Residual Stress Profiles in a Product Processed
By
Radial Forging

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ABSTRACT

Residual stress in the forged products directly affects material stability, resistance to deformation, accuracy, and fatigue life of products. It is very important to study the residual stress distributions in forged products and to monitor operating conditions for the minimum tensile or maximum compressive residual stresses. As a way to study the residual stress formation due to radial forging, a three dimensional theoretical model was developed using ANSYS finite element program. Using the developed model, residual stress distributions in forged product were calculated and selected results were compared with the published experimental data to verify the effectiveness of the developed model.

1. INTRODUCTION

Surface condition of a product can be rated according to the surface quality. Surface quality is determined by properties such as surface roughness, hardness variation, structural change, and residual stress. Among these properties, the residual stress distribution is one of the primary aspects of surface quality because of its direct effect on the fatigue life and dimensional stability of a product. Radial forging is a cost effective and material saving forming process for reducing cross-sections of rods, tubes and shafts which are made of any metal that is suited for cold forming. The advantages of radial forging are smooth surface finish, considerable material or weight savings, preferred fiber structure, minimum notch effect, and increased material strength [1]. Forged components processed by radial forging will generally have higher residual stresses and undergo some deflections after forging due to the resultant high residual stresses, thus losing dimensional accuracy. Residual stresses can also cause stress corrosion for certain materials when used in the corrosive environment. The residual stress distribution in high strength metal is of great importance since its presence, above a certain level, can shorten the service life of critical components used in the severe service conditions.

Either experiment or the theoretical simulation may be used to study the residual stress formation due to radial forging. The experimental measurements using X-ray or neutron diffraction are popular. Since the penetration depth of neutron is bigger than that of X-ray, neutron diffraction technique is recently applied to the residual stress measurement. The theoretical estimation of residual stress is to apply the FEM technique, which was developed based on the mechanics of forging operation. It enables us to analyze the deformed profile and stress distributions including residual stresses in a product. Through stress analysis in a product using the FEM technique, we can estimate the post processing conditions to relieve residual stresses and decide the optimum operational conditions for forging which will yield favorable stress conditions in a product.

There were mainly three different finite element formulations employed to simulate metal forming: (1) the rigid-plastic model; (2) the elasto-plastic model; and (3) the visco-plastic model. The rigid-plastic model was most commonly used due to its simpler formulation and better numerical efficiency [2]. Since the elastic strains were neglected, the stresses below the yield stress were not known. This implied that effects such as residual stresses and spring-back which could be important in connection with metal forming could not be predicted. The elasto-plastic formulation was considered to be the appropriate one to represent the material behavior during cold metal-forming processes [3-5]. The visco-plastic model used two types of material such as rigid-visco-plastic and rigid-thermo-visco-plastic materials to study temperature gradients or strain rate variations due to process variables [6, 7].

The only published work conducted to study the residual stresses in radial forging process was made by T. C. Tszeng [8]. He used an axi-symmetric model of rigid-plastic FEM code ALPID in the simulation of the loading process, followed by an elastic program for the unloading process. His results indicated that the friction factor in the die-workpiece and mandrel-workpiece has a more significant effect on the residual stress formation. Since the elastic strains were neglected, the stresses below the yield stress were not known, which implied that effects such as spring-back effect could not be predicted. Furthermore, the 2-D model cannot predict the stresses in the θ direction which could be important in the radial forging process.

In this research, a 3-D finite element method model using ANSYS code was developed to calculate the residual stresses in an axi-symmetric product processed by radial forging. The workpiece was assumed to have elasto-plastic behavior during cold forging process. The Coulomb friction was assumed to act on the contact areas between the workpiece and the mandrel and between the workpiece and the die. Information of deformation shapes at various stages of each bite-operation and distributions of effective strain, stresses in different directions on the outer and inner surfaces for each bite operation were applied to calculate residual stress distributions. In the calculations, frictional stresses were assumed to exist at the interface between the die and the workpiece. The selected simulation results were also compared to the published experimental data to verify the effectiveness of the developed model [9]. The theoretical model to simulate the radial forging can be used to calculate tirbological behaviors such contact stresses and strain, residual stresses, and product quality due to variations of parameters of process and design.

