Diffraction Notes

Lambda Research 5521 Fair Lane Cincinnati, OH 45227 (513)561-0883 No. 28 Winter 2002

THE EFFECT OF PRIOR COLD WORKING ON THE DEVELOPMENT OF TENSILE RESIDUAL STRESS FOLLOWING BULK DEFORMATION

INTRODUCTION

Cold work produced during machining or shot peening can have a dramatic influence on the formation of tensile residual stress following bulk plastic deformation. Components subjected to applied stress levels that cause localized or wide spread yielding may develop high tensile residual stresses in the previously cold worked surface layers.

Several investigations undertaken at Lambda Research have demonstrated the dramatic influence of prior plastic deformation on the formation of tensile residual stress. Components for aerospace, nuclear and automotive applications have been shown to contain tensile stresses much higher than would be expected as a result of this phenomenon. Finite element analysis (FEA) has been successfully employed at Lambda Research to predict this occurrence.

Tensile residual stress development due to mechanical overload was recently investigated at Lambda Research. A controlled laboratory test was conducted in which Alloy 718 samples were processed to induce varying degrees of cold working. The samples were then further deformed to produce different degrees of bulk plastic deformation. The residual stress, cold work and yield strength were measured using an x-ray diffraction (XRD) technique and correlated to the applied plastic strain.

Manufacture of Samples

Alloy 718 was acquired as 38 x 12.7 mm (1.5 x 0.5 in.) bar stock in the mill annealed condition certified to AMS 5662J and AMS 5596G. The material was solution treated and aged to produce a hardness of 43 ± 2 HRC, a tensile strength of 1364 MPa (198 ksi), and a 0.2% yield strength of 1109 MPa (161 ksi).

Three beam samples were machined from the bar stock to final dimensions of 305 mm (12 in.) x 11 mm (0.43 in.) x 38 mm (1.5 in.). Approximately 0.25 mm (0.010 in.) of material was electropolished from both the top and bottom surfaces of the samples to produce a surface layer free of residual stress and cold work.

The first sample was shot peened in a laboratory peening facility using CW14 steel shot to an 8A intensity and 100% coverage. The second sample was low plasticity burnished (LPB). The LPB process produces a deep layer of high compression with improved surface finish at a relatively low cost and with minimal cold work.[1-5] The third beam remained in the as-electropolished condition. The three surface conditions (shot peen, LPB and electropolished), produce high, low and zero plastic deformation, respectively, providing a range of surface cold working for comparison of their respective influence on the post-bending residual stresses.

Alloy 718 3-Point Bending

The 3-point bend fixture, shown schematically in Fig. 1, was used to deform the beam samples to known amounts of plastic deformation. The fixture consists of a steel base supporting two adjustable 12.7 mm (0.5 in.) diameter hardened tool steel rollers for the outer supports and a single central roller. A span of 127 mm (5 in.), between the center and either outer roller, was used. The center of the beam was deflected 38.1 mm (1.5 in.).

ANNOUNCEMENTS

Paper on Corrosion Damage Mitigation and Improved Fatigue Performance of Aluminum

A paper focusing on the use of Low Plasticity Burnishing (LPB) to improve fatigue performance and mitigate corrosion in 7075-T6 aluminum appeared in ASM's ~~Journal of Materials Engineering and Performance~~, October 2001. LPB easily yields itself to a wide range of alloys and component geometries.

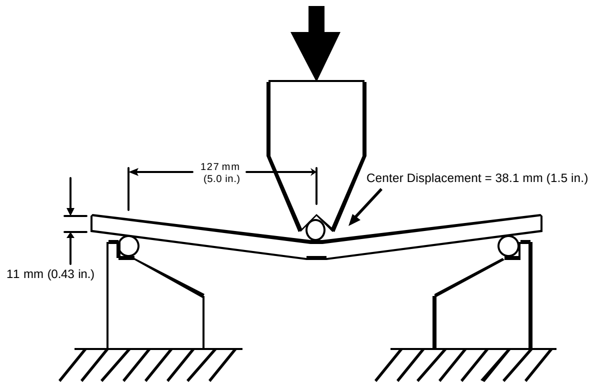


Figure 1 - 3-point bend setup for Alloy 718 beam samples.

XRD residual stress measurements were made employing a $\sin^2$ø technique and the diffraction of manganese Ká1 radiation from the (311) planes of the Alloy 718. It was first verified that the lattice spacing was a linear function of $\sin^2$ø, as required for the plane stress linear elastic residual stress model.[6-9]

The value of the x-ray elastic constants required to calculate the macroscopic residual stress from the strain normal to the (311) planes of the Alloy 718 was determined in accordance with ASTM E1426-91.[10] Systematic errors were monitored per ASTM specification E915.

The Ká1 peak breadth was calculated from the Pearson VII function fit used for peak location during macroscopic stress measurement.[11] An empirical relationship was established between the material cold working and the Ká1 line broadening for Alloy 718.[12] The "percent cold work" is defined as a scalar quantity, taken to be the equivalent true plastic strain necessary to produce the diffraction peak width measured.

