JMEPEG (2000) 9:138-146

Deformation of Specimen During Laser Surface Remelting

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(Submitted 14 June 1999; in revised form 1 December 1999)

During laser surface remelting, thermal expansion in heating, and contraction of material in cooling, and due to microstructure changes in the heated surface layer, the specimen deforms. This induces volume changes during the process of remelting the thin surface layer and causes internal stresses. By measuring the deformation of the specimen during the remelting process as well as after the laser beam interaction, *i.e.*, to the moment when the specimen cools down to the ambient temperature, it is possible to follow the progress of deformation in the specimen material. Detailed information on the deformation events in the specimen material during the laser remelting process of a thin surface layer enables the engineer to optimize the process variables in terms of amount of deformation or magnitude of residual stresses on completion of cooling.

Keywords laser surface remelting, nodular iron, deformation, residual stresses

1. Introduction

The application of different conditions of laser surface remelting of thin specimens results in different amounts of specimen deformation on the same measuring spot.[1,2] In addition, different modes of traveling the laser beam on the specimen surface produce differences in the local energy density and different amounts of heat energy in the specimen material. The mode of traveling the laser beam across the specimen surface can also change the degree of laser trace overlapping. The mode of laser beam traveling and degree of overlapping can exert a considerable influence on how much a thin surface layer will be preheated. The degree of overlapping the adjacent remelted trace influences the stress relieving process taking place in the previously remelted layer.[3–6] A result of preheating is an increase in the temperature of the specimen material effecting a lowering of its yield point.[7] Because of a lower yield point and occurrence of internal stresses in the material during the treatment, the specimen develops a curved form. Gradual remelting causes changes in the temperature field distribution inside the specimen material, which results in different cooling rates in the particular traces of the modified surface layer.[8,9] Different cooling down rates in the particular traces lead to the formation of different microstructures in the modified surface layer.

It has also been shown that different heat conditions have a significant influence on the size and distribution of internal stresses during heating and cooling of the specimen, as well as on the size and distribution of residual stresses after the specimen with a modified surface layer has cooled down. Thus, it is generally required that laser remelting on the specimen's thin sheet would cause the smallest deformations possible and that products would contain the smallest tensile residual stresses or even small compressive residual stresses.

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2. Experimental Procedure

In the experiment, the chosen thickness of the specimen was 5.5 mm and was such that the maximum achieved temperature on the bottom side of the specimen was always less than 350 °C. This temperature was dictated by strain gauges used for measuring the specimen deformation.

Figure 1 shows the experimental system for continuous measurements of deformation and temperature on the bottom side of the specimen during the process of laser remelting a thin surface layer on the top side of the specimen. On the bottom side of the specimen were placed a three-legged, 45° high-temperature self-compensating resistance measuring rosette designated KFU-5-120-D17-11 manufactured by Kyowa (Graham & White Instruments Ltd., England) and two thermo-couples of class K.

With a high-temperature, resistance-measuring rosette, deformation of the specimen was measured during the process in three directions, namely, in the longitudinal direction (ε_a), in the transverse direction (ε_c), and at 45° to the longitudinal direction of the specimen (ε_b). The thermocouples, placed in the longitudinal direction of the specimen on the left and right sides next to the high-temperature resistance-measuring rosette, continuously measure the temperature and thus define the temperature cycles on the bottom side of the specimen material induced by transverse passage of the laser beam on the specimen's top side. This kind of placement enables continuous monitoring of the deformation state and specimen material temperature during the process itself, on completion of laser beam interaction, and on completion of cooling. The high-temperature resistance-measuring rosettes allow measuring of specimen deformations up to the temperature of 350 °C.

In Fig. 2, we can see the dimensions of the specimen and the size of the remelted and hardened surface layer. The laser beam was traveled in the transverse direction across the specimen, the outer laser beam traces being 14 mm away from the specimen edge. The entire width of the remelted area was in all experiments the same irrespective of the energy input. Since the width of the remelted layer in a single laser beam passage depends on the degree of defocusing and speed of the beam traveling, it is important that for each next layer to be remelted the laser head motion is very accurately defined. Another condition that should be fulfilled is the touching of the remelted layers

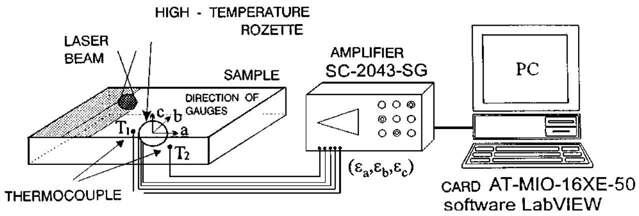


Fig. 1 Experimental system for measuring the temperatures and deformation of the specimen during the process of thin surface layer laser remelting

