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Numerical Analysis of the Contour Method for Measuring Residual Stresses in Laser Shock Peened Ti-6Al-4V Strips

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Abstract : The contour method is based on the elastic superposition principle, and relies on deformations that occur when a residually stressed part is cut along a plane. During the cut, the part is constrained at a location along the cut so that deformations are restrained as much as possible. The displacement is applied to an elastic FE model of the half. When plasticity is involved in the relaxation process, the superposition principle is no longer valid, and stress error in the resulting measurement of residual stress would be caused. Residual stress states in a laser peened Ti-6Al-4V strip were taken for the FE simulation.

Key words : Contour method, Laser shock peening, Numerical analysis, Plasticity effect, Residual stress

1. Introduction

Residual compressive stresses induced by a peening process are beneficial in enhancing resistance to fatigue failures, corrosion fatigue, stress corrosion cracking, fretting and hydrogen assisted cracking. Laser Shock Peening (LSP) is a very attractive, promising fatigue enhancement surface treatment for metallic materials. The purported advantage of LSP over conventional surface treatments such as shot peening is that the depth of the compressive stress layer produced via LSP is much larger[1]. LSP is gaining renewed interest in improving the damage tolerance and durability of an engine material, Ti-6Al-4V.

The measurement of residual stress near the edge of a Ti-6Al-4V strip is of practical concern due in part to recent applicants of laser peening to the leading edge of fan and compressor blades in gas turbine engines. Surface enhancement techniques such as laser peening have been used to induce a state of compressive residual stress near the blade leading edge in an attempt to mitigate fatigue crack growth initiating from sites of foreign object damage[2]. In

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order to develop a methodology of the measurement of residual stress and its distribution near the blade leading edge, Rankin and Hill[3] applied the crack compliance method for measuring the residual stress created by LSP on a Ti-6Al-4V strip. The contour method[4] has recently been developed and has the capability to determine a two-dimensional map of the residual stress component normal to a plane through an object. The contour method can also be effectively applied to measure the residual stress with position from the leading edge. However, the effect of plasticity on the measurement of such a residual stress distribution by the contour method has not been investigated.

The contour method for measuring residual stresses of a component created by such as LSP is based on a variation of Bueckners superposition principle[5] in elasticity and measuring deformations normal to the plane created by a cut. Common to other destructive and semi-destructive methods, the assumptions are the relaxation process during material removal is elastic and the material removal process itself does not introduce substantial residual stresses into the body. The method is relatively simpler to apply over the other relaxation methods since the deformation is measured directly on the plane of the cut rather than on other free surfaces. The method is especially effective for measuring a 2-D profile of residual stress such as in a welded strip. Wire Electric Discharge Machining (WEDM) is typically applied for making the cut, and the specimen is constrained at a location near the cut in order to hold the cutting plane from moving during cutting.

The assumption of elastic relaxation in the contour method is not valid when yielding occurs during cutting. When plasticity is involved during the relaxation process, the residual stress profile measured by the contour method would no longer represent the original residual stress state in a body. It is, however, believed that constraining the body during cutting at a proper location can minimize the plasticity effect. Thus, as described above, constraining a specimen during the cut can serve the purposes of not only preventing the plane of the cut from moving but also minimizing the effect of plasticity.

In this paper, the plasticity effect on measuring residual stress using the contour method is numerically simulated for a residual stress distribution under different constraining locations from the plane of the cut. These analyses were performed using a commercial FE package, ABAQUS/Standard[6]. A Ti-6Al-4V strip(Fig. 1) was assumed to have a residual stress profile created by laser shock peening process. The displacements along the plane of the cut were read after completing cutting the specimen and releasing the constraint, and the displacement field was imposed in an elastic model of the undeformed configuration, as would be done when executing a contour method measurement.

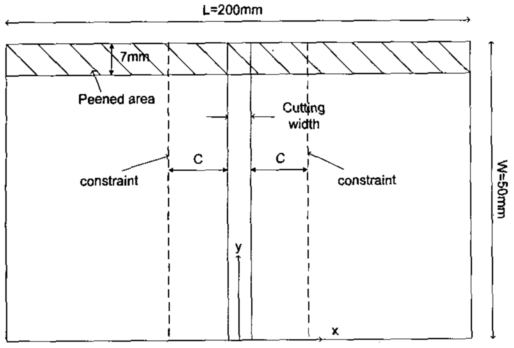

Fig. 1 Dimensions of theTi-6Al-4V strip with the laser peened area (hatched)

