Finite Element Analysis of Effects of Strain Hardening Rate on Cold Expansion of Fastener Holes

RAVIKUMAR S. KURHADE

Department of Mechanical Engineering, Shri Sant Gajanan Maharaj College of Engineering, SHEGAON, Dist.- Buldana (M.S.) 444 203 INDIA

A. P. WADEGAONKAR

Department of Mechanical Engineering, Government Polytechnic, Khamgaon Dist.- Buldana (M. S.) INDIA

B. PRADHAN

Department of Mechanical Engineering, Indian Institute of Technology, Kharagpur (W. B.) 721302 INDIA

Abstract

Residual stress is having a significant effect on fatigue lives of the structural engineering components, particularly in aerospace industry. Mandrelizing expands the hole diameter by means of a radial interference pressure to allow radial plastic flow of material and some elastic recovery after the removal of the mandrel. Thus, it produces a large residual compressive zone around the hole. This zone acts as a barrier to crack growth thereby enhancing the service life of the structural components. In this work, an attempt has been made to simulate a newly proposed CsSmPCx process by using ANSYS FEM code. The critical effects of material properties variation on the residual stress field are analyzed. The drawbacks of the presently used hole cold expansion mandrelizing methods are removed thereby giving nearly uniform residual stress distribution around the hole. This newly proposed method is more reliable and gives increased service life enhancement compared with the presently used mandrelizing methods, without any weight and risk penalty.

Introduction

Aircraft structural integrity requirements now embrace damage tolerance requirements as the basis for design and continued safe operation. The challenge facing industry is how to economically achieve these requirements in both new and the growing volume of aging aircraft. Compensating for damage tolerance analysis lead to overweight structures. Not allowing for residual cracks in repairs could compromise the long-term structural integrity, induce on-going inspection penalties and possibly result in unnecessary major structural replacement or repair. Hole cold expansion is proven method for retarding crack growth originating in hole.

Cold expansion of fastener holes is now a proven method to increase the fatigue life of assemblies, particularly aircraft parts joined by mechanical fasteners. Fastener holes may cause a major source of fatigue cracking when high shear loads are transferred through these joints. Cold expansion introduces compressive residual stresses around the hole, which delay or suppress the crack initiation or reduce the crack propagation rate. An attempt is made in this work to simulate a continuous sleeve split mandrel and pilot cold expansion (CsSmPCx) process to introduce a uniform compressive residual stresses around the fastener hole.

Background

The cold expansion of holes is a well-known technique for fatigue performance enhancement, which has been used for over many years. Extensive research into the cold expansion process has resulted in various technological methods using some means for expansion as below, and possibly some others.

Using kinetic energy of shots: Shot peening.

Using body pressure: Stress coining, Roller burnishing, Ballizing.

Using fluid pressure: Autofrettaging

Using interference fit pressure: Mandrelizing- Solid mandrel cold expansion, Split mandrel cold expansion, and Split sleeve cold expansion.

Numerous practical problems occur in which accurate elastic-plastic solutions are needed for the analysis of circular holes loaded by uniform radial pressure. Requirements at present for these solutions are in aircraft structural fatigue analysis and in stress analysis of high-pressure boilers and heat exchangers where tubes are fitted by plastic enlargement into head plates. For aircraft the enlargement is caused by the use of interference fasteners. A number of authors have obtained the solution to this class of problems under different circumstances with the required assumptions.