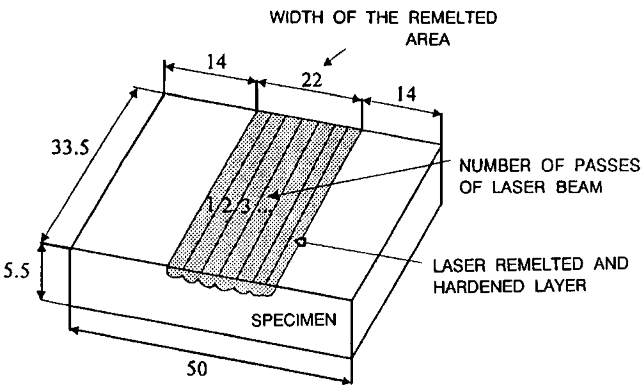


Fig. 2 Laser remelted and hardened area on the specimen

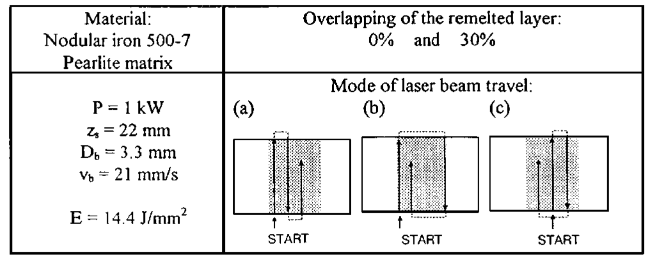


Fig. 3 **(a)** to **(c)** Modes of laser beam travel across the specimen surface

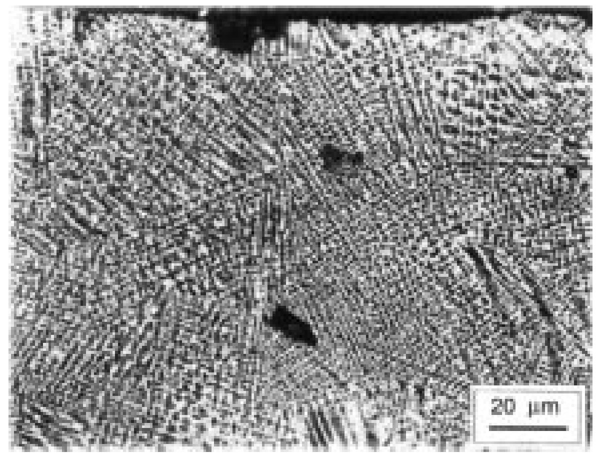


Fig. 4 Microstructure of the remelted zone

crossways or their overlapping expressed in percent with respect to the width of a single remelted layer.

In this way, we can achieve a fully remelted surface on the laser hardening spot. It is important to accurately define the number of laser beam passages since in all cases that can involve different treatment conditions equal sizes of the remelted surface area have to be ensured. The amount of the energy input is constrained by the highest temperature that can be achieved on the bottom side of the specimen. The measurements of specimen deformations during the remelting and cooling process and subsequent calculations of the main stresses were made on the nodular iron 500-7 (ISO) with a pearlite-ferrite matrix. This iron is very appropriate for laser hardening by remelting a thin surface layer.

Considering the very small depth of the remelted surface layer with respect to the specimen thickness, it was also decided to apply different modes of laser beam traveling across the specimen surface. The chosen modes of laser beam traveling are presented in Fig. 3. Because of the predefined width of the entire remelted and hardened area of 22 mm, in different laser treatment conditions, and the different degrees of laser trace overlapping, 15 to 22 laser beam passages were made. After each laser beam pass across the specimen surface, the laser beam was turned around 5 mm away from the specimen. By turning the laser beam around outside the specimen, overheating of the specimen edges was avoided.

3. Experimental Results

3.1 Microstructure and Microhardness Analysis

The microstructure changes in the laser remelting of the nodular iron are dependent on temperature conditions during surface layer heating and cooling. In the case of laser surface remelting, a modified layer was obtained consisting of characteristic microstructure zones, *i.e.*, remelted zone and hardened zone.

The microstructure of the remelted zone is affected by the cooling rates and degree of graphite dissolution in the melt. Because of a short interaction time, the graphite dissolving in the melt is incomplete and may be brought to the surface due to the buoyancy and dynamic forces. The graphite on the surface of the melt may evaporate due to intensive heat or may be blown away by a jet of protective gas. Therefore, the carbon content of the liquid may be less than the overall carbon content of the alloy, which has an effect on the formation of different structures. By diffraction X-rays in the remelted layer and by means of optic microscopy, it was found that the remelted zone consists of austenite dendrites, ledeburite, and a small portion of martensite and undissolved graphite. The austenite dendrites grow during rapid solidification of the remelted zone in the direction toward the surface, which corresponds to the direction of heat conduction (Fig. 4).

Very rapid cooling rates of the remelted surface layer of nodular iron can, depending on the treating conditions, produce the following effects:

- incomplete dissolution of graphite nodules; and
- redistribution of larger undissolved graphite nodules due to hydrodynamic forces and buoyancy in the molten pool.

In the hardened zone, only solid-state transformation can be noted. During heating, the basic pearlite microstructure transforms into austenite, which in cooling transforms into martensite with some residual austenite and graphite nodules.

