Diffraction Notes

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# Minimizing Distortion in Machining

## Relaxation of Existing Residual Stresses

Distortion of the work piece during machining can result in costly increases in scrap rates. Residual stresses may be present in the original forging or casting. When machining away portions of the material relieves these residual stresses, the re-equilibration of the remaining residual stresses distorts the shape of the work piece. Secondly, machining and grinding operations used in finishing a component invariably induce residual stresses. If the net section is thin such as a web area of a disk or a blade, the stresses induced during machining and grinding may distort the finished component. This article addresses the case of existing residual stresses present in the work piece. Hypothetical but typical residual stress fields illustrate how measurement of residual stress distributions can be combined with finite element analysis to minimize distortion and costly scrap in a machining operation.

Heat treatment of superalloy forgings generally requires a quenching operation to obtain the desired mechanical properties. Quenching produces residual stresses that exist throughout a large percentage of the forging. Distortion occurs as a result of removing stressed material from the forging. The component will re-equilibrate and distort as each layer of stressed material is machined away. The direction and magnitude of the distortion is dependent upon not only the magnitude and sign of the stress in the material being removed, but also the geometry of the component being machined. Quenching stresses, when machined away, generally cause the largest amount of distortion, not necessarily due to the magnitude of the quenching stresses, but as a result of the large amount of material in which quenching residual stresses exist.

The machining sequence used in disk production can be optimized to minimize distortion. Residual stresses in a forging can be quantified using a mechanical or x-ray diffraction measurement technique in the envelope of material which will eventually be removed during machining. Stresses in the material to be removed dictate the distortion that will occur during machining. Destructive mechanical measurement of the residual stresses, if performed only in the material which will be removed during machining, preserves the forging for purposes of manufacturing a turbine disk.

## Residual Stress Measurement Techniques

Residual stresses in nickel superalloy forgings can be determined by various methods. Some methods are more practical than others, depending upon the geometry and desired locations and depths of measurement.

X-ray diffraction (XRD) provides an accurate and well established (1,2) method of determining the residual stress distributions produced by various manufacturing processes. XRD methods are based upon linear elasticity, in which the residual stress in the material is calculated from the strain measured in the crystal lattice. XRD methods are capable of high spatial resolution, on the order of millimeters, and depth resolution on the order of microns, ideal for studying machining and grinding. The macroscopic residual stress and information related to the degree of cold working can be obtained simultaneously by XRD methods (3). XRD methods are applicable to most polycrystalline materials, metallic or ceramic, and are nondestructive at the sample surface.

Mechanical techniques, which involve removing material and monitoring strain relaxation, often provide the most efficient and cost effective method in determining the stresses in the envelope of material to be removed in a forging. Mechanical techniques allow determination of the principal residual stresses as a function of depth, and can be fully automated.

The ring-core method is a mechanical technique used to quantify the principal residual stresses within a specified depth of material (4). This technique is based upon linear elastic theory and consists of dissecting a circular plug containing a strain gage rosette. During the sectioning operation the residual strain on the part is relieved. The change in strain is monitored by on-line computer as a function of cut depth. The principle residual stresses are determined using the derivative of the strain data as a function of depth. The ring-core technique can be used on metals, ceramics, and polymers, where linear elastic theory can be assumed. This technique is most useful in quantifying the residual stresses in coarse grained weldments or castings, in which diffraction techniques cannot be used, and is practical for large nickel-base forged components because of its efficiency in determining the residual stresses at greater depths.

The ring-core method offers some advantages over the hole-drilling method. The strain signal produced in the ring-core method is nominally an order of magnitude larger than in hole-drilling because stresses are more fully relaxed under the strain gage rosettes. Residual stresses up to the yield strength can be measured reliably, nearly twice the range for hole drilling. The ring-core method is also less sensitive to errors involved in the location of the material being removed relative to the strain gages.

The principal residual stress data obtained by the ring-core method on an Iconel 718 disk forging are shown in Figure 1. Both the maximum and minimum principal stresses are in compression ranging from -50 to -400 MPa. Quenching stresses are typically compressive near the surface, depending upon the quenching conditions and gorging geometry.

