Development of Machining Procedures to Minimize Distortion During Manufacture

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ABSTRACT

Distortion during machining can result in high scrap rates and increased manufacturing costs. Distortion results from either the introduction or elimination of residual stresses during manufacture. Residual stresses which are induced in the surface by machining and grinding, or throughout the body by welding or heat treatment, can generally be measured and controlled. Distortion caused by re-equilibration after removal of stressed material during machining is more difficult to avoid, and is the primary cause of scrap in precision components.

Heat treatment required to develop desired mechanical properties will generally produce residual stress distributions. During machining, the distortion of a part depends upon the geometry, order of removal, and stress state in the material removed. If the change of shape which occurs is not accommodated, the part may be scrapped during machining. Measurement of the initial residual stress distribution and the use of finite element modeling allow the development of machining procedures which minimize distortion.

Examples of the residual stress distributions typically seen in heat treated components and the development of finite element models to minimize distortion are presented. Control of distortion is demonstrated with a detailed example of machining a nickel-base superalloy turbine disk from a quenched forging.

DISTORTION OF NICKEL-BASE ALLOY FORGINGS can be a potential problem when machining turbine disks. The distortion, if substantial enough, can lead to scrapped forgings due to machine crash or out of tolerance components. The cost of producing a disk can vary from $10,000 to over $100,000. It is in this context that distortion should be minimized in order to decrease the amount of lost revenue and time invested in the manufacture of the disks.

Distortion occurs as a result of removing stressed material from the forging. The heat treatment of nickel 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. The disk 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.

There are several other manufacturing processes generally used in the production of turbine disks that create residual stresses, such as turning and shot peening. 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. Turning and shot peening stresses, although typically higher in magnitude than quenching stresses, exist in a shallow layer of near-surface material and, therefore, have less influence on distortion than quenching.

The focus of this paper is to demonstrate that the machining sequence used in disk production can be optimized to minimize distortion. The 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. The stresses in the material to be removed dictate the distortion that will occur during machining. Destructive measurement of the residual stresses only in the material which will eventually be removed during machining preserves the forging for purposes of manufacturing a turbine disk.

The residual stresses which are measured in the forging, either by mechanical or diffraction methods, will be simulated using a finite element model of the

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forging. The finite element model allows the machining sequence to be optimized. The optimization method presented eliminates the need to calculate the quenching residual stresses, theoretically, using nonlinear finite element methods. The quenching stresses are measured directly, employing well known and time-tested empirical methods and the machining sequence is optimized using linear finite element methods.

RESIDUAL STRESS MEASUREMENT TECHNIQUES

Various methods exist to determine the residual stresses in nickel superalloy forgings. Some methods are more practical than others, depending upon the geometry and the 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 types of 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. 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. The mechanical techniques allow determination of the principal residual stresses as a function of depth.

The ring-core method is a mechanical technique used to quantify the principal residual stresses within a specified depth of material(4). The technique is based upon linear elastic theory and consists of dissecting a circular plug containing a strain gage. During the sectioning operation the residual strain in the part is relieved. The change in strain is monitored by on-line computer as a function of cut depth. The principal 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. The technique is most useful in quantifying the residual stresses in coarse grained weldments, in which diffraction techniques cannot be used. The method 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. The hole-drilling method can only be used to quantify the residual stresses which are less than nominally half of the yield strength of the material(5). This is due to the stress intensity factor around the hole which is introduced inside the monitoring strain gage grids. Using the ring-core method, material around the strain gage grid is removed, which does not produce a stress intensity factor under the active strain gage grid. The high-speed bit used to introduce the hole in the hole-drilling technique can often cause significant residual stresses in work-hardening materials such as the nickel based superalloys. Machining stresses have no significant effect in the ring-core method. The ring-core method is also less sensitive to errors involved in the location of the material being removed relative to the strain gages.