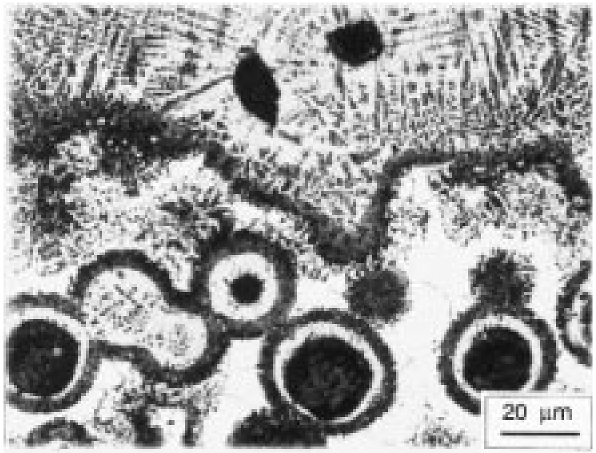


Fig. 5 Microstructure of the hardened zone

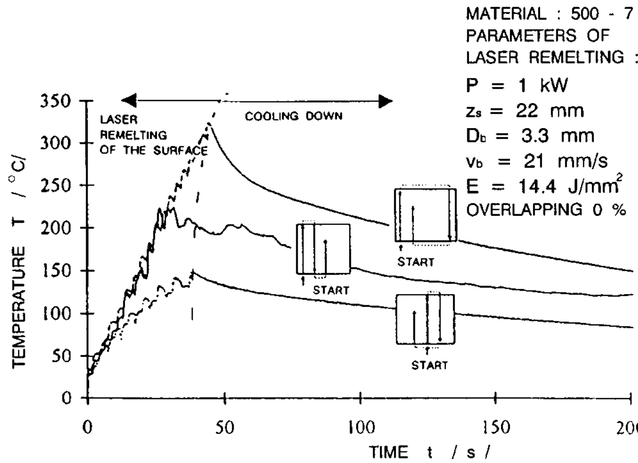


Fig. 6 Temperature measured in the middle of the bottom side of the specimen during and after the laser surface remelting obtained with different modes of laser beam travel

Fig. 5 shows a hardened zone consisting of martensite with a presence of residual austenite, ferrite, and graphite nodules. Typical martensite shells have formed around the graphite nodules. The preconditions for the formation of the martensite shells are a ferrite structure around the graphite nodules, heating above the austenitization temperature, and a high-enough cooling speed. The thickness of the martensite shells depends on the time-temperature variation during heating and cooling. Here, we should also consider the differences in the thermal diffusivity of carbon in the surrounding ferrite or austenite matrix, depending on the temperature. The figure shows the microstructure of the martensite shell consisting of two parts: the inner ledeburite cap and the outer martensite shell.

The results of microhardness measurements have confirmed the structure changes in the material and have shown that laser surface remelting can be a successful method. The hardness of the base material in soft state ranges between 200 and 250 $HV_{0.1}$ and after laser treatment increases to 800 to 950 $HV_{0.1}$ in the remelted zone and to 600 to 830 $HV_{0.1}$ in the hardened zone.

3.2 Analysis of Heat Conditions in the Specimen for Different Modes of Laser Beam Traveling

Fig. 6 presents the results of the measured temperature cycles in the middle of the specimen bottom side during and after the process of laser surface remelting for three different modes of laser beam traveling. The temperature gives information on the temperature changes in heating and cooling of the material on the bottom side of the specimen. To measure the effects of different modes of laser beam traveling and the different number of laser beam passes across the surface, thermocouples were placed on the bottom side of the specimen so that they registered partial temperature during the heating process. In the phase of heating the specimen, partial temperature occurs with a period of laser beam passage across the specimen surface. In the phase of heating, the highest peaks of partial temperature can be noted with the zigzag mode of laser beam traveling from the left to the right side of the specimen. The process of cooling can be described in general from the moment the maximum temperature in the specimen material on the bottom side was reached. From the measured temperature, it is thus possible to conclude that the time in which the maximum temperature is reached depends on the laser beam traveling mode. The cooling rates are changing gradually, being highest directly after maximum temperature has been reached and then gradually decreasing. For the chosen three modes of laser beam traveling at 0% laser trace overlapping, the same amount of energy E = 14.4 J/mm^2 was provided. Each laser beam passage across the specimen surface induces gradual heating of the material on the bottom side of the specimen, the result of which is preheating of the material before the next passage. The increased temperature of the specimen material makes the yield point of the material slightly lower, which may, with the given internal stresses, result in greater deformation of the specimen. How much the specimen will preheat depends on the mode of laser beam traveling or on the direction in which heat energy is transferred into cooler parts of the specimen material. Considering the three different modes of laser beam traveling across the specimen surface, we can state the following.

- The lowest maximum temperature on the bottom side of the specimen is reached with the circular mode of laser beam traveling, starting in the middle and ending on the edges of the heat-treated area. With this mode of laser beam traveling from the middle of the specimen toward the edges of the entire heat-treated area, heat energy is conducted from the specimen middle inside the cool material toward the longitudinal edges of the specimen. Therefore, the local concentration of the heat energy is relatively small, which ensures a small and gradual increase in specimen material temperature. In this way, we can ensure a considerable high cooling rate in the created modified surface layer, which has an influence on the amount of the residual austenite in the remelted layer.
- Somewhat higher temperatures of the material are achieved by zigzag laser beam traveling mode. With this mode of laser beam traveling, the heat energy is conducted more intensively in the longitudinal direction of the specimen, that is, in the direction of the particular remelted traces or in the

direction where the laser beam traveling is parallel. As expected, the maximum temperature of the material on the bottom side of the specimen is slightly increased. Due to this, the cooling rates in the modified surface layer are a bit lower and so is the amount of the created residual austenite in the remelted layer. As is known from volume changes in phase transformations, a smaller amount of the created residual austenite has a decisive influence on the size of tensile residual stresses in the remelted layer.

