IMEKO TC15 - Experimental Mechanics - Proceedings of the
11th Youth Symposium on Experimental Solid Mechanics
Brasov, ROMANIA, 2012, May 30-June 2

PRELIMINARY ANALYSIS FOR A NEW APPROACH TO RELIEVE RESIDUAL STRESSES BY LASER HEATING

C. BARILE, C. CASAVOLA, G. PAPPALETTERA, C. PAPPALETTERE [1]

Abstract: *Stress relief heat treatment is used to reduce the residual stresses in a structure produced from manufacturing processes. There are many sources of residual stresses, and in particular those due to welding process could be of a magnitude roughly equal to the yield strength of the base material. Uniformly heating a structure to a sufficiently high temperature, but below the lower transformation temperature range, and then uniformly cooling it, can relax these residual stresses. In this paper the attention is focused on the possibility to use a high power laser source that local heats a component in order to relieve the residual stresses. An experimental set up is carried out on aluminum specimen and the preliminary results reported in this paper.*

Key words: *Residual stress relaxation, high power laser, local annealing*

1. Introduction

Residual stresses can be relaxed by supplying a sufficiently high amount of thermal [1, 2, 3] and/or mechanical energy. Several works, based on this principle, were carried out in the last years. Studies were realized on the prolonging fatigue life of a damaged steel by using the annealing treatment in a protective environment atmosphere [4], the effects of annealing prior to material dealloying on the mechanical properties [5] and in cold-rolled stainless steel [6] were also investigated; annealing treatments by a laser or a furnace were compared [2].

Since the purpose of this research was the measurement of materials' residual stress relief and not the materials' recover, a diode laser was preferred to a furnace heating treatment. The aim of this study, in fact, was to define a new way of localized material relaxation able to replace the traditional hole drilling (semi-destructive) method. So this study aims to develop this innovative process of relief residual stresses, applying the annealing technique by using a high power laser source on an aluminum sample. X-ray diffraction was used to investigate residual stresses and the effect of annealing. The research aimed to identify the proper process' parameters that influenced the measurements: laser's power, exposure time, local temperature, mechanical and thermal materials' properties.

[1] Politecnico di Bari, Dipartimento di Ingegneria Meccanica e Gestionale, Bari, Italy.

This novel approach for relieving residual stresses has the advantage of being nondestructive and can be easily applied to in situ tests.

2. Material and methods

A prismatic aluminum (Al5068) specimen was obtained by manufacturing process with squared cross section of sizes 10 mm x 10 mm and length of 100 mm.

The residual stress field of the sample was firstly determined by using X-ray diffractometry. To perform strain measurements the specimen was placed in the X-ray diffractometer, and it was exposed to an X-ray beam by a Cr tube through a 3mm collimator that interacted with the crystal lattice to generate diffraction patterns. Residual stresses were calculated by the $\sin^2 y$ technique. Three measurements were performed by scanning through an arc between -45° and -45° with a ψ oscillation of ±5°.

Fig. 1. *Laser Diode experimental set-up: Detail of the cooling and powering system.*

Successively the same specimen was locally heated and then the residual stress relieving was evaluated. Figure 1 shows the setup of the system used to produce the local annealing. The heating source is a laser diode with a maximum nominal power equal to 50 W and a wavelength of 810 nm. It was powered at a load-current of 5 A, corresponding to a power of 16.3W as shown in Figure 2.

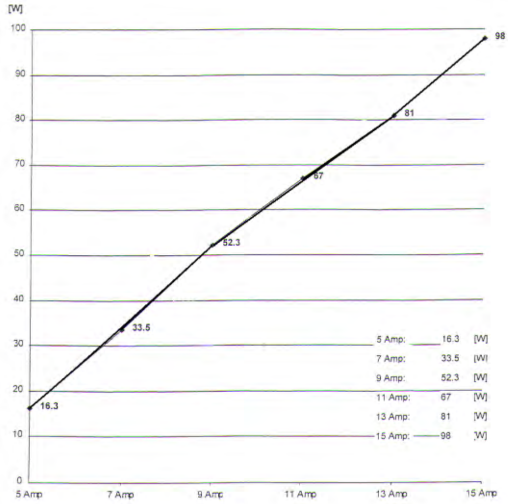

Fig. 2. *Trend of laser power vs. supply current*

The focused spot had an elliptical area with a horizontal diameter of 386.3 μm and a vertical diameter equal to 705.0 μm (Figure 3).