C. Poussard, et. al., 1995 [1], conducted 2-D finite element analysis for plane stress, plane strain and axisymmetric conditions, on 2024-T351 aluminum alloy. They used ABAQUS finite element code for the analysis and plate was modeled by using 712-second order iso-parametric elements. They found that- large compressive tangential residual stresses were at the hole edge with reversed yielding on unloading; an axisymmetric model of the cold working process gives non-uniform residual stress distribution through the plate thickness; and the maximum compressive residual stress has been overestimated in 2-D plane stress analysis whereas underestimated in 2-D plane strain analysis**.** M. J. Pavier, et. al., 1997 [2], conducted 2-D axi-symmetric finite element simulation for the cold working of fastener holes in an 2024-T351 aluminum plate. The simulation models the actual cold working process where an oversize mandrel is pulled through the fastener hole. They compared the results of the simulation with simplified finite element model where the cold working process is reduced to applying a uniform radial expansion to hole edge. They found that the simulation of the actual process shows tensile residual radial stresses on the plate surface after cold working whereas simplified simulation shows only compressive ones. This difference may be due to improper simulation of cold working process or improper simplified model. In the analysis, they used ABAQUS finite element code and modeling consists of 3 sets of elements and 2 sets of contact elements. The plate was modeled using 1500 elements. M. J. Pavier, et. al., 1998 [3], conducted 3-D finite element simulation for the cold working of fastener holes in an 2024-T351 aluminum plate. The finite element simulation shows that cold working has beneficial effects by reducing the stress intensity factor for a crack under applied mechanical load compared to a non-cold worked plate. They used ABAQUS finite element code for the analysis. The model consists of 5460 3-D 20 noded quadratic elements for the plate. In addition 290 3-D 9 noded contact elements were used between the mandrel and the plate. P. Papanikos & S. A. Meguid, 1998 [4], conducted 3-D elasto-plastic finite element analysis to evaluate the development and growth of plastic zone and unloading the residual stresses resulting from the cold expansion of two adjacent holes. Both simultaneous and sequential expansion of two holes is carried out in an 7075-T651 aluminum alloy. They found that the sequential expansion drastically reduces the compressive residual stresses and it is validated with existing experimental results. They modeled the plate by using 20 noded hexahedral elements and 10 noded tetrahedral elements, with ANSYS finite element code. They also found that compressive residual stresses are maximum around mid-thickness of the plate and minimum at the entry face of the mandrel. P. Papanikos & S. A. Meguid, 1999 [5], have done the elasto-plastic 2-D finite element analysis of the cold expansion of the adjacent fastener holes by using ANSYS code. They found that- a) increasing the expansion level results in a reduction of the residual stresses in the region contained between the two holes; b) center distance between the two holes can drastically influence the residual stress field, leading to high tensile residual stresses; and c) sequential expansion of two adjacent holes leads to a much higher tensile residual stress than simultaneous expansion. They used rigid mandrel and split sleeve method of cold expansion. The plate material was 7075-T651 aluminum alloy.

Though the radial expansion of the fastener holes into the plastic zone results in the favorable residual compressive hoop stress near the hole after the mandrel is removed, certain drawbacks are recognized in the mandrelizing cold expansion techniques. In the solid tapered mandrel cold expansion, there is undesirable axial flow of material along the hole surface, which may lead to the extrusion of the hole and loss of dimensional stability. Sometimes, the buckling of the thin plate in the vicinity of the hole may take place. In the sleeveless, split tapered mandrel cold expansion, the undeformed regions of the hole at the four mandrel split lines could be the site for the fatigue crack initiation. Also, these undeformed zones at the mandrel split lines should have to be removed by reaming operation, which increases the cost and complexity of the cold expansion process. In the split sleeve, solid tapered mandrel cold expansion, the undeformed region of the hole at the sleeve split line could be the site for the fatigue crack initiation. Also, this undeformed zone at the sleeve split line should have to be removed by reaming operation to get a dimensional preciseness, which increases the cost and complexity of the cold expansion process. A small shear discontinuity at the surface of the hole associated with the split in the sleeve exists, which may also form a site for the fatigue crack initiation. Some tears also exist which originates from a corner of the ridge left in the hole after cold expansion, i.e. the location corresponding to the split in the sleeve. In order to remove these drawbacks of the presently used cold expansion processes, a new process is developed which consists of continuous (non split) sleeve with split mandrel and pilot cold expansion and can be called as CsSmPCx process. Of course, the main intention is to produce an even radial plastic deformation of the material and to get the uniform residual stress distribution around the cold expanded hole, so that there will not be any site for the fatigue crack initiation. The process consists of- 1) slipping the continuous lubricated sleeve onto the split mandrel, 2) inserting the split mandrel and the continuous sleeve sequentially into the hole, 3) activating the pilot to make the mandrel solid with the nose cap in proper position, and 4) drawing the mandrel through the hole to complete the cold expansion process.

Finite Element Modeling

The simulation of newly prescribed CsSmPCx process is divided into two steps,

Hole expansion: Uniform displacements are added on the nodes at the hole edge to simulate percentage of cold expansion. Although the axial movement of the mandrel accomplishes the cold working, uniform radial expansion has been used to simulate the process. It is felt that the continuous sleeve inserted in between mandrel and the material minimizes the effect of axial movement of the mandrel.

