Analysis of quenching and stretching processes of aluminum alloy thick plates

GONG Hai[1,2,3,a*], WU Yun-xin[2,3,b], YANG Zhao-peng[2,3,c], LIAO Kai[4,d]

[1]School of Materials Science and Engineering, Central South University, Changsha, China;

[2]State Key Laboratory for High Performance Complex Manufacturing, Changsha, China;

[3]School of Mechanical and Electrical Engineering, Central South University, Changsha, China;

[4]School of Mechanical and Electrical Engineering, Central South University of Forestry and Technology, Changsha, China

[a]gonghai@csu.edu.cn, [b]wuyunxin@csu.edu.cn, [c]yzp.hb@163.com, [d]liaokai102@163.com

Abstract. 7050 aluminum alloy thick plates are usually heat treated and then aged to improve mechanical properties; however, residual stresses in the plates are developed during quenching. In this study, the influences of non-uniform factors on residual stresses in aluminum alloy thick plates during the quenching and stretching processes are studied. The results show strong inhomogeneity of the residual stress distribution in the plates, and the length of influenced area of the stretched plate is discussed.

Introduction

7050 aluminum alloy is precipitation-hardened alloy mainly made into thick plates then machined into fuselage frames, stringer, etc. in the aerospace industry. Its high mechanical performances are achieved through solution heat treatment, quenching process and after aging heat treatment. Usually, in the quenching process aluminum alloy plates are cooled down from about 475℃ to room temperature rapidly using immersion quench with room temperature water, which introducing great quenching residual stresses, leaving the material unsuitable for further machining operations. Thus a residual stresses relief process is required. Pre-stretching is known to be very effective and convenient in reducing the residual stresses in rectangular and symmetric parts such as aluminum alloy plates based on both production and experimental results [1-8].

In this study, residual stresses in quenched plate and stretched plate are studied combined with FEM and the crack compliance method, and local inhomogeneity of residual stresses caused by non-uniform factors is analyzed.

Analysis of quenching residual stresses

Using the finite element software MSC.MARC, quenching and stretching processes of aluminum alloy plate of size 10000mm×4000mm×50mm are analyzed. As the plate is regular cubic shape with length and width much bigger than thickness, eight-node hexahedral element (HEX43) mesh is used in the models. In the quenching model, a coupled solution of heat and stress is used. Aluminum alloy is defined as continuous, homogeneous and isotropic solid material. Thermal and mechanical properties of the material are of nonlinear relationship with temperature, specific parameters such as elastic modulus, Poisson ratio, yield strength, density, thermal expansion, thermal conductivity, specific heat are taken from references [1-3].

Quenching residual stresses in aluminum alloy plate. In the quenching process cooling rate depends mainly on quenching method (such as immersion quench, liquid water spraying quench, and mist spraying quench, etc.), quenchant and quenchant temperature. While heat transfer coefficient at plate surface reflects the cooling rate, which has great influence on quenching residual stresses. Typical heat transfer coefficient changes as surface temperature changing, as shown in Fig.1.

In the quenching simulation, aluminum alloy plate is cooled down from 475 ℃ to room temperature with 20℃ water by immersion quench. Simulation result and testing result of quenching residual stresses in aluminum alloy plate are shown in Fig.2. In the experiment the crack compliance method is used; first sample of size 120mm×120mm×50mm is cut down from the plate, then a crack is introduced into the sample incrementally by electric discharge machining, and strain components normal to the cut plane are measured. At last the original stresses are determined from the measured strains using the series expansion approach. Since plate thickness is much smaller than length and width, heat exchange between the plates and outside environment is mainly through the two L-T surfaces symmetrically in the quenching process, thus thickness direction (Z direction) residual stresses are very small, while longitudinal (X direction) and horizontal (Y direction) residual stresses are rather bigger and symmetrical along the thickness center.
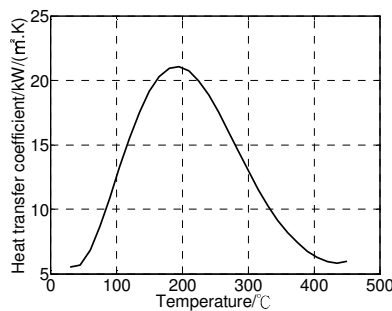