RESIDUAL STRESSES PRODUCED IN NICKEL-BASE DISKS

Both x-ray and ring-core techniques have been employed to quantify the residual stresses in forged nickel-base disks. The results obtained by x-ray diffraction on a superalloy nickel-base disk are shown in Figure 1. The near surface compression is a result of a shot peening or grit blasting operation. The stresses below nominally 1 mm are due to the forging heat treat. The quenching stresses are tensile, ranging between 0 and +200 MPa.

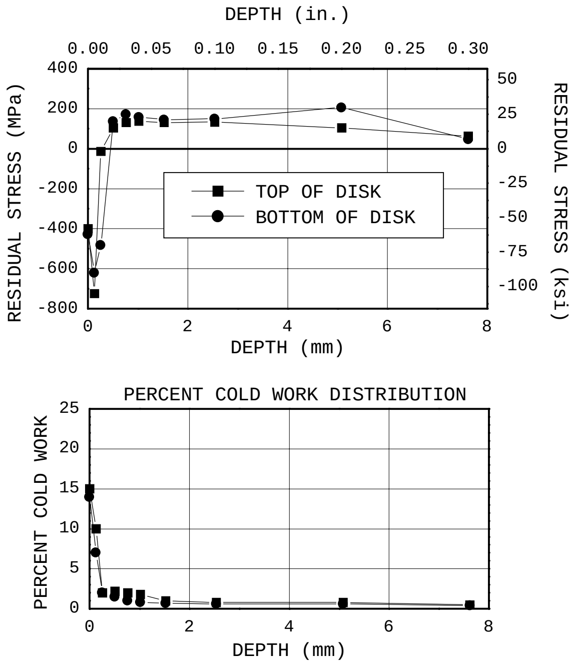

Fig. 1 - a) X-ray diffraction residual stress distribution in nickel-base alloy disk indicating near surface compression due to shot peening and subsurface tension due to the heat treat process. b) X-ray diffraction percent cold work results exhibiting near surface cold working due to the shot peening process.

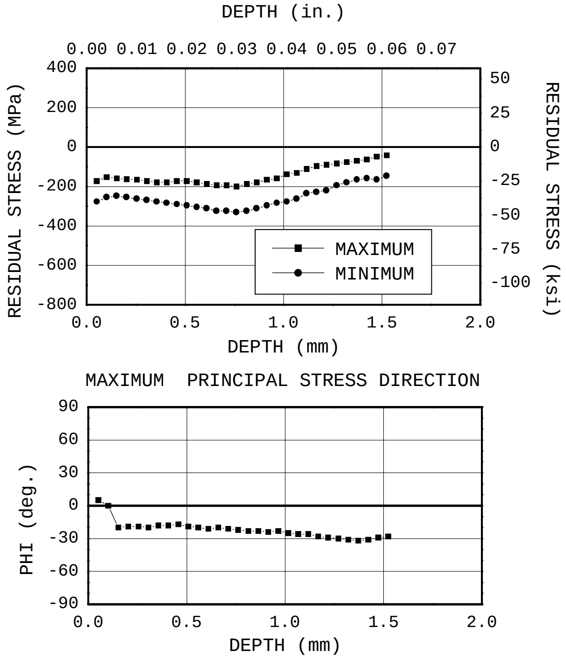

Fig. 2 - a) Ring-core principal residual stress distribution in a nickel-base alloy disk showing compression from the surface to nominally 1.5 mm resulting from the heat treat process. b) Direction of maximum principal stress, defined as the angle phi in degrees, taken to be counterclockwise positive from the circumferential direction.

The principal residual stress data obtained by the ring-core method on an Inconel 718 disk forging are shown in Figure 2. Both the maximum and minimum principal stresses are in compression ranging from 0 to -400 MPa. The results demonstrate that quenching stresses can be either compressive or tensile, depending upon the heat treat parameters.

Typical turning and shot peening residual stress distributions, obtained by XRD methods, on nickel-base material are shown in Figure 3. The turning process generally produces tension near the surface and compression below. The magnitude and shape of the turning residual stress distribution depend on such variables as the cutting tool geometry and the feed and speed of the turning process.