Hole recovery: The removal of the mandrel and the corresponding unloading process is simulated by the removal of the boundary condition at the hole edge.

The hole expansion process is simulated by enforcing appropriate constraint condition for the nodes on the hole geometry, and prescribing that the hole expands radially in a uniform manner to a diameter corresponding to the initial expansion level given.

At this point the sheet experiences elastic deformation and its behavior is governed by the equilibrium equation written in matrix form as $[K]\{u\}=\{F\}+\{Q\}$. It should be noted that $\{F\}$ represent a set of forces determined from the applied displacements (including the constraint conditions to ensure uniform radial expansion). The vector $\{Q\}$ is the set of nodal forces developed from prevailing plastic strains present in the structure. The plastic strains are treated as initial strains. The residual stresses corresponding to a spring back from the cold expansion are determined by removing the multipoint constraint conditions previously imposed during the radial expansion of the hole. Accordingly, the equilibrium equation becomes $\left[\bar{K}\right]\{u_R\}=\left\{\bar{Q}\right\}$, where the elastic stiffness matrix $\left[\bar{K}\right]$ and plastic residual load vector $\left\{\bar{Q}\right\}$ differ from $[K]$ and $\{Q\}$ in equilibrium equation, to account for an additional independent nodal degrees of freedom resulting from the release of the multipoint constraints. The vector of radial displacement $\{u_R\}$ is then used to establish corresponding levels of residual stresses and strains. Here $\{F\}$ is the vector of constraint forces, $[K]\,and\left[\bar{K}\right]$ are stiffness matrices, $\{Q\}\,and\left\{\bar{Q}\right\}$ are plastic residual load vectors, $\{u\}$ is the vector of independent nodal displacements, and $\{u_R\}$ is the vector of residual nodal displacements.

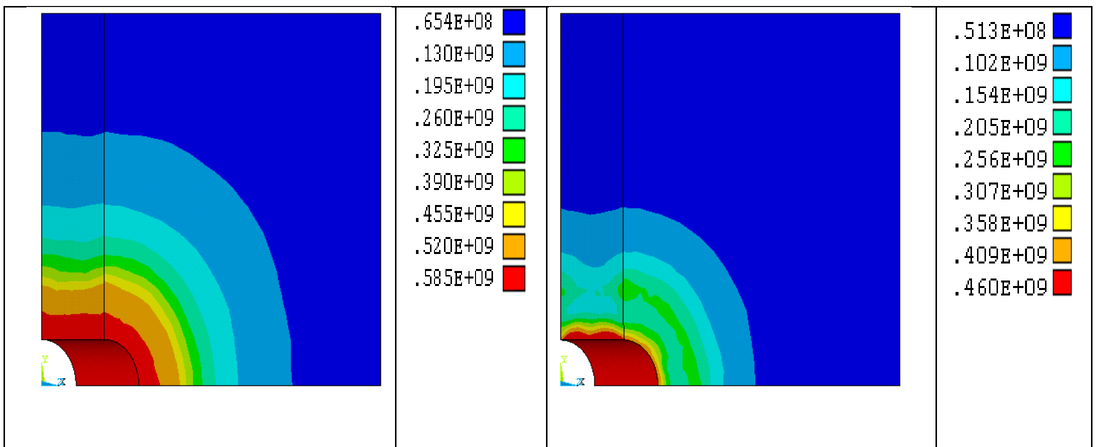
Because of symmetry, one quarter of the hole is the representative of the entire hole. The model size analyzed is 25.4 mm by 25.4 mm by 6.35 mm in length, width and thickness, respectively. The initial hole diameter is 6.15 mm. ANSYS 6.0 is used for the analysis. The 8 noded, 3-D solid elements have been adopted for the analysis. The analysis model contains 10797 elements and 2426 nodes.

The material used for the analysis is 7050-T7451 aluminum alloy with BKIN model, having properties-Elastic modulus E = 71.8 GPa, Poisson ratio υ = 0.33, Density ρ = 2.79e-6 kg/mm^3, Strain hardening rate 200 MPa, Yield stress σ_y = 506 MPa. The various other values of tangent modulus used for the analysis are 1000, 2000, 10000, and 20000 MPa. The values of E, υ, and □ are kept same as for 200 MPa tangent modulus.