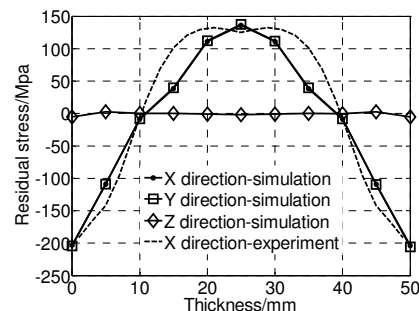Fig.1 Heat transfer coefficient of immersion quech

Fig.2 Quenching residual stresses in aluminum plate

Influence of heat transfer coefficient on quenching residual stresses. In the quenching simulation, an average heat transfer coefficient is used. Longitudinal residual stresses in quenched aluminum plates of different average heat transfer coefficients are shown in Fig. 3. It can be seen that both compressive stress on the plate surface and tensile stress in the center increase following the increase of heat transfer coefficient.
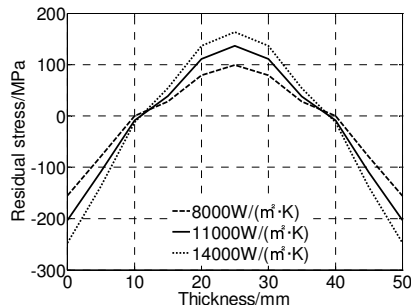

Fig.3 Residual stresses in aluminum plates
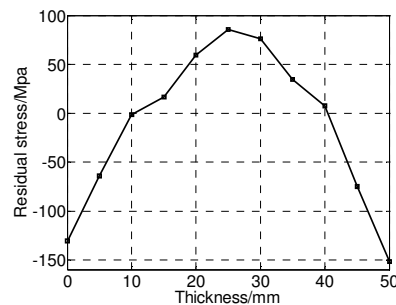of different average heat transfer coefficients

Fig.4 Residual stresses in aluminum plates
under asymmetric quenching condition

Residual stresses are symmetrically distributed in plate thickness direction and inevitable in quenching. Large residual stress (even to 250Mpa) will cause unwanted deformation after mechanical machining, while asymmetrically distributed quenching residual stresses will cause deformation in the quenching process. Ideally, heat transfer coefficients on the plate surfaces are uniform, but in practice they are different in different positions on the surfaces. In extreme cases, heat transfer coefficients at the two L-T surfaces of the plate are quite different, for example average heat transfer coefficients at the two L-T surfaces are respectively 4000 $W/(m^2 \cdot K)$ and 11000 $W/(m^2 \cdot K)$, through thickness distribution of quenching residual stress in a 50mm thick plate as shown in Fig. 4. In this situation, residual stresses are no longer symmetrical along the thickness center, which results in deformation of the plate. While under symmetric quenching condition, residual stress distribution in thickness direction is symmetrical along the thickness center, with tensile stresses in the center and compression stresses at the surfaces as shown in Fig. 2 and Fig.3.

Analysis of residual stresses relief in the stretching process

Large deformation will be introduced to the plate in the following machine process because of the quenching residual stress, thus a residual stress relief process such as stretching is required. In the stretching models, quenching strain and stress fields are taken as initial conditions, the material is defined as continuous, homogeneous and isotropic, and the Von Mises yield criterion and the Prandtl-Reuss plastic flow rule are used.

In the simulation, actual conditions are taken into account, aluminum plates are not directly pulled at the two ends but stretched with two groups of clamps, and the stretching clamps are defined as rigid body. The stretching process is divided into three stages: clamping, stretching and releasing, as shown in Fig. 5.