## Finite Element Analysis

A finite element model of a disk forging was built in order to determine the displacements of the disk forging during machining. The model was comprised of nominally 700 first-order axi-symmetric elements simulating a hypothetical, but typical, forging. The mesh was generated manually to coincide with the machining passes. The entire envelope of material to be removed was nominally 5 mm thick around the entire final disk geometry. Each row of elements was nominally 1 mm thick to simulate a machining process, which removes 1 mm of material per pass. The model is shown in Figure 2a. High production forgings will be a near net shape in order to minimize machining time and material waste. The shaded elements indicate the material that will be removed in various sequences to simulate machining the final disk geometry.

The residual stress field, measured empirically, was induced in the disk model through a series of fictitious loads. The loads were adjusted to accurately imitate the measured stresses. Two loading conditions were employed to provide a symmetric (Figure 3) and non-symmetric (Figure 4) stress field in the envelope material. The compressive symmetric stress field shown was imposed on both the top and bottom sides of the disk model. The residual stresses shown are the radial residual stress, which exist in the 5 mm envelope to be removed from the finite element model. The magnitude of the finite element model stress distribution was chosen to correspond to the measured distribution.

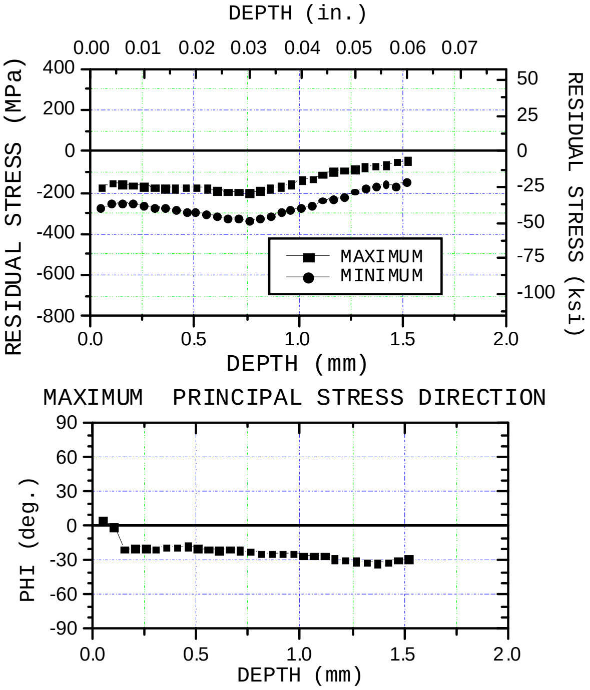

Fig. 1 a) Ring-core principal residual stress distribution in a nickel-base alloy disk showing compression from the surface to nominally 1.5 mm resulting from the heat treat process. b) Direction of maximum principal stress, defined as the angle phi in degrees, taken to be counterclockwise positive from the circumferential direction.

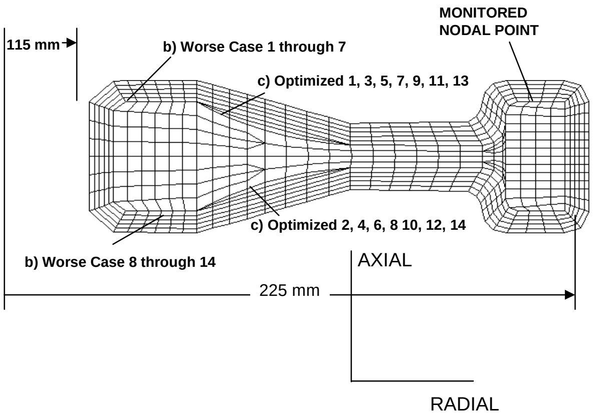

Fig. 2 a) Finite element model of forging geometry with shaded elements indicating material to be removed, center elements signifying the final disk geometry. b) Machining sequence applied to FE model for worse case distortion (top material machined away followed by bottom material) applied to both the symmetric and non-symmetric stress conditions. c) Optimized machining sequence applied to FE model for symmetric stress state, where a 1 mm layer of material is removed from each side of the forging in a number of stages to minimize distortion.