Results And Discussion

Numerous finite element runs are conducted to examine the effect of hole cold expansion on stresses, strains and deformation. The effect of change of the tangent modulus on the residual stresses at various sections of the plate is analyzed. A typical development of plastic deformation in terms of von Mises stresses is shown in the form of contours. The plastic deformation prevails after each of the two process steps: expansion and release. Since the compressive tangential residual stress is responsible for the enhancement of fatigue life, only results on tangential residual stress are shown for the parametric analysis. Significant differences between the different material models examined are revealed for both the maximum values and distribution of the residual stresses at the surfaces and mid section of the plate.

Figure 1 shows that there is uniform stress distribution when the mandrel is inserted into the plate hole. When the mandrel is removed, due to the constraints on the hole surface, slight deviation in the stresses occurs at different sections through thickness. Figure 2 makes clear the residual tangential stress variation along plate edge due to cold expansion.



(a) von Mises stress contour when mandrel is inserted into the hole | **(b) von Mises stress contour when mandrel is removed from the hole**

Figure 1. von Mises stress contours due to cold expansion (Et = 200 MPa)

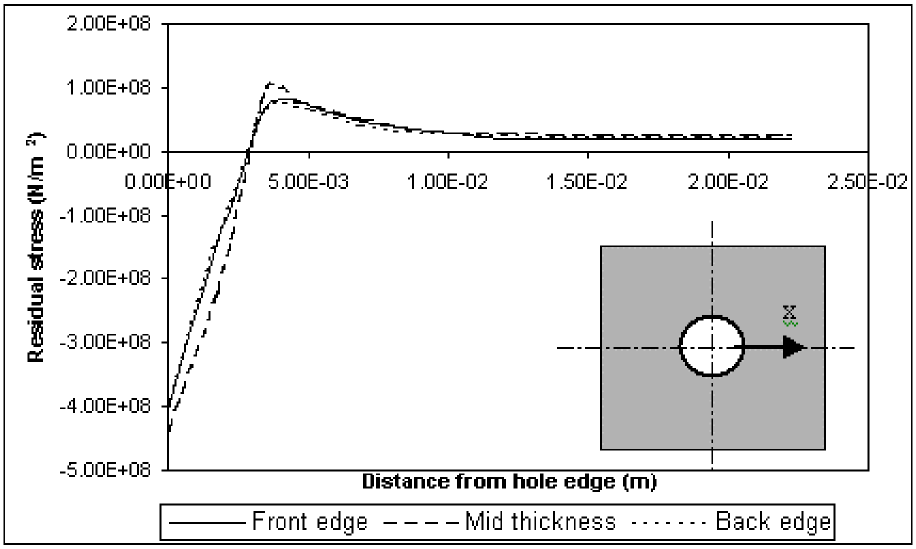


Figure 2. Variation of residual tangential stresses along the plate edges (Et = 200 MPa)

Influence of strain hardening rate on the residual stress field

Figures 3, 4, and 5 give the variation of residual compressive tangential stresses along the plate edge for the different material models. As the tangent modulus of the material increases (i.e. material stiffness is increasing after yield point or strain hardening rate is increasing), the residual compressive stresses along the plate front and back edges decreases with some rise in the tensile stresses away from the hole edge. This is because of the ability of the material to withstand at more loads due to increased tangent modulus. Higher the strain hardening rate, higher the ability of the material to withstand at higher loads, and less is the variation of residual stresses along front and back edge of the plate. The residual stresses around the mid thickness of the plate also vary in the same trend as the variation trend on the front and back plate edges.