2. Numerical Model

A Ti-6Al-4V strip of 200mm x 50mm was modeled with lengthwise symmetry. The modeled half of the strip was meshed with 199(x-direction) x 100(y-direction) 4-noded plane strain elements (CPE4), and the mesh was biased toward the plane of symmetry. The material properties are: Sy=945MPa, E=112Gpa, =0.342. It was assumed that the material has isotropic hardening at stress level of 1014MPa with plastic strain of 0.051 and perfect plasticity after that point. Longitudinal residual stress across the width was initialized such that the strip can have a residual stress distribution similar to one induced by laser shock peening process on the top portion of 7mm. The original longitudinal residual stress distributions were given with the peak values of 95%, 60% yield strength (Fig. 2). Each element of 0.5mm depth and 0.254mm width was removed in one step along the mid-plane of the strip. The total 100 steps were taken to complete the cut. For each removal process the strip was constrained at the location of C=5mm, 10mm, 15mm, 20mm, 30mm and 40mm from the cut, respectively. Convergence analysis was primarily conducted by increasing the element refinement to ensure the independence of the solution from the mesh.

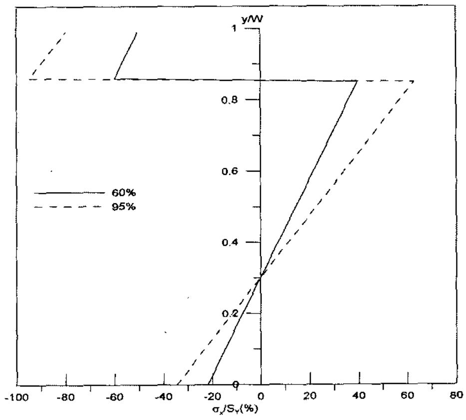

Fig. 2 Original residual stress distributions with peak values of 95%, 60% yield strength

3. Results and Discussion

The cutting process for the laser shock peened strip was performed either from peened edge or unpeened edge. The displacement profile after completing the cut by each direction is shown in Fig. 3 and 4 with different constraining locations when the peak value of the original residual stress is of 95% the yield strength. Fig. 5 and 6 represent the simulated residual stress distributions with different constraining locations when the peak original residual stress has a value of 95% yield strength. Fig. 5 is for the cutting direction from peened to unpeened edge, and Fig. 6 is for the direction from unpeened to peened edge. Constraining the specimen closer to the cutting edge brings about less plasticity effect on the measurement of the residual stress using the contour stress error.

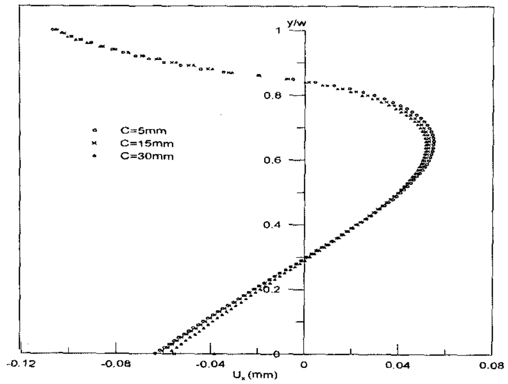

Fig. 3 Displacements to be imposed to FEM model in case of peak original residual stress value of 95% yield strength (cutting direction: from peened to unpeened edge)

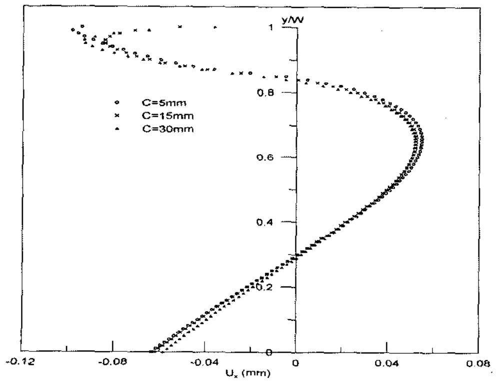

Fig. 4 Displacements to be imposed to FEM model in case of peak original residual stress value of 95% yield strength (cutting direction: from unpeened to peened edge)

method. As shown in Figure 9, the constraining location C=5mm gives the Root-Mean Square (RMS) error of about 2% (maximum error of 5%) yield strength averaged over the stresses across the width for the cutting direction from the peened edge to unpeened edge, and 3% (maximum error of 11%) for the cutting direction from the unpeened edge to peened edge. The stress value of the last element of the cutting process was not taken into account in computing the RMS

When only the compressive residual stress state at the peened region is concerned, the constraining location C=5mm gives the averaged RMS error of about 3% yield strength for the cutting direction from the peened edge to unpeened edge and 8% yield strength from the unpeened edge to peened edge. Thus, the cutting direction from the peened edge to the unpeened edge provides better measurement especially when the compressive residual stress state due to peening process is a main concern.