2. FEM MODEL OF RADIAL FORGING

In the finite element analysis, the workpiece was assumed to obey the Von-Mises yield criterion and its associate flow-rule. The workpiece used in the simulation was alloy steel MILS 11595. The corresponding stress-strain curve of the workpiece material is shown in Fig. 1.

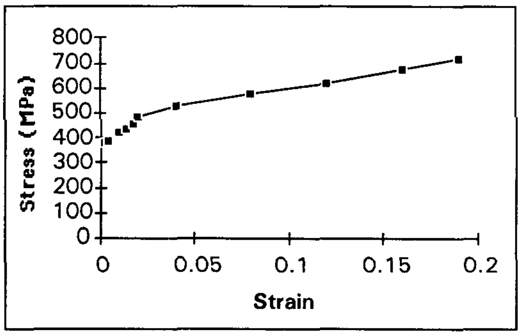


Fig. 1 Stress-Strain curve used in FEM simulation[9]

The deformation process of the elasto-plastic materials in the analysis was assumed to be associated with the boundary value problem where the stress and strain field solutions satisfy the equilibrium equations, and the constitutive equations in the domain, and the prescribed boundary values.

Deformation in the radial forging process is due to many continuous short-stroke, high-speed, and radial inward striking dies. The radial hammer dies, usually four, are arranged radially around the workpiece as shown in Fig. 2. In order to obtain round forged workpieces and better finished surfaces, the workpiece rotates during the interval between two strokes. The rotating chuck heads stop during the inward motion of forging dies to prevent the workpiece from twisting. The radial forging is generally used in coaxial bimetallic tubing, in reducing the wall thickness of tubes, and in generating internal profiles [8].

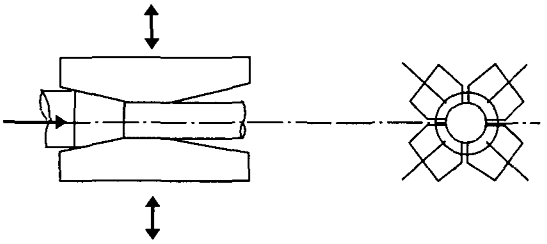


Fig. 2 A schematic showing the arrangement of forging dies in radial forging machine

Friction between the workpiece and the die plays an important role in deciding the forming forces and strain distributions in the forged parts. It also controls the incidence of failures due to cracking, scoring, wrinkling, tearing, and geometric variability. Therefore, in order to treat the boundary condition in FEM, reflecting the lubrication layer between the surface of the workpiece and the die, a stiffness relationship between two contact areas was established. Friction in the contact surfaces was simulated by the tangential force of the contact elements. The sliding force F_s transmitted between the two bodies cannot exceed a fraction of the normal force F_n. Once F_s is exceeded, the two bodies will slide each other. In this study, the rigid Coulomb model was applied since in the radial forging process, the workpiece slides continuously between the die and the mandrel. Due to the axisymmetric characteristics of radial forging process, only a section of workpiece was simulated as Fig. 3. Additional assumptions were made for the accurate results as follows:

(i) rotational feed was neglected,
(ii) the material followed elasto-plastic behavior during manufacturing process,
(iii) the deformation process was isothermal,
(iv) the deformation of forging dies and mandrel was neglected, and
(v) the die and mandrel were rigid bodies with higher elastic modulus.

The workpiece was assumed to be symmetric on both sides which were composed of r-z planes. The die was first moving radially inward to contact with workpiece, then the workpiece was stroke-by-stroke moving in the axial direction. For each stroke (increment), a new equilibrium position was obtained by Newton-Raphson iteration method. The new equilibrium position was applied as the referenced position for the next increment. The stroke was continuous until the workpiece passed through the die. In the simulation of forging process, the whole process was divided by five stages and each stage included hundreds of strokes. The numbers of stroke depended on the contact area. The final stresses in the workpiece are the residual stresses due to forging process. The forming geometry and process parameters were obtained from the published experimental data [9].

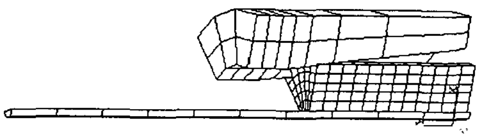


Fig. 3 Finite element model for radial forging simulation

In most radial forging analyses, the effect of die chilling has been assumed to be negligible due to the relatively short time over which the die is in contact with the workpiece [11]. It has been estimated that tools are in contact with the workpiece for less than 10-15% of each forging cycle [12].