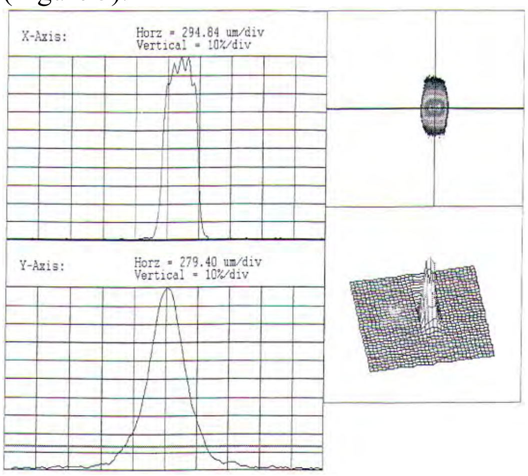

Fig. 3. *Laser beam power distribution along x and y axis: bi-Gaussian distribution*

To obtain this heat spot, the diode laser beam was guided and focused using a biconvex lens with 110 mm focal length. After the heating has finished, the specimen was analyzed again and in the same points using the X-ray diffractometer.

The heating process must be realized carefully since nonlinear response of the material could be introduced. If the material is heated too much or too fast, the local thermal expansion will create plastic compressive strains [7]. Therefore, there would be two types of strains: one due to the residual stress relaxation and the other due to the induced plastic compressive deformation which would introduce significant errors in the measurements of the residual stresses, they can be avoided by using an appropriate heating cycle [7].

Hence, the following heating cycle was chosen: the diode laser heated the specimen at approximately 30% of its power for a period of 20 s. This cycle created a power density in the focused spot area of about 8300 W/cm^2 and increased the local temperature of the specimen to approximately 270°C. This value was computed integrating the analytic model for an instantaneous stationary point source over time but maintaining the power constant and then calculating the temperature at the center of an area corresponding to a Gaussian beam. It was assumed a thermal conductivity equal to k= 250W/(m °K) and a thermal diffusivity equal to $\alpha=8.23\cdot10^{-5}$ m/s^2 for the aluminum specimen.

$$T = \frac{Q}{8(\pi\alpha t)^{\frac{3}{2}}} e^{\frac{-[(x-x')^2+(y-y')^2+(z-z')^2]}{4\alpha t}}$$

The differential equation for the conduction of heat in a stationary medium, assuming no convection or radiation, is satisfied for the case of an instantaneous point source of energy QρC by [8, 9]

Integrating over time, in order to consider the effects of the heat cycle, but assuming Q constant, it results [8, 9]:

$$T(x,y,z,t) = \int_0^t \frac{Q}{8(\pi\alpha t')^{\frac{3}{2}}} * \\ * e^{\frac{-[(x-x')^2+(y-y')^2+(z-z')^2]}{4\alpha t'}} dt'$$

Considering a constant Gaussian beam, the temperature at the center of the area ($r = r_0 = 0$) is [8, 9]:

$$T(r=0,t) = \frac{2P_0(1-R_f)D}{\pi D^2 k\sqrt{\pi}} \tan^{-1}\frac{2\sqrt{\alpha t}}{D}$$

Where:

- P_0 is the laser power
- R_f represents the aluminum reflectivity corresponding to λ=810 nm laser energy (Figure 4) which has a minimum in correspondence of the wavelength used in the experiment

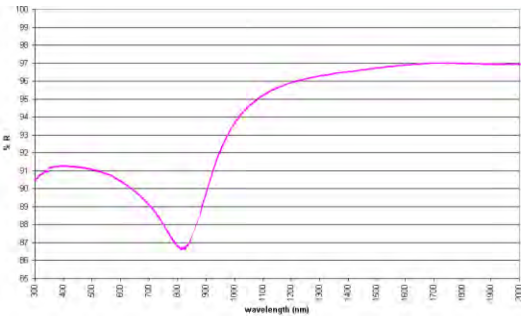

Fig. 4. *Graph of aluminum reflectivity related to laser wavelength [10]*

- D is the mean value of horizontal and vertical beam diameters
- k is the thermal conductivity
- a is the thermal diffusivity.

