Deformation Analysis Based on Residual Stresses in Aluminum Plate

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A quenching process during the manufacturing of aluminum plate enhances precipitation hardening so as to reach a satisfactory strength, but rapid-cooling inevitably induces excessive residual stresses in the material. If the stress is not properly relieved, deformations due to material removal processes such as machining degrade the precision and dimensional accuracy. This paper proposes a method for predicting such deformations according to the measured residual stress and the simulation of the machining process. By applying the residual stress profiles on the 3D model, the machining process can be simulated using the Finite Element Analysis software. It was found that the distortion calculated by the method is consistent with the real world case. To enhance the stress relieving effect, a stretch leveling model was developed to identify the elongation of the plate with satisfactory accuracy. Finally, the residual stress was decreased by 65% with the new stretch settings.

Keywords: Aluminum Plate, Quenching, Stretch Leveling, Residual Stress

1. INTRODUCTION

Aluminum is an attractive material for the applications require demanding dimension tolerance, such as aerospace structure and semiconductor equipment. Precipitation hardening aluminum alloys such as 6000 and 7000 series have superior strengths due to supersaturation achieved by quenching process. By rapid cooling of the alloy at solubilization temperature around 550°C, the diffusion rate is limited such that supersaturated solid solution αss is formed is shown in Fig.1. Later on, thermal aging heat treatment drives the segregation process to generate particles with optimal size. The magnitude of hardening is built on the interaction of the precipitation particles with dislocations. The mechanism generates satisfactory hardening effect, however, plastic deformations accompanied by fast cooling often result in highly compressive residual stress, which brings harmful effect when ultra precision machining is desired.

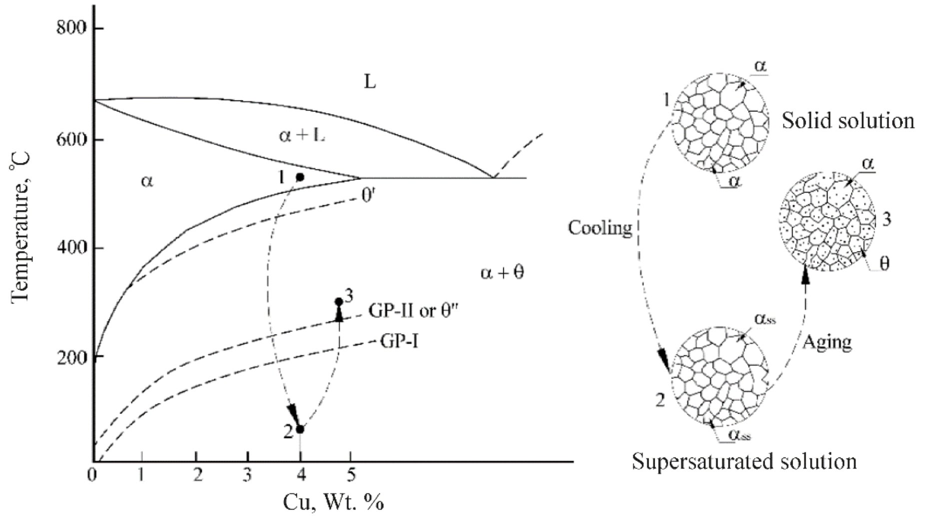


Fig.1. Solubilization and precipitation process of aluminum alloy(1)

Achieving machining accuracy is demanding in the community of precision engineering. However, dimensional instability during material removal process such as milling and drilling often leads to profit losses and elevated cost due to remanufacturing. Such problem is largely attributed to the release of internal residual stress. A few studies regarding the correlation between residual stress and machining deformation have been reported. Enormous deflections (over 50mm) of steel plate can be observed during the slitting process. To investigate the problem, the residual stress data is acquired by a homemade portable device based on the magnetostrictive principle[2,3]. Stress distribution along the width of the plate demonstrates a highly correlated relation to its deflection nature by showing significant tensile stress close to both sides. By simulating the plate with the roller leveling process, the magnitude of residual stress shows a substantial attenuation[4]. As a result, less than 5mm of deflection is achieved, demonstrating the feasibility of applying residual stress techniques to support the quality of the product. Some other studies focus on machining distortion of aluminum alloy. Around 44μm of bending was found by manufacturing slim beams from a large 7050 slab pre-processed by quenching process[5]. The residual stress of the slab characterized by contour measurement is found ranging from -150MPa to 150MPa. In another experiment slitting method was employed to reconstruct the residual stress of the bulk material. The data of thickness variation of 7050 plate is collected by machining real components. It was found the distortion of the work piece thinner than 3mm is mostly contributed by the machining-induced residual stress[6].