- The highest maximum temperature in the material on the bottom side of the specimen is achieved with the circular mode of laser beam traveling beginning on the edges of the hardened layer and ending in the middle of the specimen. In this case, heat conduction toward the middle of the cool area is increased so that, in the middle part, a higher concentration of heat energy is obtained. Thus, the created heat conditions cause lower cooling rates in the modified surface layer. On completion of cooling, the remelted layer contains a smaller proportion of residual austenite, which strongly lowers the unwanted tensile internal stresses during the cooling process and lowers the residual stresses in it on completion of cooling to ambient temperature.

3.3 Continuous Measurement of Specimen Deformation

Since the action of the laser beam is so narrowly focused, the remelting of the surface layer remains local. In the thin surface layer on the top side of the specimen where remelting has taken place, the temperatures achieved are much higher than on the bottom side. This kind of heating and cooling creates very-high-temperature gradients on the measuring spots in the specimen material. A rapid increase in the temperature during heating causes larger expansion of the material in the thin surface layer of the specimen than on the bottom side. These kinds of heat conditions as a function of specimen height cause a concave curving of the specimen during the remelting process (Fig. 7a).

In cooling, the just remelted surface layer solidifies, and cooling is continued in solid state involving phase transformations, which are reflected in a characteristic microstructure in the lower area of the modified surface layer. Due to microstructural changes in solid state, *i.e.*, due to the austenite-martensite transformation, an increase in the volume of the layer takes place. On the other hand, in the remelted surface layer, the volume decreases slightly relative to the hardened microstructure, which causes the occurrence of tensile stresses in it during the process of cooling or upon its completion. The decrease in the volume of the remelted surface layer is greater than the increase in the volume of the hardened layer. Therefore, in the modified surface layer, forces of contraction prevail, and a result of this is deformation of the specimen.

The combined effects of nonuniform extension of the material due to temperature gradients and specimen deformation due to phase transformations in the modified surface layer are shown in Fig. 7.

From the figure, we can see the following.

- When the effects of increased thermal expansion of the material in the surface layer are greater than the effects of material contraction due to phase transformations in the modified layer, then the specimen undergoes concave curving. This is caused by the forces of moment occurring due to material expansion in the modified surface layer (Fig. 7a).
- When the effects of thermal expansion of the material in the surface layer are equal to the effects of material contraction due to phase transformations in the modified layer, then the specimen does not undergo any deformation (Fig. 7b).
- When the effects of material contraction due to phase transformations in the modified layer prevail over the effects of thermal expansion of the surface layer material, then the specimen undergoes a convex curving. The convex curving is caused by the forces of moment occurring due to material contraction in the modified surface layer (Fig. 7c).

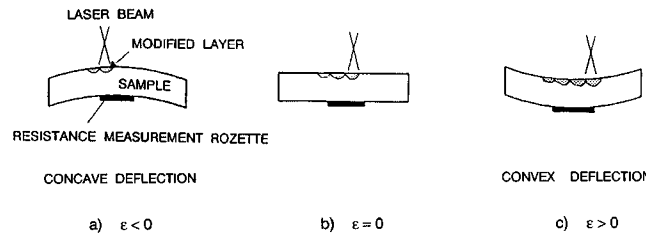


Fig. 7 **(a)** to **(c)** Specimen deformation during the remelting and cooling process

Fig. 8 shows measurements of deformation of the specimen ε vs the temperature during the laser surface remelting process for circular laser beam traveling mode beginning in the middle of the specimen and moving toward the edges of the hardened area. In the initial period of laser remelting, intensive heating of the surface layer material takes place. This causes larger material expansion in the surface layer resulting in concave deformation of the specimen. When the effects of contraction due to phase transformations in the modified layer become predominant, then the specimen undergoes convex curving causing tensile internal stresses on the bottom side of the specimen.

From the figure, we can see the beginning of surface remelting on the first trace, where the prevailing influence on specimen deformation is exerted by thermal expansion of the material in the surface layer. Approximately in the middle of the specimen, width deformations induced by phase transformations in the modified layer begin to prevail. From the measured results, we can conclude that, after the passage of the laser beam over the entire width of the specimen, the achieved convex deformation is maximum. At that time, the effect of the contraction forces caused by phase transformation in the remelted surface layer is maximum. On interruption of the laser remelting process, when the beam is turning around outside the specimen, the convex deformation in the specimen gets slightly smaller. The reason for this is the prevailing effect of thermal expansion of the surface layer material on specimen deformation, since phase deformations in the remelted layer have already taken place and there is no other important influence that would affect the deformation of the specimen.

In Fig. 9, we can see the results of deformation measurements in three directions, ε_a, ε_b, and ε_c, and the variation of temperature on the bottom side of the specimen. From the results, the