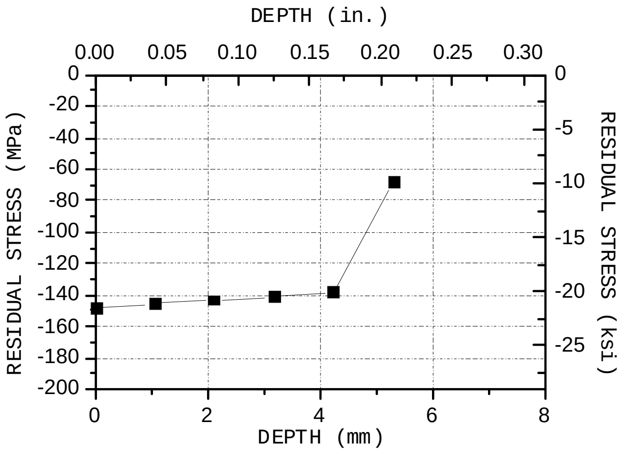

Fig. 3 Simulated compressive residual stress distribution applied to top and bottom envelope material to achieve symmetric stress field in disk finite element model.

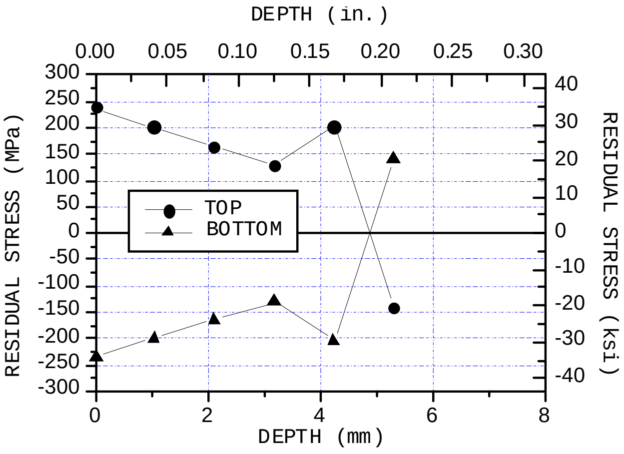

Fig. 4 Simulated compressive/tensile residual stress field induced in envelope material to produce non-symmetric stress field in disk finite element model.

The worse-case sequence of machining steps was modeled to show the maximum distortion which could exist. The worse-case sequence consisted of removing all of the material from the top side of the forging before removing all of the materials from the bottom side. This sequence is illustrated in Figure 2b. Machining steps 1 through 7 remove the entire top side, followed by steps 8 through 14, which remove the entire bottom side of the forging. The displacement was monitored at the nodal point at the rim of the finished disk. The worse-case machining sequence was investigated for both the symmetric and non-symmetric residual stress cases.

An optimum machining sequence was examined for both the symmetric and non-symmetric case. The displacements were measured and optimized to minimize deflection at the nodal point shown in Figure 2c, although the distortion at any or several positions could easily be monitored.

## Results

The plot of axial and radial displacement of the disk rim as a function of the machining passes for the symmetric residual stress field is shown in Figure 5. The displacements reach a maximum value of nominally 1.75 mm in the axial direction and -0.2 mm in the radial direction. The final disk geometry returned to the original position due to the symmetry of the initial residual stress field in the forging.

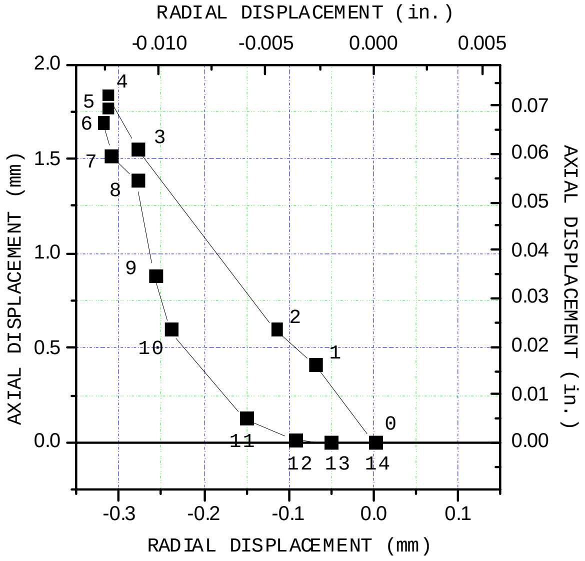

Fig. 5 Finite element determined axial and radial displacements for symmetric residual stress field using worse case machining sequence showing a maximum axial displacement of nominally 1.75 mm.

The optimized sequence of material removal for the symmetric residual stress field is shown in Figure 6. It is apparent that for a symmetric stress field and component geometry the optimal sequence would employ a machining pass on the top of the forging, followed by a machining pass on the bottom of the forging. This optimal sequence yielded a maximum radial displacement of nominally -0.15 mm, an order of magnitude less than the worse case, and a maximum axial displacement of approximately 0.23 mm. Machining steps 7 and 9 yielded the largest distortion. The distortion could be decreased even more if a depth of cut less than 1 mm is used.