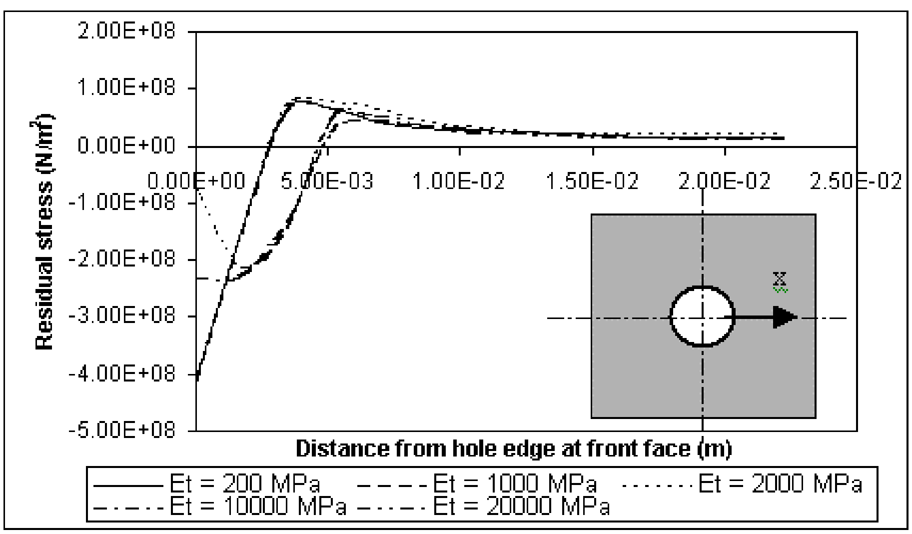


Figure 3. Variation of residual tangential stresses over the plate front face for five different material models

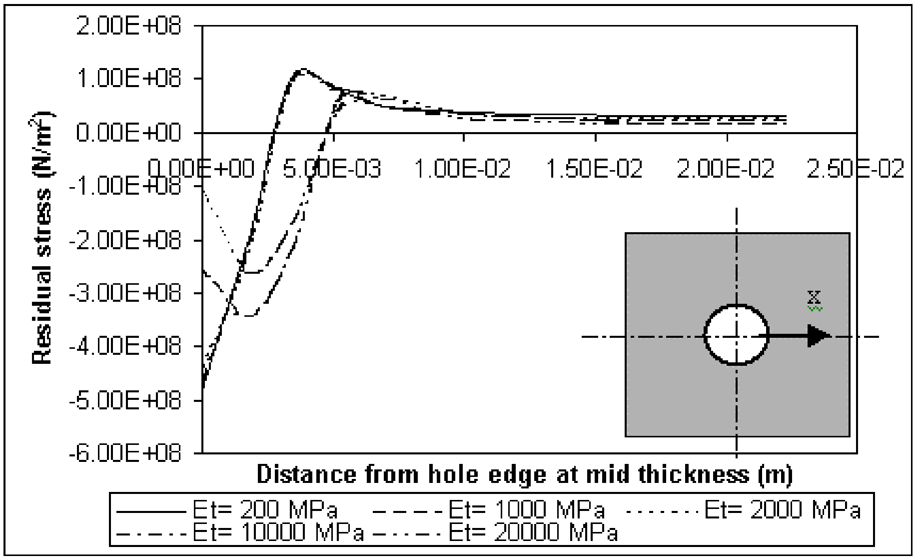


Figure 4. Variation of residual tangential stresses along the plate mid thickness for five different material models

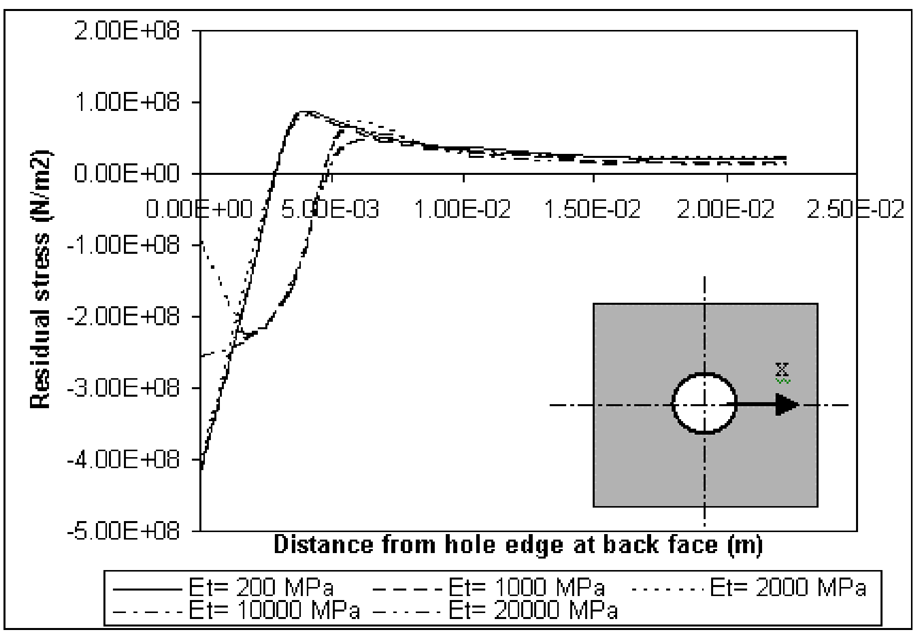


Figure 5. Variation of residual tangential stresses over the plate back face for five different material models