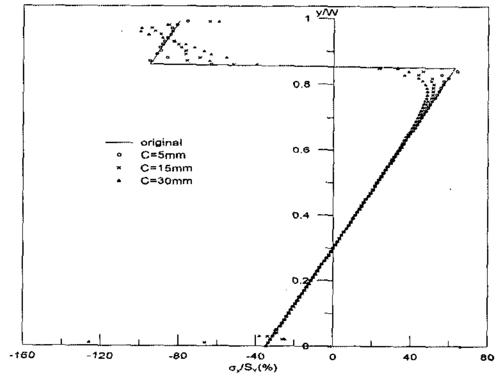

Fig. 5 Recomputed residual stress distributions for peak original stress of 95% yield strength (cutting direction; from peened to unpeened edge)

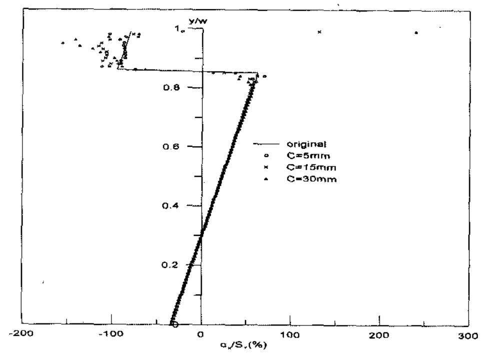

Fig. 6 Recomputed residual stress distributions for peak original stress of 95% yield strength (cutting direction; from unpeened to peened edge)

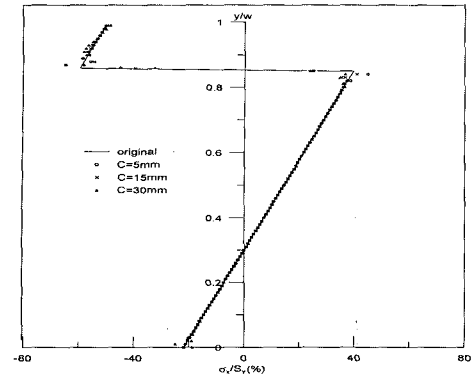

Fig. 7 Recomputed residual stress distributions for peak original stress of 60% yield strength (cutting direction; from peened to unpeened edge)

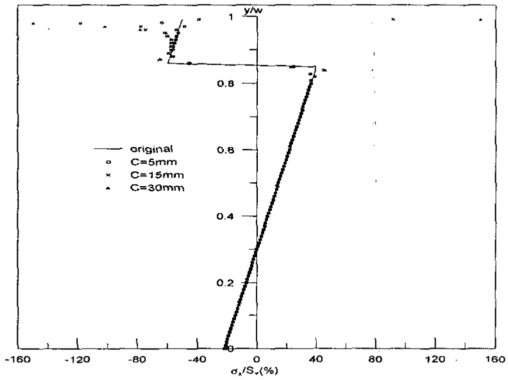

Fig. 8 Recomputed residual stress distributions for peak original stress of 60% yield strength (cutting direction; from unpeened to peened edge)

Fig. 7 and 8 show the residual stress distributions obtained for each cutting direction when the peak residual stresses are of 60% yield strength. Due to the lower magnitude of the residual stress the plasticity effect is far less than in the case of peak stress of 95% yield strength. Fig. 10 shows the RMS stress error due to the plasticity effect when the peak original residual stress is of 60% yield strength. For the cutting direction from peened to unpeened edge, the constraint C=5mm induces almost no plasticity effect on the measurement. For the other direction, the constraint C=5mm gives RMS stress error of 1% yield strength averaged through the entire region of the cutting plane, and 4% yield strength for only the peened region.