An aluminum plate made of 7075 alloy was manufactured by China Steel Aluminum Corporation (CSAC) and was sent to the customer for further machining. A circular shaped ring was then manufactured by removing a very large portion of material, which included thinning by end milling. The nominal path of the tooling curve as well as its tolerance limits are shown in Fig.2. The critical dimensions and geometry of the final part acquired by a coordinate measuring machine (CMM) are also shown in the same figure. The illustrated distortion is scaled up 100X compared to its original dimensions. It was observed that after machining, the deformation caused by residual stress expands the work piece towards the C-direction, while compressing itself in the L-direction. Such distortions deviate the final geometry from its original design significantly, resulting in unacceptable errors for any further assembly process. Since the thickness of the blank material is large enough to ignore the machining-induced stresses, only bulk stress is considered in this research. In this paper, the process of residual stress characterization and improvement of the above case is introduced. Residual stress profile measurement by a promising technique, namely the slitting method, is explained in Section II. To estimate the deformation caused by the residual stress, a numerical finite element model was developed so as to simulate the material removal process in Section III. In Section IV, the stress relieving process is further improved by a more accurate analytical model which offsets the elongation setting by the amount of elastic spring back. Finally, conclusions and contributions to this research are organized in Section V.

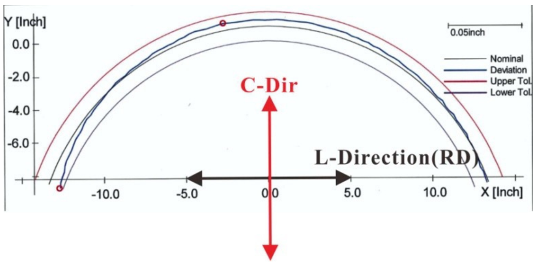


Fig.2. Measured geometry and its deviation after the machining process.

2. RESIDUAL STRESS MEASUREMENT

Residual stress is a self-balanced stress embedded inside the material. When material is removed by the machining process, the balanced nature of the stress distribution changes to a new state, therefore triggering undesirable deformation. The measurement of residual stress is a complicated technique since the stress "locked" inside the material cannot be directly observed. Several methods have been proposed to provide reliable measurements, including both destructive and non-destructive approaches. The slitting method, while still establishing itself as a standard engineering method over the last few years, it is the most promising technique for obtaining through-thickness stress distribution[7,8]. The technique originated from the concept of crack compliance which destructively released the stress by opening a slit across the thickness[9,10]. A sample with proper dimension is taken from a plate, followed by strain gauge application on its back surface as shown in Fig.3. A wire EDM machine creates a slit with progressively increasing depth to release the stress. At the same time the strain gauge reading is recorded at the corresponding depth a. The collected strain data $\varepsilon(a)$ is converted to a stress profile $\sigma(a)$ by following three steps as seen in Fig.4. , namely simulation, experiment and calculation. In the simulation step, a two-dimensional FEM model is used for calculating the compliance matrix $[C]_{ij}$ which consists of all the strain information resulted from the release of either piecewise[11] or polynomial basis distribution[12,13]. The calculation step takes the strain data from the experiment step and obtains σ(a) via $[C]_{ij}^{+}\,\varepsilon(a)$, where $[C]_{ij}^{+}$ is the pseudo-inverse of $[C]_{ij}$. In order to dampen the noise effect, Tikonov regularization is also incorporated in the calculation process(10).

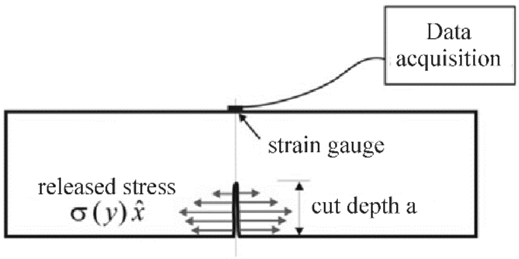


Fig.3. Measurement principle of slitting method.

To verify the feasibility of the slitting method developed in CSC's laboratory, a four-point-bending experiment was conducted on an aluminum plate to generate residual stress. The bending was precisely controlled and monitored so that the stress profile could be estimated through simulation and theoretical calculations. Afterwards, the sample was arranged to be sliced by the EDM machine and strain data $\varepsilon(a)$ as shown in Fig.5. was acquired and converted to a stress profile σ(a). The measured result as shown in Fig.6. is in high accordance with the FEM simulation and theoretical curve, which proved the validity of the established slitting method.

The 7075 aluminum plate is sampled with proper dimensions so as to reserve residual stress during the sampling process. As depicted in Fig.7, the cutting slit is at least 1.5X the thickness (130mm) away from the free end so as to avoid unwanted deformation caused by sampling. The wire is vertically aligned with the direction of the stress and the back strain gauge is applied to monitor the deformation. Following the standard procedure, the strain data is converted into a stress profile as shown in Fig.8. The excessive compressive stress of 70MPa near the surfaces explains that the thermal stress was not relieved efficiently in the leveling process. As a comparison, a second aluminum plate from a different manufacturer, showed a much lower machining deformation in the ring-shape work piece, having only 20MPa of magnitude in the stress profile.