The yield strength of Alloy 718 can be estimated at each measurement location from percent cold work (true plastic strain) and a true stress-strain curve for this alloy. The deformation in the surface layers resulting from machining operations can exceed 50% true plastic strain and significantly increasing yield strength of work hardened alloys.

XRD residual stress and cold working measurements were obtained for the shot peened and LPB sample, in the longitudinal direction, as a function of depth in an area of the beam that was not deformed by the bending process. These results served as a baseline set of data for comparison to the data obtained in areas deformed by the bending process and for input to a finite element model of the beam. A surface measurement was made to verify the electropolished sample had negligible residual stress and cold working.

XRD surface residual stress measurements were made as a function of position from the center of the bend on all three samples. An automated translation device, capable of rapidly mapping the surface residual stress along the length of the bar, was used for the surface measurements.[13] Measurements were made in the longitudinal direction on the convex side of the sample that was deformed in longitudinal tension during bending.

Finite Element Analysis

The residual stresses produced by the bending operation were predicted using a finite element model of the beam sample that included the near surface yield strength gradient in the material property data.

A 3-dimensional finite element model of the beam was made. Dimensions of the model matched those of the test samples discussed earlier. Half of the beam was modeled assuming symmetry about the center of bending. The model contained 4920 brick elements with 5709 nodes. FEMAP v6.0 pre-processing software was used to generate the mesh. In order to define the relatively shallow residual stress and yield strength gradients in the surface layers, a fine mesh was used on both the top and bottom sides of the model.

Displacements were prescribed on the nodes along a line corresponding to the line of contact of the center roller of the 3-point bend fixturing. The nodes were displaced a distance of 38.1 mm (1.5 in.), duplicating the displacement used in the bending of the beam samples. Nodes were constrained along a line corresponding to the line of contact with the outer roller, 127 mm (5 in.) from the center of the bend.

Residual stress and yield strength gradients measured by XRD were introduced by modifying the material properties of those elements corresponding to the surface layer deformed by either shot peening or LPB. A bi-linear stress-strain relationship was assumed. The Von Mises yield criteria was assumed.[14-16] Abaqus v6.1 commercial software was used for the analysis.

RESULTS

Baseline residual stress and cold work distributions for the Alloy 718 3-point bend beam samples are shown in Fig. 2. The shot peening process produced over 35% cold working at the surface with a 200 ìm compressive layer, 15 times more cold working than the LPB process. The depth of compression was seven times deeper for the LPB process. A surface XRD measurement on the electropolished beam verified there was no cold working and the residual stress was negligible. The range of induced cold working within the group of samples was chosen to provide a comprehensive investigation of the effect of cold work on residual stress following subsequent deformation.

Surface residual stress distributions obtained on the tensile (convex) side of the beam samples, measured with the automated translation device, are shown in Fig. 3. Tensile stresses as high as +600 MPa are produced on the shot peened surface following bending plastic strain greater than nominally 0.6%. Tensile residual stresses in the shot peened sample decrease as the bending deformation decreases below 15%. Compressive residual stresses would normally be expected on the side of a homogeneous beam deformed in tension with no prior cold working, which is observed for the electropolished and LPB samples. However, this is not the case for the shot peened sample, which has relatively high cold working and correspondingly high yield strength at, and near, the surface.

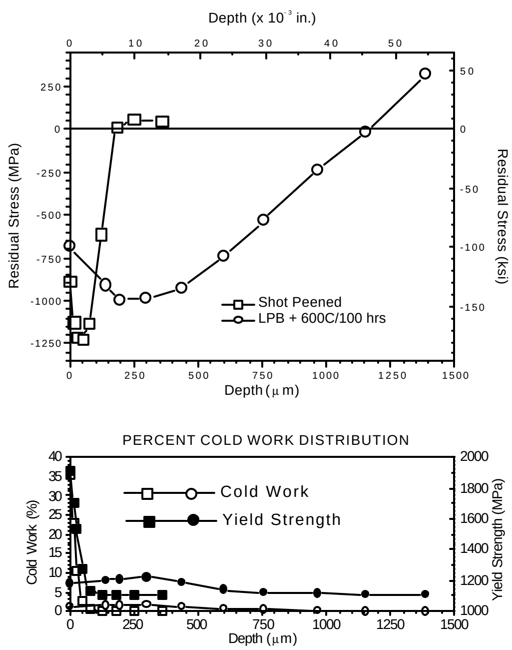


Figure 2 - Subsurface residual stress, cold work and yield strength distributions in baseline region of shot peened and LPB 3-point bend Alloy 718 beam samples.