(a) clamping;   (b) stretching;   (c) releasing
Fig.5 Three stages of the stretching process
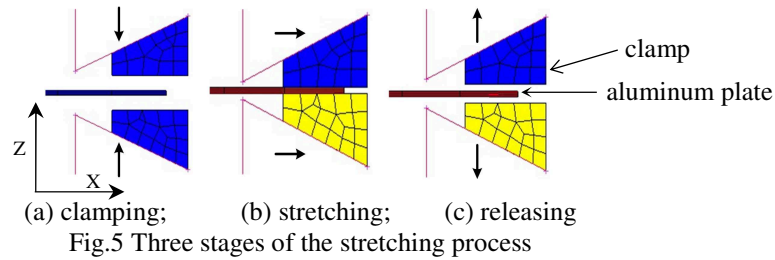
Residual stresses in stretched plates under ideal condition. As mentioned above, during the stretching process aluminum plates are clamped at the two ends of longitudinal direction. Typical distribution of surface residual stress in stretched plate is shown in Fig. 6, it can be seen that residual stresses are uneven along longitudinal direction especially at the end. According to the characteristic of residual stress distribution in stretched plate, the plate can be divided into three different regions along the longitudinal direction from the end to the center: clamping region, transition region and uniform region.
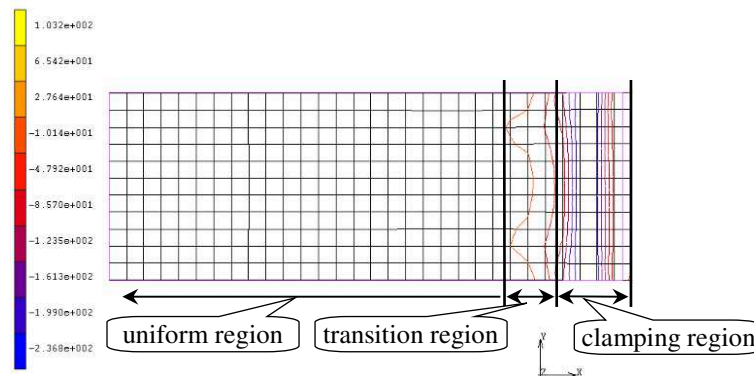

Fig. 6 Surface residual stress distribution in stretched plate

Clamping region. During the stretching process, the clamping region and the clamps move together as a whole, thus the clamping region is not deformed in the stretching direction, and residual stresses in this region are almost not changed.

As plates are clamped at the two ends by thickness direction pressure and longitudinal friction, large stresses and severe plastic deformation are induced in the clamping region, which may cut down the clamping region along the direction of maximum shear stress. Therefore, the clamping length should be long enough by ensuring the clamping stability; on the other hand, the clamping length should be as short as possible by making full use of stretched plates. The clamping length is a contrast and needed to be optimized. Calculation and experiments shown that for safe stretching the clamping length should be not less than the plate thickness.

Transition region. The transition deformation region lies between the clamping region and the deformation uniform region. According to the Saint-Venant principle [9], the difference between the effects of two different but statically equivalent loads becomes very small at sufficiently large distances from load, in this study away from the clamps the stretching load can be seen as uniform,

and the deformation is uniform. As the clamping region is almost not deformed, deformations from the clamping region to the uniform region are gradually increasing until a stable value, while residual stresses in this region are gradually decreasing until a stable value.

In this study, using FEM three different plates of size 1000mm×4000mm×30mm/50mm/80mm are immersion quenched, then stretched by 3.0%. In the stretching models, corresponding to the plates of thickness 30mm, 50mm and 80mm, the clamping lengths are set as 60mm, 60mm and 100mm respectively. Results of residual stresses are shown in Fig.7. It can be seen that, corresponding to the plates of thickness 30mm, 50mm and 80mm, lengths of the transition region are about 80mm, 90mm and 100mm respectively. It can be concluded that away from the clamps the residual stress distribution gradually become even and the length of transition region increases with the increasing of plate thickness.