4. RESULTS AND ANALYSIS

Effectiveness of the FEM simulation of radial forging operation was verified by comparing simulated results with Hoffmanner's [9] experiments. In his works, the residual stresses in the workpiece using Sach's boring technique were measured after the dimensional inspection of each part. They were attached to the workpiece with stainless steel fixtures.

Table 1 Comparison between experimental and FEM results of forged residual stresses

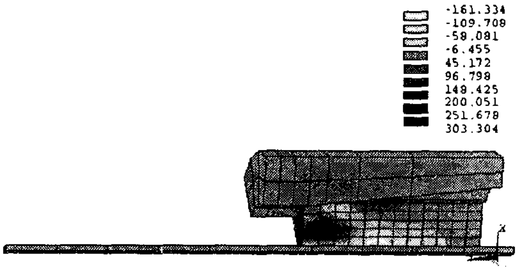
	Hoop Stress (MPa)	Axial Stress (MPa)	Radial Stress (MPa)
Experiment [9]	248	335	-
FEM Simulation	232	317	173

As can be seen from Table 1, peak residual stresses from the FEM simulations were 232 MPa and 317 MPa in the hoop and axial directions. Table 1 shows good agreement between experiments and simulations. Differences were less than 10%. The difference might be due to the thermal effect which was neglected in this study. It could be also concluded that the mechanical loads dominated the residual stress developments while the thermal effect was negligible in the cold forging process.

Using the proved FEM model as shown in Fig. 3, calculations of strain and stress distributions, deformation, and residual stress were performed. The deformation during forging can be divided into three zones [11] and deforming process was divided into five steps. The deforming zones are sinking, forging, and sizing zones.

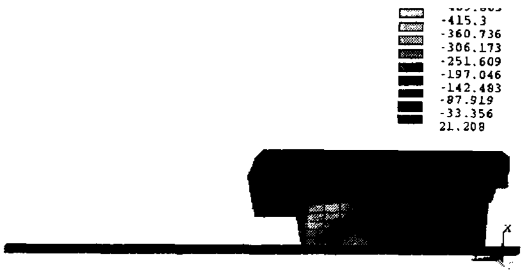
The stress developments in the direction (axial, radial, and hoop) for stage 1 are shown in Fig. 4. At the beginning of forging, the outer surface of the sizing zone showed a small tensile stress region. However, the sinking and the forging zones were dominated by compressive stresses. As the workpiece continued to feed into the die land, the tensile stress region increased and the compressive region decreased. An interesting result of the simulation was that although the tensile stress region increased during the forging process, the magnitude of compressive stresses in the forging zone remained constant at each stage. The stresses in the radial direction showed the similar pattern as the axial stresses, but values of tensile stresses in the radial direction were smaller than those in the axial direction. The maximum tensile stress was located at the beginning of deformation, when the die initially contacted the workpiece. It was found that radial stresses in the sizing zone were smaller than those when workpiece passed the sizing zone. This was due to the effect of spring-back (elastic recovery) after the sizing zone and caused the existence of the higher tensile stresses [9]. The radial stresses exhibited radial variations from compressive stresses at the inner surface to tensile stresses at the outer region. It also showed the tensile stresses at the outer surface and compressive stresses at the inner surface, but the maximum tensile stress occurred at the middle part of the outer surface.

The instantaneous stress distributions in the axial, radial and hoop directions are shown in Fig. 5. The stresses in Fig. 5 are equivalent to residual stresses since this stage shows at the final step of radial forging. It can be seen that the residual stresses were tensile at the outer surface with the maximum 317 MPa and compressive stresses at the inner surface.



(a)

(b)

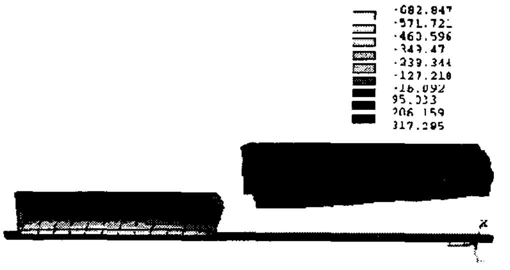


(c)