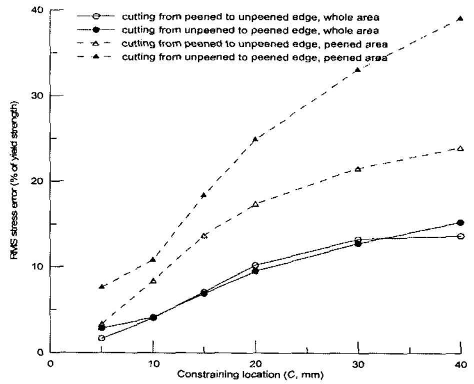

Fig. 9 RMS stress error for peak original stress of 95% yield strength

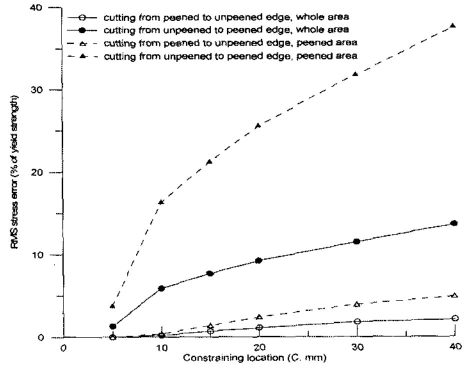

Fig 10 RMS stress error for peak original stress of 60% yield strength

The effect of plasticity in measuring residual stresses by the hole-drilling technique becomes significant due to local yielding caused by stress concentration around the hole when residual stresses are over 60% of the materials yield strength[7]. In measuring residual stress of 70% yield strength by the hole-drilling technique[8] an overestimation of 15% can be given by the plasticity effect. For residual stresses of 90% yield strength, an error of 20% can be expected in stress calculation[9]. An error of 35% was computed in measuring residual stresses of 95% yield strength by the hole-drilling technique[10]. In comparison of the contour method with the hole drilling method, it is believed that, by applying proper constraining and cutting direction, the stress error due to the plasticity effect in the contour method can be limited to a lower level than in the hole-drilling method where no constraint is applied.

4. Conclusions

The contour method is based on the principle of superposition in elasticity. If residual stresses are large enough to cause yielding during cutting, the measurement using the contour method may lead to an erroneous result. The plasticity effect is also dependent on the clamping distance from the plane of the cut, while the clamping arrangement is to hold the cutting plane from moving during the cut. The stress error due to the plasticity effect can be minimized by constraining the specimen at a possibly closest location from the plane of the cut. It is also suggested that the specimen be cut from peened to unpeened surface for better accuracy in measuring residual stresses in the laser shock peened strip.

References

[1] Ruschau, J. J., John, R., Thompson, S. R. and Nicholas, T., Fatigue Crack Growth Rate Characteristics of Laser Shock Peened Ti-6Al-4V, ASME J. Engineering Materials and Technology, vol. 121, pp. 321-329, 1999.

[2] Smith, P.R, Shepard, M. J., Prevey III, P. S. and Clauer, A. H., Effect of Power Density and Pulse Repetition on Laser Shock Peening of Ti-6Al-4V, ASME J. Materials Engineering and Performance, vol. 9, pp. 33-37, 2000.

[3] Rankin, J. E. and Hill, M. R., Measurement of Thickness-Average Residual Stress Near the Edge of a Thin Laser Peened Strip , ASME J. Engineering Materials and Technology, vol.125, pp. 283-293, 2003.

[4] Prime, M. B., Cross-Sectional Mapping of Residual Stresses by Measuring the Surface Contour After a Cut , ASME J. Engineering Materials and Technology, vol. 123, pp. 162-168, 2001.

[5] Buecker, H. F., The propagation of Cracks and the Energy of Elastic Deformation, Trans. ASME, vol. 80, pp. 1225-1230, 1958.

[6] ABAQUS, *Users Manual*, Version 6.2, Hibbitt Karlsson & Sorensen, 2000.

[7] Measurement of Residual Stresses by the Hole-drilling Strain Gage Method, Technical Note No. TN-503-4, Vishay-Measurement Group Inc., 1-19, 1993.

[8] Beaney, E. M., Accurate Measurement of Residual Stress on any Steel Using the Center Hole Method, Strain, Journal BSSM, vol. 12, pp. 99-106, 1976.

[9] Beghini, M., Bertini, L., and Raffaelli, P., Numerical Analysis of Plasticity Effects in the Hole-drilling Residual

Stress Measurement, J. of Testing and Evaluation, vol. 22, pp. 522-529, 1994.

[10] Nobre, J. P., Kornmeier, M., Dias, A. M. and Scholtes, B., Use of the Hole-drilling Method for Measuring Residual Stresses in Highly Stressed Shot-peened Surfaces, Experimental Mechanics, vol. 40, pp. 289-297, 2000.

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