central part of the fused laser track, the residual stresses, σ_{res}, are at a minimum and are equal to 210–230 MPa (Fig. 3a). Near the edges they increase up to 550 MPa and then gradually decrease down to the initial value of − 110 MPa in cast iron. At the central part of the laser-hardened track, the residual stresses are at a maximum and reach the value of 2140 MPa (Fig. 3b). Approaching the edges, these values are gradually reaching the initial values.

The formation of tensile residual stresses at the zone of laser effect in cast iron is mainly caused by the interaction of the compressed austenite at cooling microvolumes with the surrounding initial structure. The difference in the level of residual stresses at the zone of solidified melt and at the hardened zone is the result of plastic deformation [12]. In the first case, the plastic deformation of compressible austenite microvolumes (which lowers the level of residual stresses) is facilitated as austenite occupies practically the whole volume of the melt owing to the dissolution of the coarse eutectic carbides $(Cr,Fe)_7C_3$. In the second case the plastic deformation is hindered by the presence of eutectic carbides $(Cr,Fe)_7C_3$, conserved due to heating only to lower temperatures.

A similar pattern of residual stress distribution over the surface of the laser effect is observed in heat-treated iron (Fig. 4). In particular, at the central part of



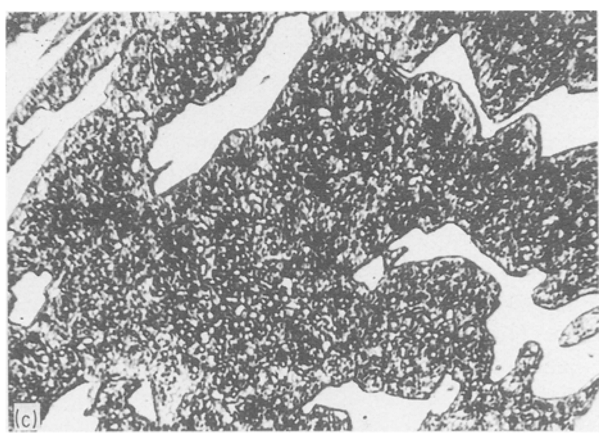


Figure 2 The structure of (a) the solidified melt zone; and of the hardened zone in (b) cast iron and (c) heat-treated iron × 3490.

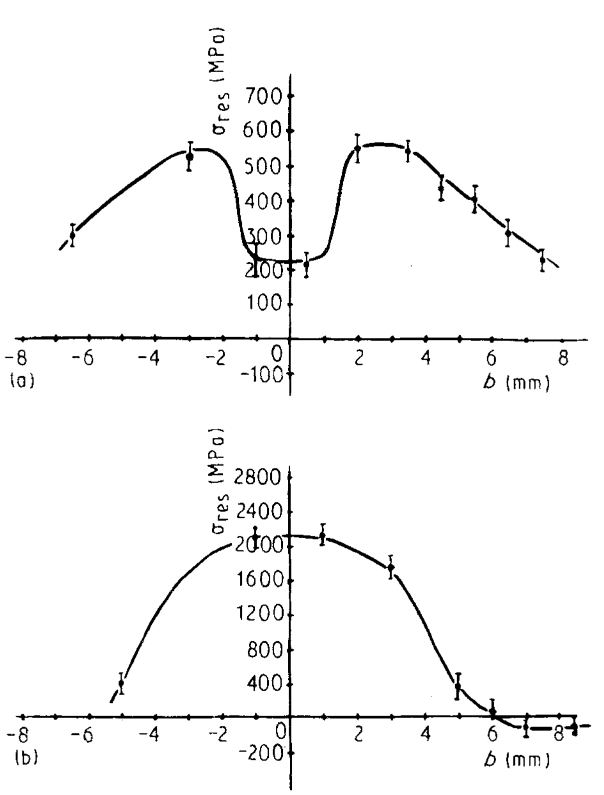


Figure 3 The variation of residual stresses over (a) the zone of solidified melt and (b) the hardened zone in cast iron, with distance, b, on both sides of the central axis of the laser tracks.

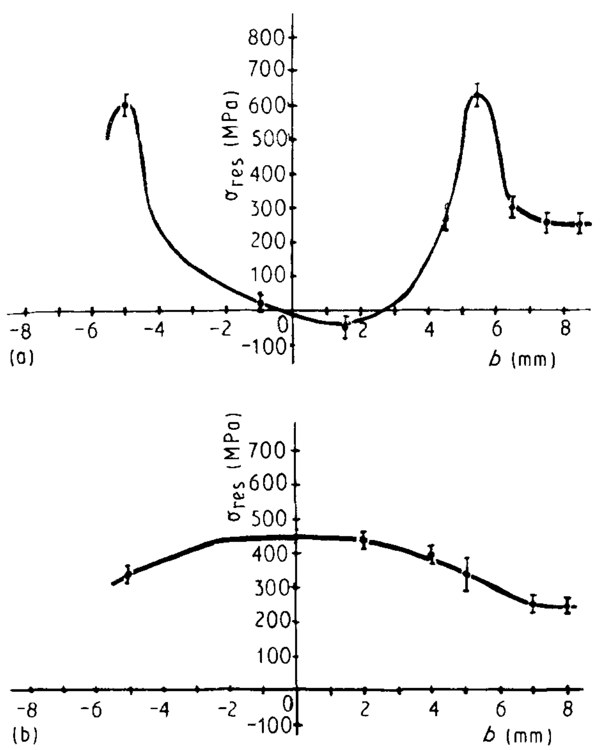


Figure 4 The distribution of residual stresses over (a) the zone of the solidified melt and (b) the hardened zone in the heat-treated iron on both sides from the central axis of the laser tracks.