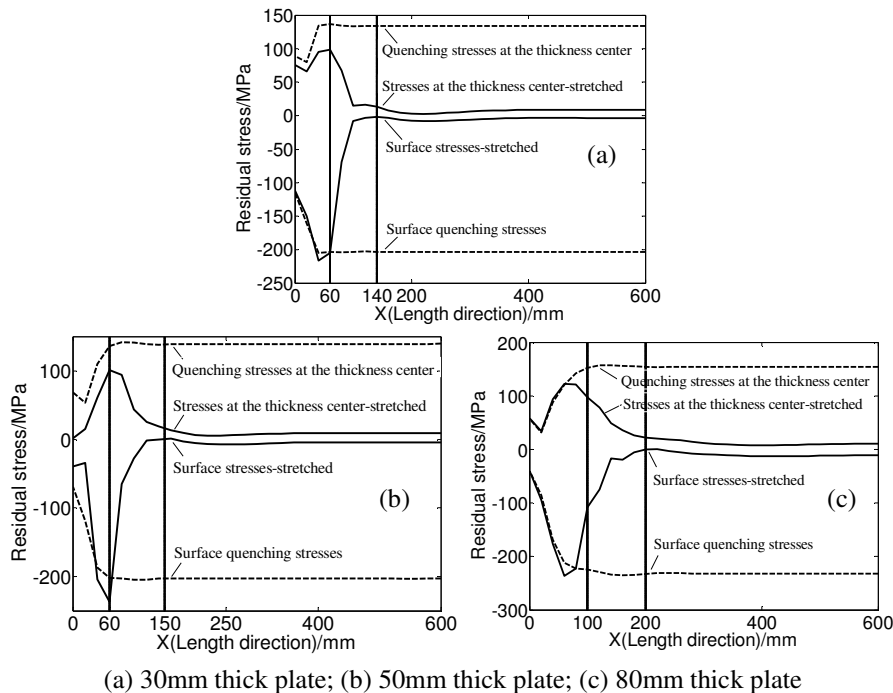(a) 30mm thick plate; (b) 50mm thick plate; (c) 80mm thick plate
Fig. 7 Residual stresses in the stretched plates

Uniform deformation region. In the uniform deformation region the plate deformation is uniform, thus residual stresses in this region can be controlled to a lower level. As residual stresses in the clamping region and transition region are almost as large as quenched plates and the distribution is uneven, thus in actual production these two regions should be cut down.

Residual stresses in stretched plates with clamps failure. Ideal stretching of symmetrical conditions are discussed above, in this section, asymmetric factors such as clamps failure are considered. In actual production plate length is larger than 10000mm, width is larger than 4000mm, and thickness is larger than 50mm, thus the stretchers have a group of clamps at each end. Occasionally some clamps are not working properly (such as wear and tear on clamps) during the stretching process, material near the failed clamps are not exposed to sufficient plastic deformation. Therefore, the effect of residual stress reduction in these areas is influenced, and the size of uniform deform region will be influenced by the failure of clamps. Thus, the influenced region can be seen as transition region.

In the simulation plates of size 10000mm×4000mm×50mm are stretched 3.0% with 13 clamps at each end, ideal stretching and three typical conditions with invalid clamps (outside clamps failure at one end, clamps failure symmetrically at one end, central clamps failure at both ends symmetrically) are analyzed.