3. Results Analysis and Discussion

Several measurements of residual stress field, before and after the local annealing process, were evaluated in correspondence of the center point of the specimen surface, named 'A', by using an X-ray diffractometer (Figure 5).

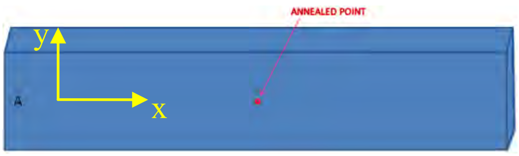

Fig. 5. *Schematic of the specimen annealed: A surface.*

A set of measurements was performed along the longitudinal and transverse specimen axes. Before the heating process the sample presented a hydrostatic state of stress whose mean value (calculated on four measurements) was evaluated to be $\overline{\sigma}$ = -158.5 MPa. After the local annealing the same measurement set was realized, and it provided a comparative mean residual stress value equal to $\overline{\sigma}$ = -93.4MPa.

It should be noted that, distinguishing between the longitudinal stresses and the transverse ones, the resulted stresses relieving is more evident for the longitudinal direction than for the transverse one, as shown in Figure 6.

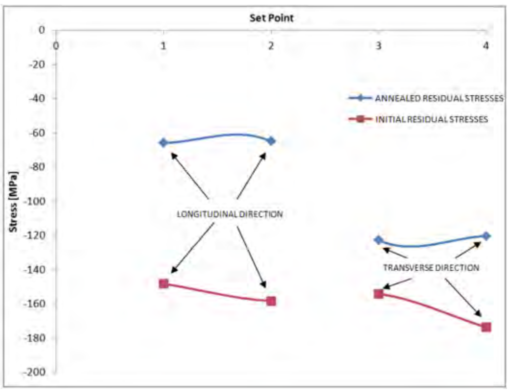

Fig. 6. *Calculated residual stresses before and after annealing, along two directions: longitudinal and transverse.*

This result can be justified in view of the fact that the laser beam power distribution is an ellipse, and so it has different diameters along x and y-axes (see Figure 3). This condition implies that during the annealing process the power density along the beam y-axis corresponds to 32% of the power density along the x-axis. And so the relieving attitude is more accentuated along the x-axis. It corresponds to the longitudinal direction during the annealing process.

Referring to the mean values the stresses relaxation results of about 65MPa, but if one considers only the longitudinal stresses the stresses reducing is equal to 88 MPa, as suggested in Figure 6.

On the basis of these considerations a set of measurements were executed on the opposite side, named 'B', of the same specimen. Since the sample's thickness was of 10 mm, it can be assumed that the B surface stress field was not influenced by the previous treatment on the A surface. Two point locations were fixed, and for each one three measurements of stress field were realized, for both longitudinal and transverse directions (Figure 7).

Fig. 7. *Schematic of the specimen annealed: B surface.*

The laser spot was focused in correspondence of the locations 1. Point 2 was far 10 mm from point 1. A comparison between initial state and annealed state is obtained. The longitudinal stresses are distinguished by the transverse ones. Only the mean value of the three measurements along each direction is reported, in correspondence of the two locations (Table 1-Table 2 and Figure 8).

Comparison of transverse stress values between initial and annealed state Table 1

Locations	Initial Residual Stress (MPa)	Annealed Residual Stress (MPa)	$\lvert\Delta\sigma_L\rvert$ (MPa)	$\lvert\Delta\sigma_L\rvert$ (%)
1	-110.9	-79.6	31.3	28.2
2	-83.6	-74.7	8.9	10.6

Comparison of transverse stress values between initial and annealed state Table 2

Locations	Initial Residual Stress (MPa)	Annealed Transverse Stress (MPa)	$\lvert\Delta\sigma_T\rvert$ (MPa)	$\lvert\Delta\sigma_T\rvert$ (%)
1	-113.4	-100.8	12.6	11.1
2	-110.3	-98.8	11.5	10.4

Also in this case, since the laser distribution maximizes the power density along the beam x-axis, it should be noted that the higher effects of annealing are on the longitudinal stresses. In particular it results that the higher relaxation is localized in correspondence of the location affected by the beam (point 1). It results, in fact, that on the point 1 the relaxation of longitudinal stresses is equal to $\lvert\Delta\sigma_L\rvert$ = 31.3 MPa, on the other side for transverse stresses the relaxation is $\lvert\Delta\sigma_T\rvert$ = 12.6 MPa The relieving effects are less marked in correspondence of the more distant point. Point 2, in fact, shows a relaxation in both directions, but not underlines the different behavior due to the beam distribution, as in point 1. This result provides interesting hints for future works, related to the extension of the heated area and on the annealing influence on distant point locations.