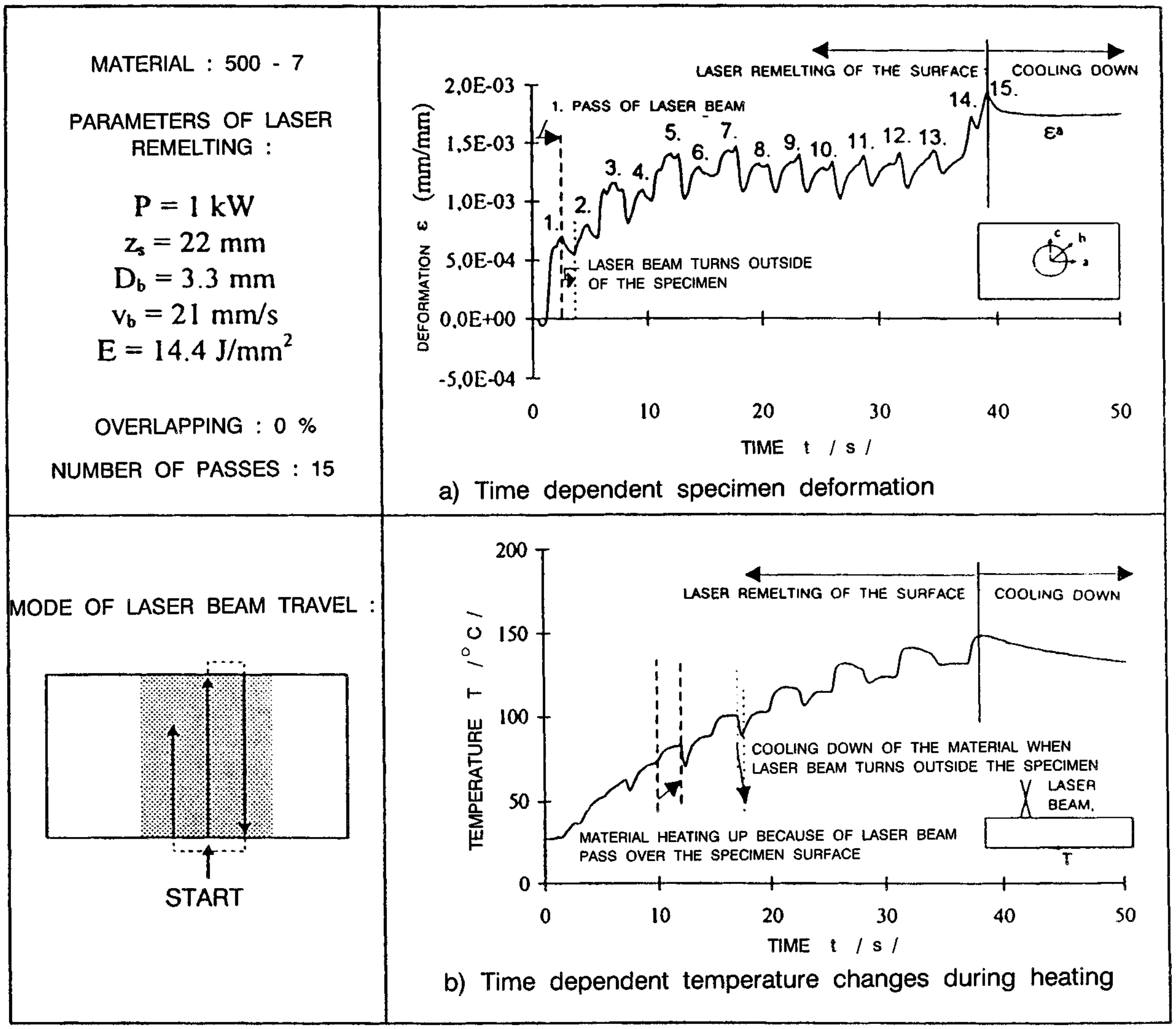


Fig. 8 Time dependence of specimen deformation **(a)** and the temperature measured on the bottom side of the specimen during laser remelting **(b)**

curvature of the specimen in the longitudinal direction W_a and in the transverse direction W_c of the specimen was calculated for the zigzag laser beam traveling mode and 30% overlapping of the traces.

From the results in the figure, we can see the following.

- A very different progress of deformation changes ε_a, ε_b, and ε_c in the particular directions.
- The largest deformations ε_a are found in the direction of the longer side of the specimen. The progress of deformation in the longitudinal direction of the specimen creates in it internal stresses during heating and cooling, and on completion of cooling, internal stresses remain in the specimen and are of tensile nature.
- In the direction of the shorter side of the specimen, *i.e.,* in the transverse direction, the deformations ε_c are at first of tensile nature but after six passes change into compressive.
- In the direction at 45° to the direction of laser beam traveling, the figure shows that the measured deformations ε_b are more than by one-half smaller than the deformations in the longitudinal direction of the specimen ε_a.

A very important conclusion is that the size of tensile deformation on the bottom side of the specimen is increasing with the increase in temperature of the specimen material. The reason for this deformation state is that at higher temperatures the yield point of the material lowers, and thus during the phase transformation in the modified surface layer, the contraction of the material is stronger resulting in specimen deformation.

From the discussed example, we can see a distinct difference in the specimen curvature in the longitudinal direction W_a and the transverse direction W_c. The measured specimen deformations are shown in Fig. 9 and schematically presented in Fig. 10. The measured deformations are a result of material contraction due to phase transformations in the phase of solidification of the laser remelted surface layer, which has an effect on the curvature of the specimen.