Ideal stretching. Plastic strain distribution in the ideally stretched plate is shown in Fig.9. It can be seen that, the plate can be divided into five different zones at each end. Among the five zones, A is located at the uniform region, and plastic strain in this zone is about 2.68%, surface residual stress is about -6.8MPa (residual stress before stretching is about -200MPa); B, C and D are located at the

transition region, and plastic strain in these zones is about 1.96%, surface residual stress is about -16.7MPa; E is located at the transition region too, and plastic strain in this zone is nearly zero, surface residual stress is almost not changed, and the size of E is about 0.15m (X direction)×1.5m (Y direction) at each end of the plate.
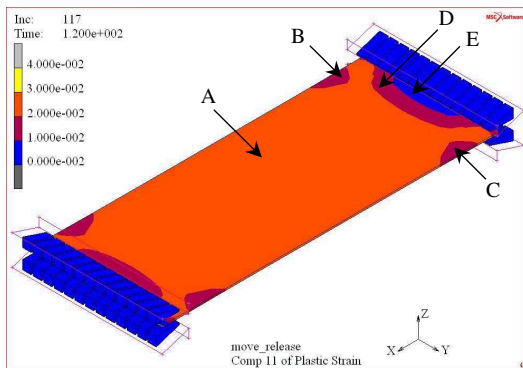

Fig.8 Plastic strain distribution in big plate
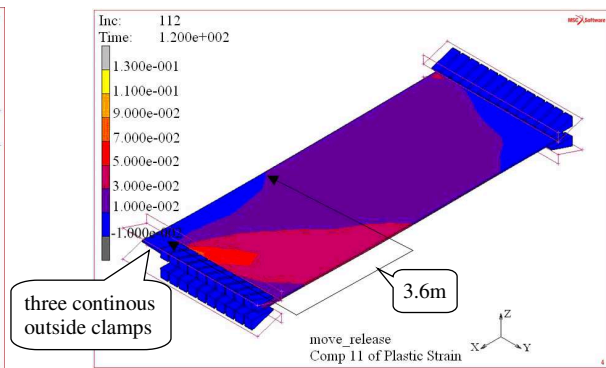of ideal stretching

Fig.9 Plastic strain distribution in big plate
with outside clamps failure at one end

Outside clamps failure at one end of the stretcher. Situation of three continuous outside clamps failure at one end of the stretcher is analyzed, the result is shown in Fig.9. In this case, the plastic strain distribution in the stretched plate is influenced, and the influenced length is about 3.6m from the clamps to the length center. As plastic strains in the influenced region are quite smaller than the uniform regions, residual stresses in this region are much larger than the uniform region.

Symmetrical clamps failure at one end of the stretcher. Situation of two groups of two continuous clamps failure symmetrically at one end of the stretcher is analyzed, the result is shown in Fig.10. In this case, the influenced length decreased to about 1.2m as the number of continuous failure clamps reduced to only two, even if the failure clamps are located at outside places too. Thus, it can be concluded that, the influenced length becomes larger with the increase of continuous failure clamps.
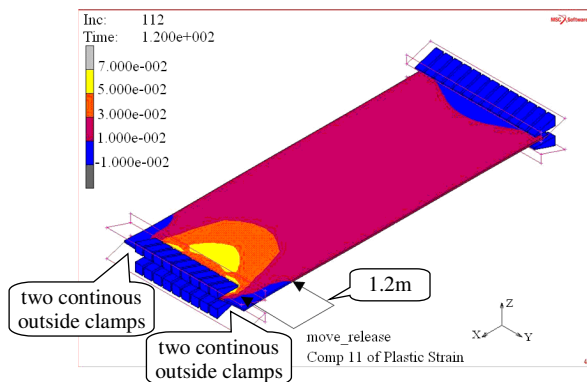

Fig.10 Plastic strain distribution in big plate
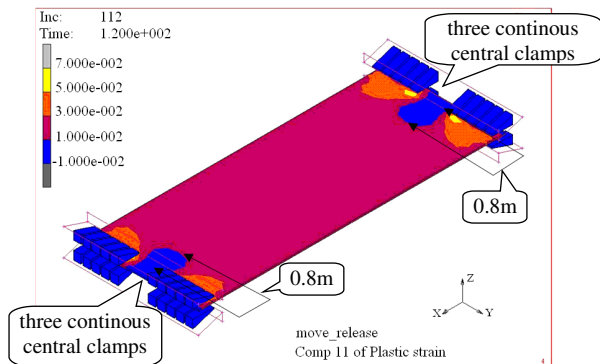with outside clamps failure symmetrically at one end