The shot peening distribution, also shown in Figure 3, is indicative of what a typical shot peening process can develop. Generally, a shot peening distribution will reach maximum compression below the surface. The shape of the shot peening distribution depends on such variables as the intensity of the peening, coverage, shot size, and material properties of the component being peened. The depth of residual stress for both the turning and shot peening is on the order of 0.25 mm, a much shallower depth of stressed material than is produced by heat treatment.

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 axisymmetric 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 4. Generally, high production forgings will be a near net shape in order to minimize machining time and material waste. The gray shaded elements indicate the material which will be removed in various sequences to simulate machining the final disk geometry.

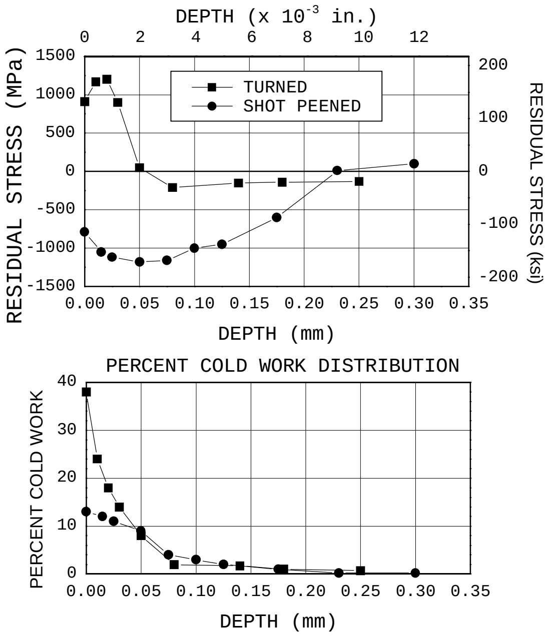

Fig 3 - a) X-ray diffraction residual stress data obtained on a turned and shot peened nickel-base alloy component showing typical near surface tension produced by turning operation and compression produced by shot peening process. b) X-ray diffraction percent cold work results showing cold working as high as 38% for the turning operation and 12% for the shot peening process.

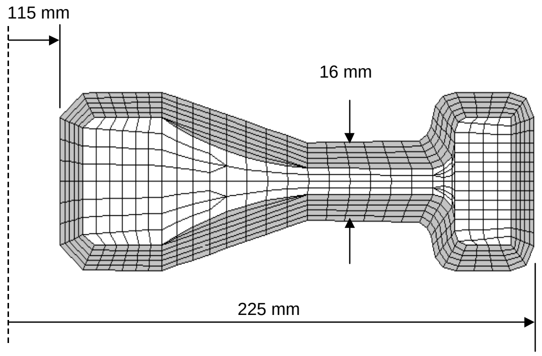

Fig. 4 - Finite element model of forging geometry with gray elements indicating material to be removed, and white elements signifying the final disk geometry.

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 and nonsymmetric stress field in the envelope material. The simulated symmetric stress field is shown in Figure 5, and the nonsymmetric stress field is shown in Figure 6. 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 stresses which exist in the 5 mm of 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.

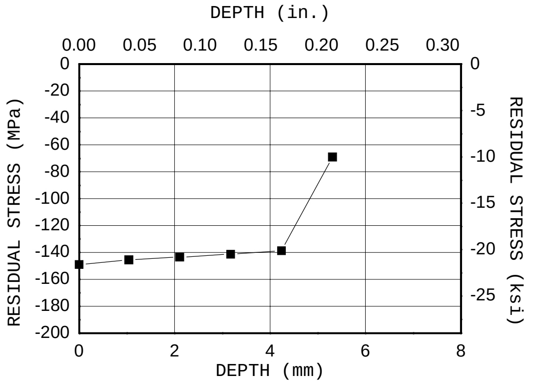

Fig. 5 - Simulated compressive residual stress distribution applied to top and bottom envelope material to achieve symmetric stress field in disk finite element model.