the fused laser track, the level of residual stresses varies in the range from − 50 to + 30 MPa, and at the edges it rises to 620 MPa (Fig. 4a). In the central part of the hardened laser track, the residual stresses are at a maximum, as in cast iron, but their level is considerably (approximately five times) lower and do not exceed 450 MPa (Fig. 4b). Approaching the edges, the residual stresses are gradually decreasing to their initial values (250 MPa) in the heat-treated iron. It should be noted that the laser influence leads to the formation of a great number of cracks, especially in the latter case.

The formation of tensile residual stresses at the surface of the heat-treated iron is caused, on the one hand, by the temperature drop in the laser effect zone [12], and on the other hand, by the interaction of the compressible austenite microvolumes with the surrounding initial structure and by the release of dispersed carbides (Cr, Fe)$_7$C$_3$ resulting in the diminishing of the volume [13]. The factors decreasing the level of residual stresses are martensite formation and crack formation. The latter is the major factor.

The major role in the crack formation process is played by the defects of the volume heat treatment, including micro cracks located in the cavities of a rough blade surface and macrocracks extending to a depth of 10 mm. Other important factors are inclusions of the size of 0.8–1.0 mm of silicon and aluminium, included as a compound of a ceramic coating of patterns manufactured by melting and cavities reaching 10–15 mm diameter in some cases.

To expose the role of the crack formation in the relaxation of stresses at the surface of the laser effect zone, a pre-polishing of the blade surface was carried out that allowed the major part of defects at casting and volumetric heat treatment to be avoided. As a result, there was no crack formation at the laser treatment and an increase of the residual stresses level up to the level of that in the hardened zone of cast iron was observed.

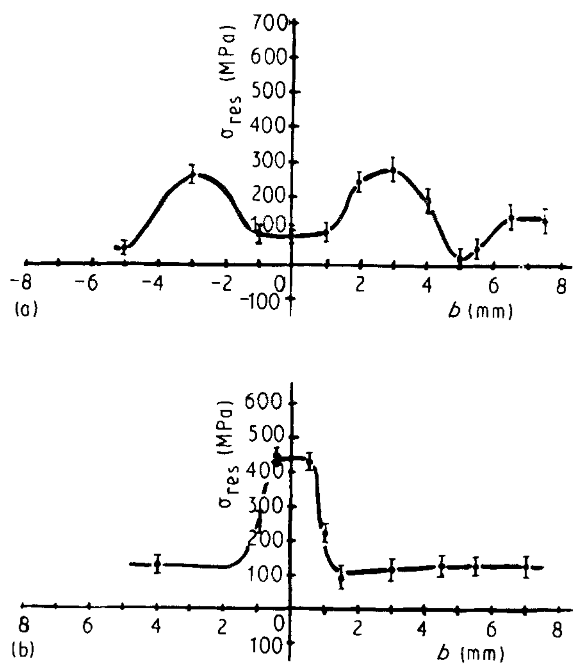


Figure 5 The distribution of residual stresses over (a) the zone of solidified melt and (b) of the hardened zone in heat-treated iron with pre-heating up to 400 °C before laser treatment on both sides from the central axis of the laser tracks.

As is known [10, 14], a preheating, for example up to 400 °C, also allows crack formation at laser treatment, to be avoided. Indeed, the laser influence on the initial surface of heat-treated blades at their preheating up to 400 °C did not result in crack formation. The measurements of residual stresses in this case showed that their level, in the central part of the laser melted track, did not exceed 95 MPa and, near the edges, it reached the value of 280 MPa (Fig. 5a). As a result of pre-heating, the width of the region of maximum residual stresses at the surface of the laser hardened track is reduced but their value (440 MPa) retains the level achieved with crack formation without any pre-heating (Fig. 5b). It should be noted that pre-heating up to 400 °C decreases the level of initial residual stresses by half from 250 MPa down to 130 MPa.

We have shown earlier [10] that in heat-treated iron, both with and without pre-heating up to 400 °C, the same structure phase composition is formed in the zone of laser effect. Therefore, the decrease in residual stress level with no crack formation at pre-heating may be explained by the presence of a lower temperature gradient.

4. Conclusions

On the basis of the investigations it was discovered that, at the surface of both cast iron and heat-treated iron, residual stresses are formed under laser influence, which are mainly of tensile character and have maximum values at the boundaries of the solidified melt zone and in the central part of the hardened zone. The highest level of residual stress was observed in the hardened zone where it reaches a value of 2140 MPa in cast iron and 450 MPa in heat-treated iron. In the latter case a great number of cracks are observed. Their appearance is followed by a significant relaxation of stresses. Pre-heating up to 400 °C at the optimum structure of the hardened zone allows crack formation to be avoided. In this case, the level of residual stress is about 440 MPa, which is comparable with the level of residual stress achieved without any pre-heating but, in the latter case, crack formation is observed.

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