Fig.11 Plastic strain distribution in big plate
with central clamps failure at both ends symmetrically

Central clamps failure at both ends of the stretcher symmetrically. Situation of two groups of three continuous central clamps failure at both ends of the stretcher symmetrically is analyzed, the result is shown in Fig. 11. In this case, the influenced length is about 0.8m, much smaller than the condition of three continuous outside clamps failure.

Compared with the four conditions discussed above, it can be concluded that as influenced by the characteristics of stretching force, failure central clamps have less influence on the plates than failure outside clamps with same number of clamps, and the more continuous failure clamps the bigger the length of deformation failure area.

Conclusions

(1) Cooing rate has great influence on the quenching residual stress in 7050 aluminum alloy plates, surface residual stress increases by nearly 67% (from 150Mpa to 250Mpa) when heat transfer coefficient is changed from 8000 $W/(m^2 \cdot K)$ to 14000 $W/(m^2 \cdot K)$. While asymmetrical quenching with

average heat transfer coefficients at the two L-T surfaces respectively 8000 $W/(m^2 \cdot K)$ and 14000 $W/(m^2 \cdot K)$, residual stresses in the plate are no longer symmetrical along the thickness center, which results in deformation of the plate.

(2) For stretched plates of same stretching ratio 3.0%, but different thicknesses 30mm, 50mm, 80mm and different clamping lengths respectively 60mm, 60mm and 100mm, the lengths of residual stress distribution non-uniform region are respectively 140mm, 150mm and 200mm.

(3) Failure of three continuous outside clamps at one end of the stretcher results in an influenced length of about 3.6m from the clamps to the length center. When the number of continuous failure clamps decreased to two, the influenced length is about 1.2m. Failure of three continuous central clamps symmetrically at both ends of the stretcher results in an influenced length of about 0.8m.

Acknowledgements

References

[1] YAO Can-yang. Numerical simulation of quench temperature field and internal stress field of aluminum alloy 7050 thick plate. Changsha: School of Mechanical and Electrical Engineering, Central South University, 2007, pp. 14-28.

[2] GONG Hai. Research on evolution and evaluation model of residual stress in aluminum alloy thick plate. Changsha: College of Mechanical and Electrical Engineering, Central South University, 2011, pp. 18-27.

[3] Muammer Koc, John Culp, Taylan Altan. Prediction of residual stresses in quenched aluminum blocks and their reduction through cold working processes. Journal of Materials Processing Technology, 174(2006)342-354.

[4] S Rasouli Yazdi, D Retraint, J Lu. Study of through-thickness residual stress by numerical and experimental techniques. Journal of strain analysis, 33 (1998) 449-458.

[5] D. A. Tanner, J. S. Robinson. Residual stress prediction and determination in 7010 aluminum alloy forgings. Experimental Mechanics, 40(2000)75-82.

[6] G. P. Dolan, J. S. Robinson. Residual stress reduction in 7175-T73, 6061-T6 and 2017A-T4 aluminum alloys using quench factor analysis. Journal of materials processing technology, 153-154(2004)346-251.

[7] Michael B Prime, Michael R Hill. Residual stress, stress relief, and inhomogeneity in aluminum plate. Scripta Materialia, 46(2002)77-82.

[8] ZHANG Dan-wen, LIU Hong-zhao, LIU Ping. Evaluation of residual stresses in 7075 aluminum alloy plate using crack compliance method. Transactions of Materials and Heat Treatment, 27(2006)127-131.

[9] CHEN Ming-xiang. Elasticity and Plasticity. Science Press, 2010, pp 4-10.