The plot of axial and radial displacement as a function of material removed for the worse-case machining sequence for the non-symmetric residual stress field is shown in Figure 7. The radial and axial displacements continue to increase in value as the material is removed. The maximum radial displacement is on the order of -0.9 mm, while the maximum axial displacement is on the order of +2.75 mm.

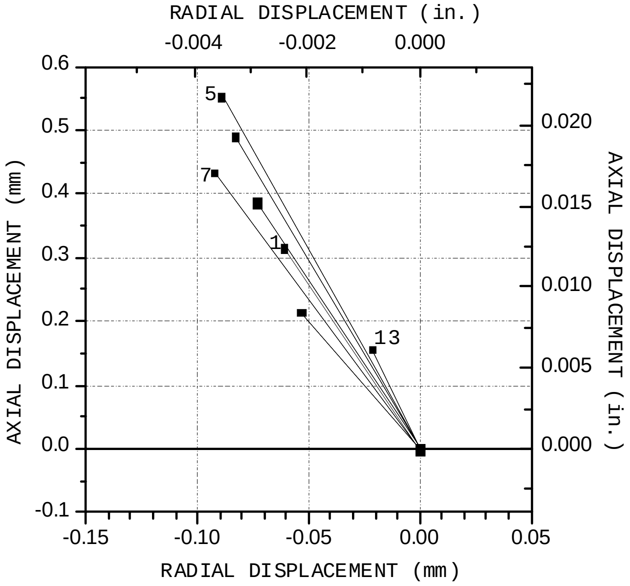

Fig. 6 Finite element determined axial and radial displacements for symmetric stress condition, using the optimized machining sequence, showing axial displacements no larger than 0.25 mm.

An optimized machining sequence, in the sense of minimizing the total distortion, is not necessarily possible in a non-symmetric stress field. The forging will distort in the same direction, when compression exists on one side of the forging and tension on the other, regardless of whether the material at the top or bottom of the disk is removed. Therefore, it is desirable that the forging contain a symmetric or near symmetric stress field to minimize overall distortion.

## Conclusions

Following are several specific conclusions of the optimization method:

1. The ring-core method offers the most practical technique for determining the residual stress field in nickel-base forgings. This method provides principal residual stress determination in the envelope of material to be machined away in the manufacture of the disk.
2. Non-linear finite element modeling of the quenching stresses is not necessary. The ring-core method directly measures the residual stresses actually created by heat treatment and quenching without destroying the forging.
3. The measured residual stress fields, determined by the ring-core method, can simply be applied to the elastic finite element model of the forging; and an optimal machining procedure can be determined.
4. In a symmetric residual stress condition the distortion due to machining can be analyzed and minimized. It is therefore, advantageous to produce a forging with a symmetric or near symmetric residual stress field.

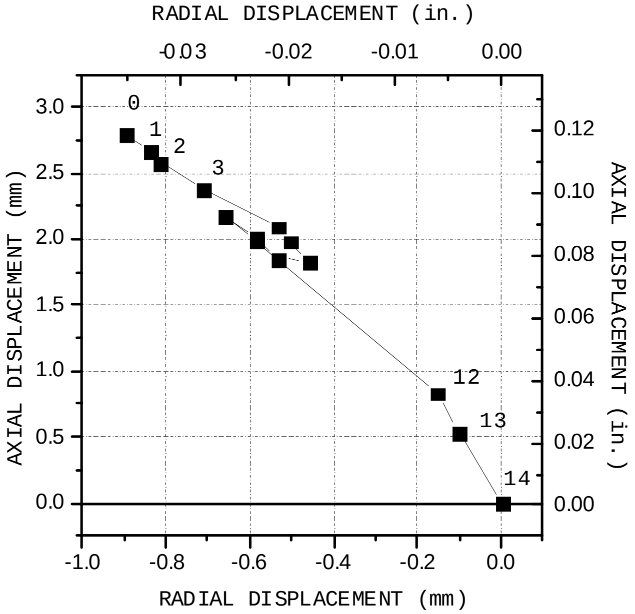

Fig. 7 Axial and radial displacements for non-symmetric residual stress field employing worse case machining sequence, illustrating distortion of over 2.5 mm in the axial direction.

## References

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