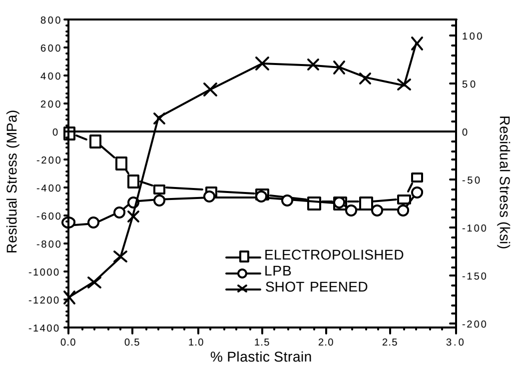
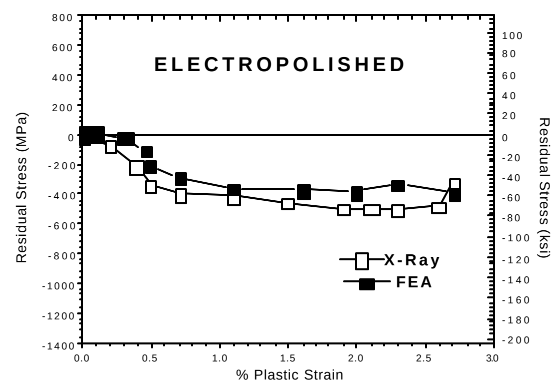
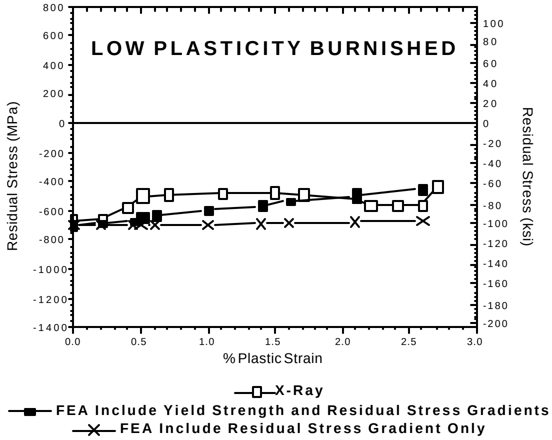


Figure 3 - XRD surface residual stress variation with plastic strain imposed by 3-point bending on tensile of Alloy 718 beam samples.

Comparison of the residual stresses, both measured by XRD and predicted with FEA, for the electropolished, LPB and shot peened Alloy 718 beams after bending are shown in Fig. 4. Residual stresses are shown as a function of bending plastic strain. The results indicate good agreement between the measured and the finite element predicted stresses when both the yield strength and residual stress gradients are used in the model. If the yield strength gradient is omitted from the model and only the residual stress gradient is considered, the predicted results are in considerable error. Small differences between the measured and FEA results are probably a result of either slight differences between the actual material properties of the beams and those prescribed in the material model and the assumption that material plasticity will behave in accordance with the Von Mises yield criteria. The Von Mises yield criteria assumes the material is perfectly isotropic and that the yield strength is the same in tension and compression.[14-16] It has been shown that Alloy 718 is not isotropic and has yield strengths in tension and compression that differ by 30%.[17]

The comparison of the measured and modeled residual stress distributions after deformation indicates that the previous cold working of the surface layer must be considered. Finite element predictions would be in considerable error, especially in the case of the shot peened sample, if the residual stress and yield strength gradients were not included in the analysis. Surface compression would be predicted where, in fact, tension exists if the surface residual and yield strength gradients were not considered.





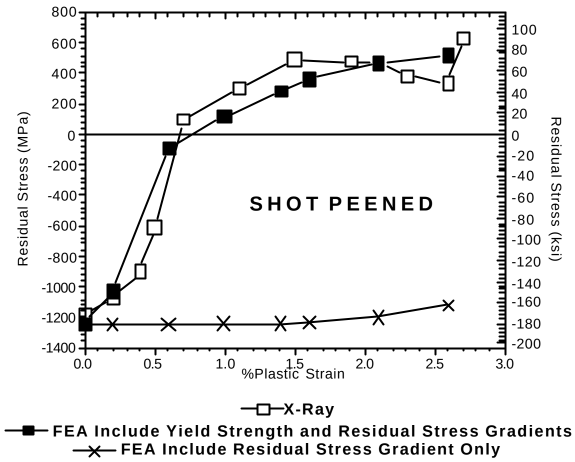


Figure 4 - Comparison of X-ray and FE surface results on electropolished, LPB and shot peened Alloy 718 3-point bend samples.

CONCLUSIONS

XRD and finite element study of the residual stress, cold work and yield strength due to bulk plastic deformation shows a strong influence of the prior deformation on the residual stress state developed.

- Finite element methods can be used to determine the influence of the increased yield strength in the deformed surface layer on the final residual stress state, provided the yield strength gradient is included.

- For accurate finite element predictions the residual stress, cold working and yield strength gradients from prior machining and processing must be taken into account.

- Machining and surface enhancement techniques that produce minimal deformation should be employed in components that may experience further bulk plastic deformation in order to minimize tensile residual stress development following mechanical overload.

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