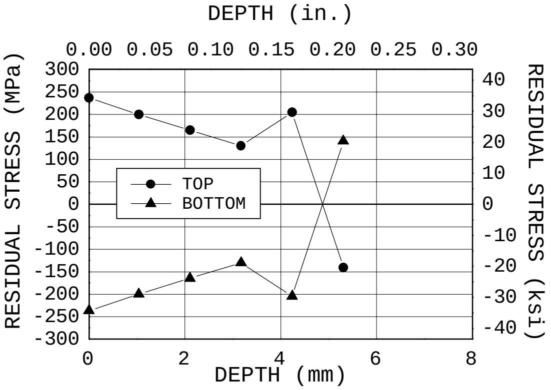

Fig. 6 - Simulated compressive/tensile residual stress field induced in envelope material to produce non-symmetric stress field in disk finite element model.

Initially a 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 material from the bottom side. The machining sequence is shown in Figure 7. 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 displacements were monitored at the nodal point at the rim of the finished disk shown in Figure 7. The worse-case machining sequence was investigated for both the symmetric and nonsymmetric cases.

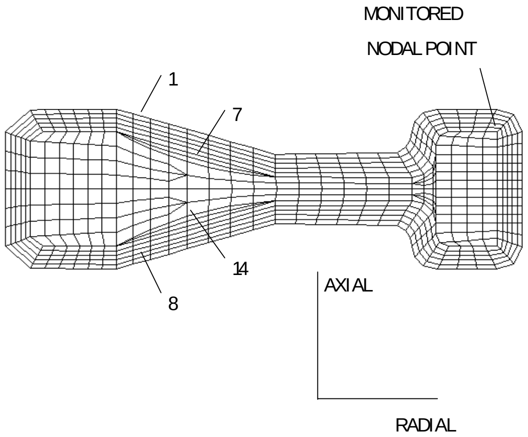

Fig. 7 - Machining sequence applied to FE model for worse case distortion (top material machined away followed by bottom material) applied to both the symmetric and non-symmetric stress conditions.

An optimum machining sequence was examined for both the symmetric and nonsymmetric case. The displacements were measured and optimized to minimize deflection at the nodal point shown in Figure 7. This was the nodal point chosen for the present analysis, although the distortion at any or several positions could easily be monitored. In order to simulate material removal in the disk model, the stiffness of each element machined away was set equal to zero.

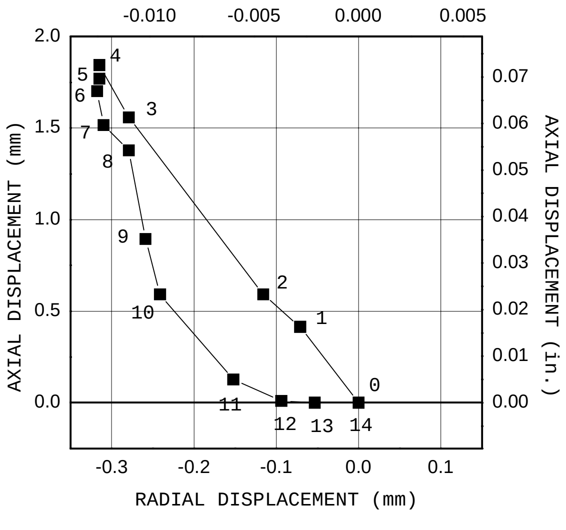

Fig. 8 - Finite element determined axial and radial displacements for symmetric residual stress field using worse case machining sequence, showing a maximum axial displacement of nominally 1.75 mm.

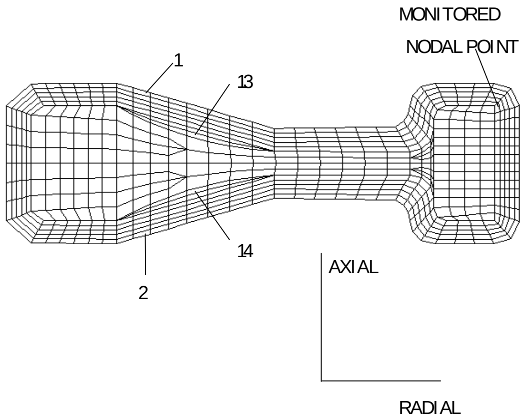

Fig. 9 - Optimized machining sequence applied to FE model for symmetric stress state, where a 1 mm layer of material is removed from each side of the forging in a number of stages to minimize distortion.