The laser remelted layer experiences a slightly greater contraction in the transverse direction than in the longitudinal

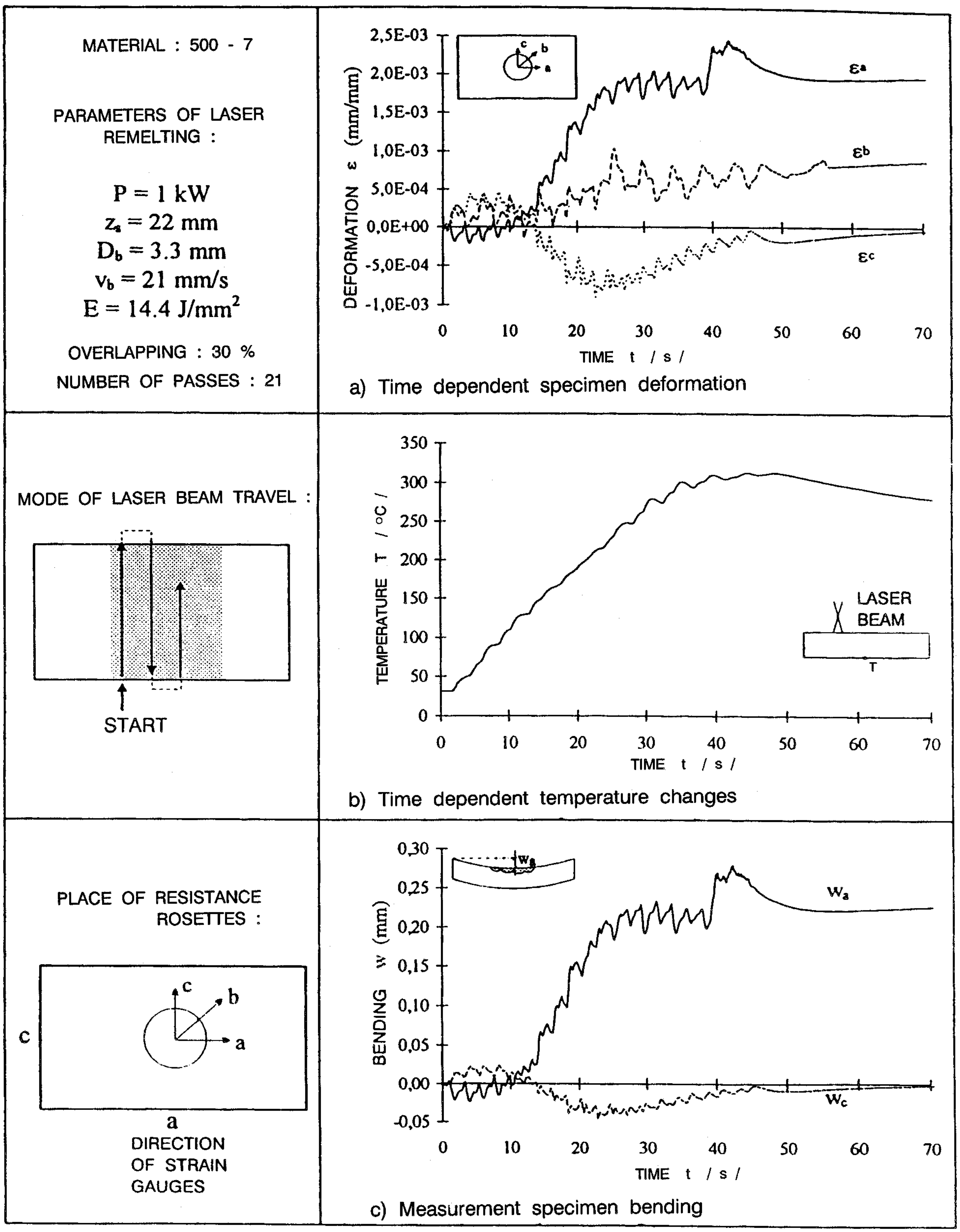


Fig. 9 Time dependence of specimen deformation **(a)**, time dependence of the temperature on the bottom side of the specimen **(b)**, and variation in specimen curvature **(c)** during the process of laser remelting using the specified parameters of laser remelting

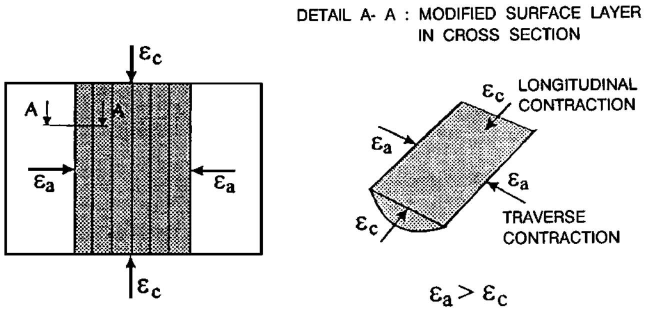


Fig. 10 Specimen deformation due to volume changes during laser surface remelting

direction. The reason for these differences in specimen contraction is greater heat conduction into the cold part of the specimen in the transverse direction with respect to the remelted trace than in the longitudinal direction of the trace. The direction of greater heat conducted in cooling defines the direction of crystallization on the boundary between the molten pool and the solid material, which at the same time defines the direction of increased material contraction. The conditions in solidification and further cooling of a thin surface layer, which affect the curvature of the specimen, are shown in Fig. 9(c) in the curvature graph.

From the measured results, we can see that the curvatures are considerably greater in the longitudinal direction of the specimen than in the transverse direction and are so in the phase of heating as well as on completion of cooling. It can also be stated that on completion of laser beam interaction, *i.e.,* in the process of cooling, the convex curvature on the bottom side of the specimen rapidly gets smaller. The reason for this rapid change in specimen curvature is to be sought in the effects of thermal expansion of the highly heated surface after the material stops contracting due to phase transformation in the remelted layer. After a certain time, when an equilibrium in temperature is reached throughout the entire specimen, no further deformations can be noted, which means that the specimen curving stopped at some point of permanent deformation.

Figure 11 shows the results of measuring the time dependence of deformation changes for different modes of laser beam traveling and 0% of laser trace overlapping.