It results also evident that the difference between the longitudinal stresses in initial state and the same in annealed state is less underlined than in A surface. Probably this result depends on the different laser stability, which is related to different initial values of residual stresses for each point.

The process seems to well operate. It ensures a good relieving of residual stresses in shorter time, than common heat treatments. After only one heating cycle a substantial decreasing of stress values is evaluated in the closest area of the annealed point.

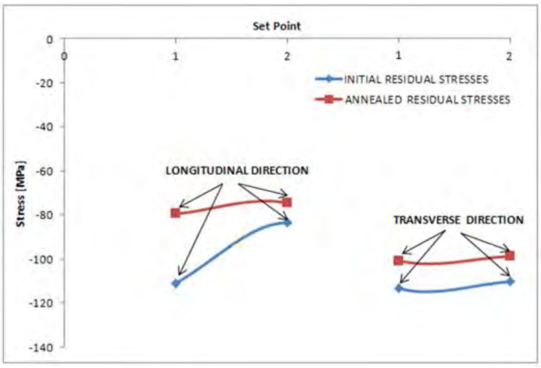

Fig. 8. *Calculated residual stresses, before and after annealing, along two directions: point 1 and 2.*

4. Conclusions

In this work the effects of laser annealing on residual stresses has been investigated. The procedure implies a substantial localized relaxation in a very short time, respect to the traditional heat treatments. Due to the elliptical distribution of beam it was found that the effects of relaxation were more evident in the longitudinal directions of specimen respect to the transverse one. The beam diameter, in fact, was shorter along the x-axis than along the y-axis and so had higher density power than along the perpendicular direction.

Actually a numerical model has been realizing. It proposes to simulate the thermal response of sample, in order to support the experimental tests.

This technique combined with an optical one is proposed to replace the traditional hole drilling method with strain gage rosettes, providing high accuracy measurements in short time and without the limitations of the conventional contact techniques.

References

1. Holzapfel, H., Schulze, V., Vohringer, O. and Macherauch E.: *Residual stress relaxation in an AISI 4140 steel due to quasistatic and cyclic loading at higher temperatures*. In: Materials Science and Engineering A, 1998, Vol. 248 (1), p. 9–18,.
2. Liu, H., Guo, R.X., Viejo, F. and Liu, Z.: *Comparison of microstructure and residual stress characteristics of electroless ni-w-p coatings annealed with a laser and a furnace.* In: Surface & Coatings Technology*,* 2012, Vol. 206 (8-9), p. 2380-2387.
3. Nikitin, I. and Besel, M.: *Residual stress relaxation of deep-rolled austenitic steel*. In: Scripta Materialia, 2008, Vol. 58(3), p. 239-242.
4. Du, B., Zhu, W., Ma, B., and Li, L.: *Prolonging fatigue life of a damaged steel by annealing*. In: International Journal of Fatigue, 2004, Vol. 26(9), p.1017-1023.
5. Seker, E., Gaskins, J. T., Bart-Smith, H., Zhu, J., Reed, M. L., Zangari, G., Kelly, R. and Begley, M. R.: *The effects of annealing prior to dealloying on to the mechanical properties of nanopouros gold microbeams.* In: Acta Materialia, 2008, Vol. 56(3), p. 324-332.
6. Wang, Y.D., Lin Peng, R., Wang, X.L. and McGreevy, R.L.: *Grain-orientation-dependent residual stress and the effect of annealing in cold-rolled stainless steel.* In: Acta Materialia, 2002, Vol. 50(7), p. 1717-1734.
7. Viotti, M.R., Suterio, R., Albertazzi, A.Jr. and Kaufmann, G.H.: *Residual stress annealing preliminary results.* In: *Optics and Lasers in Engineering*, 2004, Vol. 42(1), p.71-84,.
8. Steen, W.M.: *Laser material processing*. In: Springer, 2003.
9. Carslaw, H.S. and Jaeger, J.C.: *Conduction of heat in solids*. In: Oxford University press, 1959.
10. *Gemini Observatory*. Gemini south's secondary mirror sports shiny silver coat, 2012.