RESULTS AND DISCUSSION

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 8. 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.

The optimized sequence of material removal for the symmetric residual stress field is shown in Figure 9. It is apparent that for a symmetric stress field and component geometry the optimal sequence would contain a machining pass on the top of the forging followed by a machining pass on the bottom of the forging. Optimum sequences for more complex residual stress distributions and geometries will not generally be apparent without a finite element solution. The total amount of distortion would be a function of the depth of material being removed. The displacements for each machining sequence are shown Figure 10. This optimal sequence yielded a maximum radial displacement of nominally -0.15 mm 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 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 nonsymmetric residual stress field is shown in Figure 11. 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.

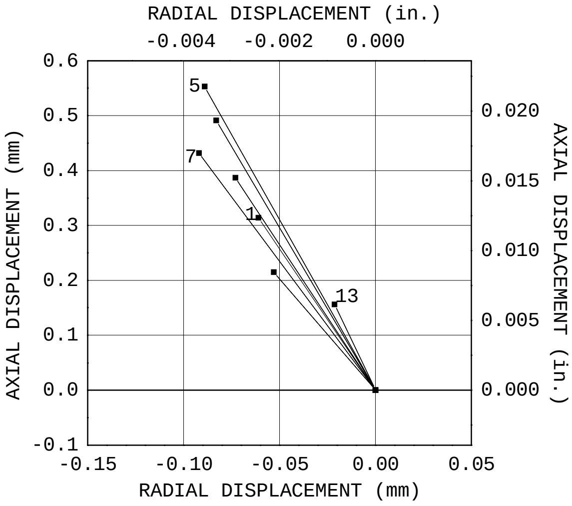

Fig. 10 – Finite element determined axial and radial displacements for symmetric stress condition, using the optimized machining sequence, showing axial displacements no larger than 0.25 mm.

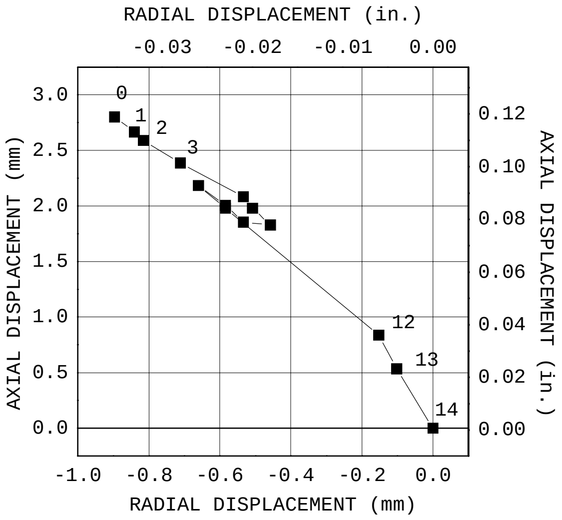

Fig. 11 – Axial and radial displacements for non-symmetric residual stress field employing worse case machining sequence, illustrating distortion of over 2.5 mm in the axial direction.

The results indicate that an optimized machining sequence, in the sense of minimizing the total distortion, is not necessarily possible in a nonsymmetric 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. It would, therefore, be desirable that the forging contain a symmetric or near symmetric stress field in order to minimize the overall distortion.

CONCLUSION

Distortion during machining of a nickel-base superalloy turbine disk employing a combination of residual stress measurement and finite element analysis techniques has been presented. Several specific conclusions of the optimization method are:

1) The ring-core method offers the most practical technique for determining the residual stress field in nickel-base forgings. The method provides principal residual stress determination in the envelope of material to be machined away in the manufacture of the disk

2) Nonlinear finite element modeling of the quenching stresses, which relies on assumptions of the material and quenching process, 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.

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