The mode of traveling the laser beam across the surface is reflected in the distribution of heat energy in the specimen material in the phase of heating and cooling and thus also in the achieved temperature field in the specimen. The lowest temperature on the bottom side of the specimen is achieved in the case of heat conduction from the middle part of the specimen toward the specimen edges and the highest in the opposite case when the heat is concentrated along the edges of the remelted area. The distribution of heat in the specimen is to a large extent dependent on the laser beam traveling mode and on the amount of energy input, which is also dependent on the degree of laser trace overlapping. Increases in the specimen temperature induce a lowering of the yield point of the material, which has a significant effect on the time changes of specimen deformation.

Good knowledge of the conditions is of vital importance for the right selection of the laser beam traveling mode. On the basis of experimentation, the following conclusions can be reached.

- With the zigzag laser beam traveling mode, a gradual change of the deformation state in heating is reached only after the fourth pass of the laser beam. This means that at the beginning the effects of thermal expansion of the material are balanced with the effects of material contraction due to austenite transformation. In the next few passes of the laser beam, due to overheating of the entire specimen and lowering of the yield point related to this, considerable higher effects of forces of material contraction can be noted, which causes a distinct convex deformation of the specimen. When the temperature in the specimen material exceeds 150 °C, the longitudinal deformations stabilize achieving values of $\varepsilon_b \cong 0.002$.
- With the circular mode of laser beam traveling starting on the outer edges of the remelted area and ending in the middle of the specimen after the initial eight passes of the laser beam, very small changes in specimen deformation can be noted. At that time, there are two remelted bands (left and right part) on the specimen surface, each with four laser traces, from which the heat energy spreads equally toward the edges and toward the middle. This leads to the effects of thermal expansion of the material being balanced with the effects of material contraction due to austenite transformation in the phase of heating. When in the subsequent few passes of the laser beam across the surface the distance between the remelted bands (left and right) is becoming smaller, a high increase in heat energy in the middle of the specimen can be noted. This further induces a distinct lowering of the yield point of the material in the middle of the specimen. All this results in significant deformation of the specimen ($\varepsilon_a \cong 0.003$) caused by the effects of forces of material contraction due to microstructural changes. In further heating of the specimen, all the accumulated heat produces tempering effects in the previously modified surface layer, relieving the stresses and diminishing the effect of material contraction forces. The effects of tempering in the modified layer are reflected in smaller time-dependent deformation changes of the specimen. When the laser beam interaction is interrupted, the temperature being lowered below the tempering temperature, the tempering effects gradually diminish and finally even disappear. At that moment, the deformation first grows a little and then soon stabilizes to a value $\varepsilon_a \cong 0.0012$.
- With the circular laser beam traveling mode starting in the middle and moving toward the edges of the remelted area, heat conduction takes place in all directions of the specimen. Therefore, already at the beginning of laser remelting, it is possible to note the remarkable effect of material contraction forces due to austenite transformation in the modified layer, which results in convex curving of the specimen. After a certain time, in our case after the fifth pass of the laser beam, the deformation state of the specimen stabilizes, the effects of thermal expansion getting balanced with the effects of material contraction due to austenite transformation in the surface layer. When the temperature on the bottom side of the specimen has reached around 150 °C, *i.e.,* in the last two passes of the laser beam, the yield point of the material falls more distinctly. At that moment, the deformation of the specimen grows to a relative value of $\varepsilon_a \cong 0.0019$. On interruption of laser beam interaction, the forces of material