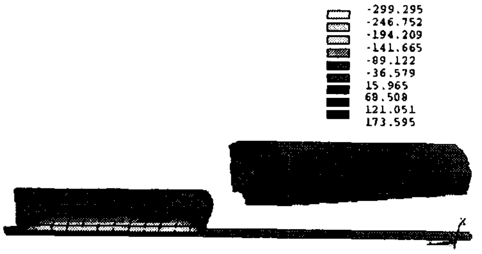
a) The instantaneous axial stress distribution
b) The instantaneous radial stress distribution
c) The instantaneous hoop stress distribution

Fig. 4 The instantaneous stress distribution at stage 1

The radial residual stresses showed that the tensile stresses were at the outer surface and the compressive stresses were at the inner surface. The maximum tensile stress occurred at the both ends of the workpiece with a maximum value of 173 MPa. The hoop residual stresses were at the outer surface of workpiece with the maximum value of 232 MPa. Compared with the axial, the radial, and the hoop residual stresses, maximum tensile and compressive stresses were found in the axial direction. The tensile residual stresses in the axial and hoop directions might have been caused by the frictional force that was always opposite to the moving direction. That is, when the workpiece was fed in the die land, the frictional force tended to pull the workpiece in the opposite direction, thus causing the tensile stresses at the outer surface of the workpiece. The tensile radial stresses might have been generated due to the spring-back effect of the workpiece in the radial direction.



(a)



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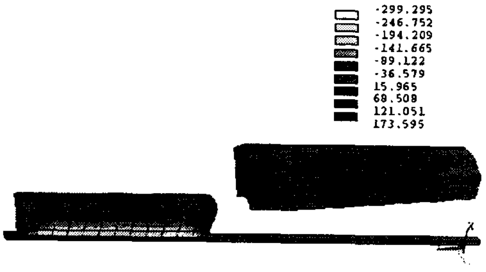

(c)

a) The instantaneous axial stress distribution
b) The instantaneous radial stress distribution
c) The instantaneous hoop stress distribution

Fig. 5 The instantaneous stress distribution at stage 5

Fig. 6-7 show the stress distributions of the outer and the inner surfaces along the axial direction. It can be seen that the outer surface was dominated by tensile residual stresses with the maximum value at the rear part of workpiece.

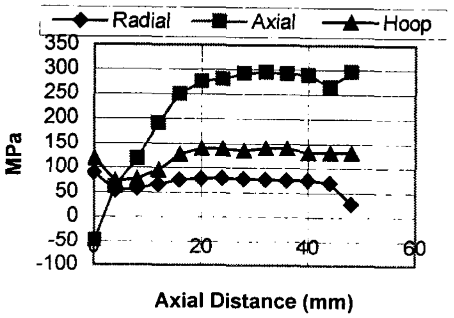

Fig. 6 The residual stress distribution along the out surface workpiece

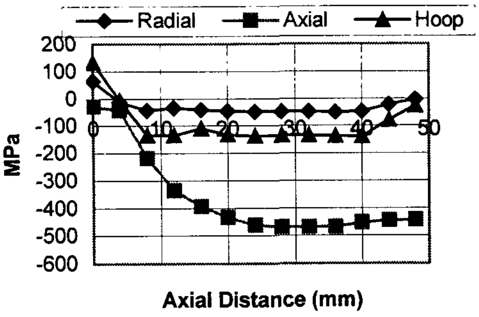

Fig. 7 The residual stress distribution along the inner surface of workpiece

The axial stresses had the minimum stress (-48 MPa) at the front part of the workpiece and increased along with the axial direction to the maximum stress (300 MPa) at the rear part of the workpiece. However, the inner surface presented most of compressive residual stresses with only small tensile stresses in the front part of the workpiece.

5. CONCLUSIONS

In the present study, a three dimensional finite element model was developed to simulate the radial forging process. The workpiece was assumed to have elasto-plastic behavior during the cold forging process. In order to show the validity and effectiveness of the developed finite element model, the results of this study were compared with the published experimental data. The comparison between simulated results and experimental data demonstrate that elasto-plastic formulation was a proper model for cold forging process. The results from this paper can be summarized as follows:

1. The outer surface of forged products was dominated by tensile residual stresses with maximum values at the rear part of the forged products.
2. The inner surface of forged products showed compressive residual stresses and only small tensile residual stresses in the front part of workpiece.
3. The highest tensile residual on the surface of forged products is in the axial direction.

6. REFERENCES

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