Figure 6 shows the vital effect of material tangent modulus on the residual compressive stresses through the plate thickness along the hole edge. Around the mid thickness of the hole edge these stresses vary in different ranges and this range changes with the material model and this variation is directly related with the slip characteristics of the material. For lesser tangent modulus such as, Et = 200 MPa, the residual stresses are more. Also for higher tangent modulus such as Et = 20000 MPa, the residual stresses are less. Whereas for in-between also, the residual stresses are decreasing with the increase in tangent modulus. Hence it is evident that an optimum value of the material property tangent modulus is desirable to advantageously use the higher residual compressive stresses for fatigue life enhancement.

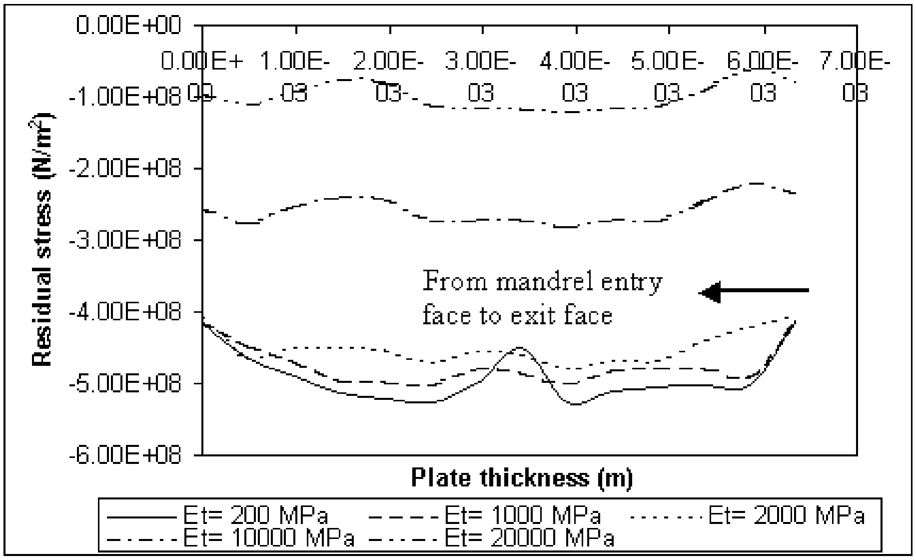


Figure 6. Variation of residual stresses through the plate thickness for five different material models

The residual stress variation through the plate thickness from the mandrel entry face to the opposite face shows uneven distribution at different locations. This has also been observed by earlier authors [3,4]. This is due to the extent of plastic zone developed and the hole edge vis-à-vis plate thickness effects and the slip characteristics of the material. The ranges of residual stress variation are: (1) For Et = 200 MPa, σc= –5260.98e5 N/m^2 to –4670.39e5 N/m^2, (2) For Et = 1000 MPa, σc= –5018.45e5 N/m^2 to –4478.96e5 N/m^2, (3) For Et = 2000 MPa, σc= –4780.13e5 N/m^2 to –4201.57 N/m^2, (4) For Et = 10000 MPa, σc= –2818.39e5 N/m^2 to –2385.22e5 N/m^2, and (5) For Et = 20000 MPa, σc= –1218.38e5 N/m^2 to –603.28e5 N/m^2.

Conclusion

From the Finite element analysis of CsSmP hole cold expansion process, following conclusions are drawn.

As the tangent modulus of the material increases, the residual stresses along the plate front and back edges decreases with some rise in the tensile stresses away from the hole edge.

The variation trend of residual stresses around the mid thickness of the plate is almost same as that of variation trend on the front and back plate edges.

Around the mid thickness of the hole edge these residual stresses vary in different ranges and this range changes with the material model due to variation in slip characteristics.

Improper simulation of cold expansion process may lead to the higher tensile residual stresses.

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