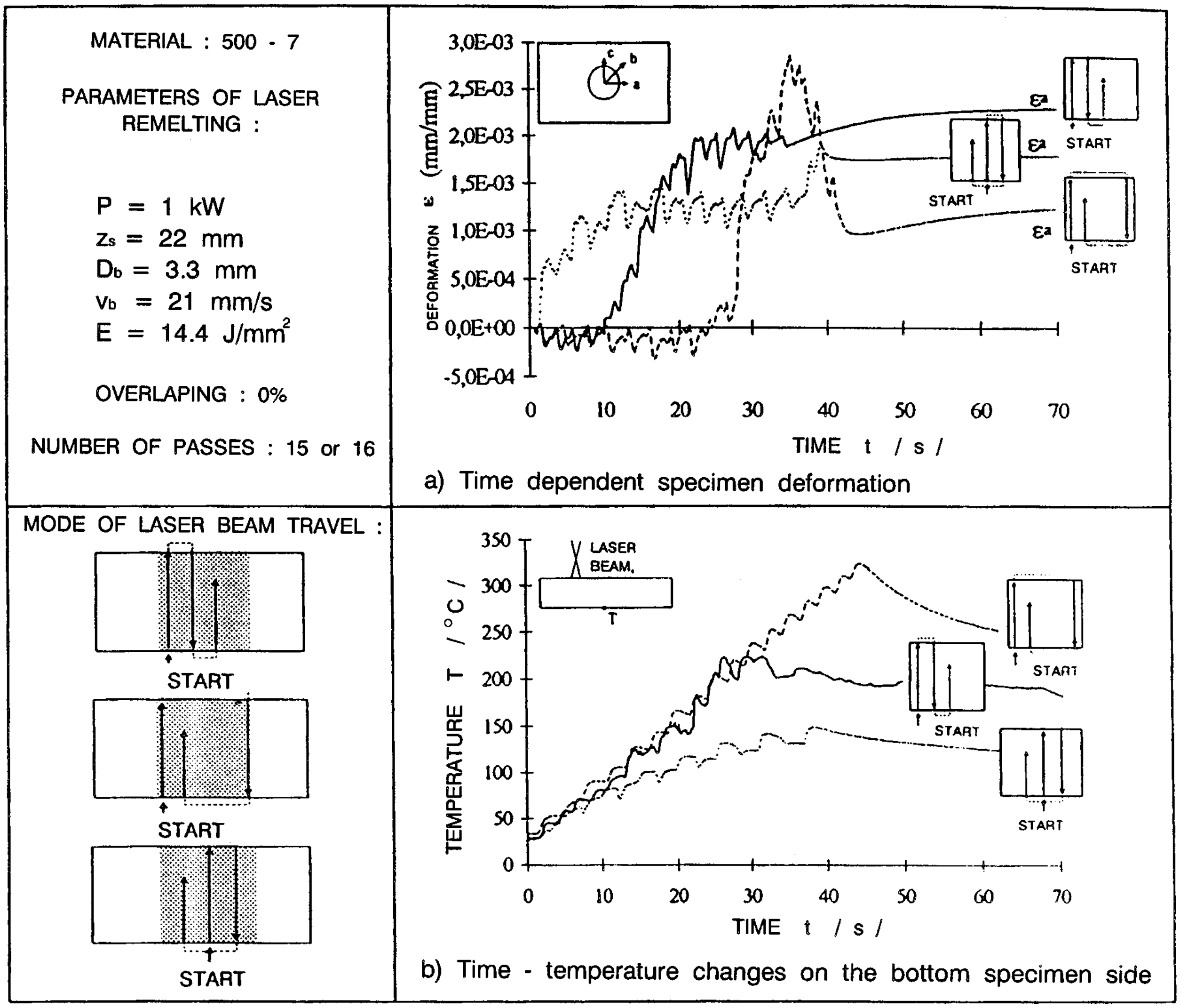


Fig. 11 The results of measuring the time dependence of deformation changes **(a)** and the temperature on the bottom side of the specimen **(b)** during the laser surface remelting process using the specified laser remelting parameters for different modes of laser beam travel

contraction due to austenite transformation in the modified layer stop acting. Thus, it is only possible to note the effects of material contraction due to specimen cooling, which is reflected in smaller convex deformation of the specimen, which soon stabilizes, $\varepsilon_a \cong 0.0017$.

Table 1 presents the final results on the longitudinal curving of specimens w_a on completion of cooling to the ambient temperature for different modes of laser beam traveling and different degrees of laser trace overlapping. The results on specimen curvature were obtained in two ways:

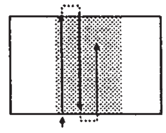
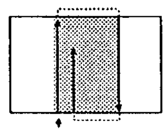
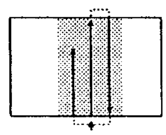
- by calculating the curvature from the measured deformation on the bottom side of the specimen during the laser surface remelting; and
- by measuring the curvature with a micrometer gauge.

The comparison between the calculated and the measured results on the specimen curvatures has shown that the differences are extremely small. This certifies that the measurements of specimen deformation during the laser remelting process were made precisely enough on a suitably selected measuring system setup. It also certifies the suitability of the physical model for the calculation of the specimen curvature considering different laser remelting conditions.

4. Conclusions

Continuous measurement of specimen deformation during laser surface remelting with a resistance-measuring rosette is a new method, not yet reported in the literature, of describing the deformation events in the specimen. It has been found that the information about time-dependent changes in specimen deformation contributes to better knowledge of the conditions during laser remelting and thus better optimization of the process. A description and evaluation is given of the effects of increased thermal expansion during heating the material in the surface

Table 1 Results of longitudinal curvature of specimens w_a

Parameters of laser remelting	Mode of laser beam travel	Overlapping (%)	Bending of the sample: Measured bending W_a^m (mm)	Bending of the sample: Calculated bending W_a^c (mm)
Material: 500-7		0 30	0.24 0.30	0.27 0.24
P = 1 kW z_s = 22 mm D_b = 3.3 mm V_b = 21 mm/s		0	0.21	0.16
Energy input: E = 14.4 J/mm^2		0 30	0.18 0.23	0.21 0.20

layer and the effects of austenite transformation in the modified layer on the progress and degree of deformation of a thin specimen. It has been concluded that the increased temperature or increased temperature field lower the yield point of the material, which results in increased specimen deformation. By continuous measurements of deformation during the laser remelting process, it has been proved that the direction of laser remelting has a considerable influence on the occurrence and size of deformation and results in different degrees of curvature of the specimen on completion of cooling. The measurements have shown that in the remelted zone a somewhat greater contraction is achieved in the longitudinal direction of the specimen than in the transverse. The reason for this is greater heat conduction into the cold part of the material in the transverse direction of the remelted traces than that in the longitudinal direction of the created traces. Here, it should be pointed out that the longitudinal direction of the remelted trace coincided with the transverse direction of the specimen. The direction of greater heat conduction in cooling defines the direction of solidification on the molten metal/solid-state boundary. This runs along the boundary between the molten pool and solidified material in the remelted layer and defines the direction of greater contraction of the material. Curving of specimens has a detrimental effect on product quality, but on the other hand, it contributes to lowering the tensile residual stresses in the remelted surface layer.

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