3. DEFORMATION ANALYSIS

In this section, deformation analysis is performed based on the measured residual stress and FEM software. In order to construct a full stress field, another sample was arranged for slitting and a stress profile in the L-direction was acquired as shown in Fig.9. The smaller residual stress shows that the elongation resulted by stretching is more effective in the L-direction. A

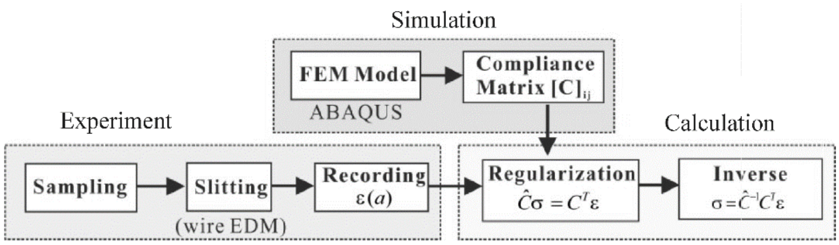


Fig.4. Slitting method is comprised of three steps.

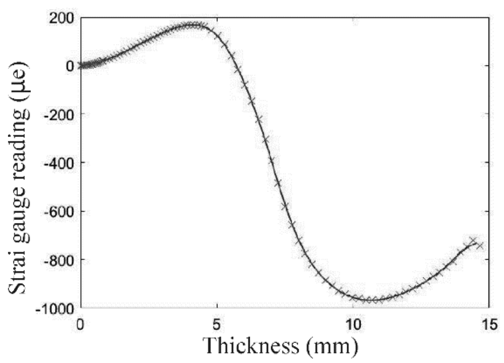


Fig.5. Strain data of a four point bending sample.

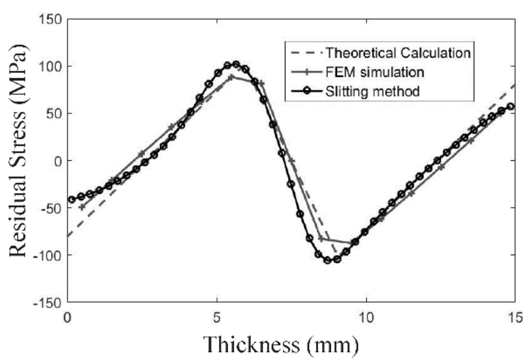
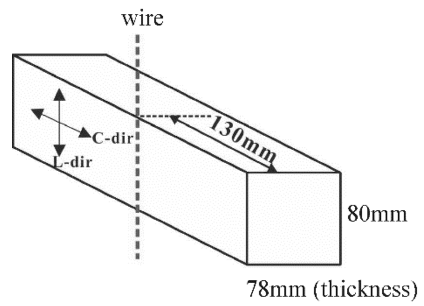


Fig.6. Measurement result along with FEM and theoretical profiles of a four point bending sample.



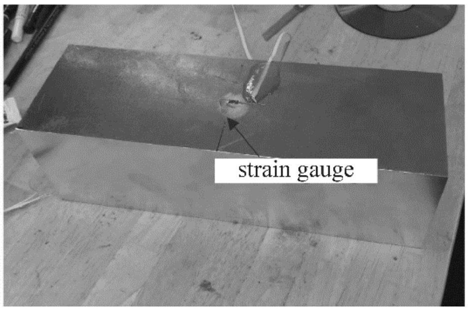


Fig.7. Sampling and strain gauge application of aluminum plate.

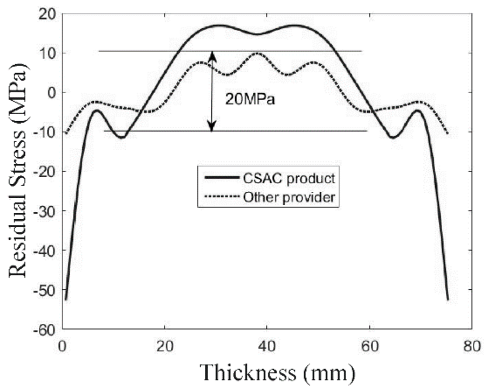


Fig.8. A comparison of the stress profile of a CSAC sample with its competitor.

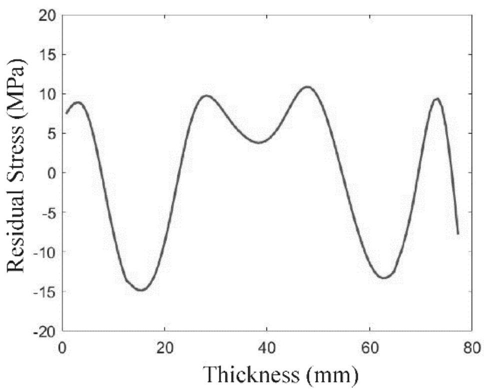


Fig.9. Residual stress in the L-direction was obtained to construct a full stress field.

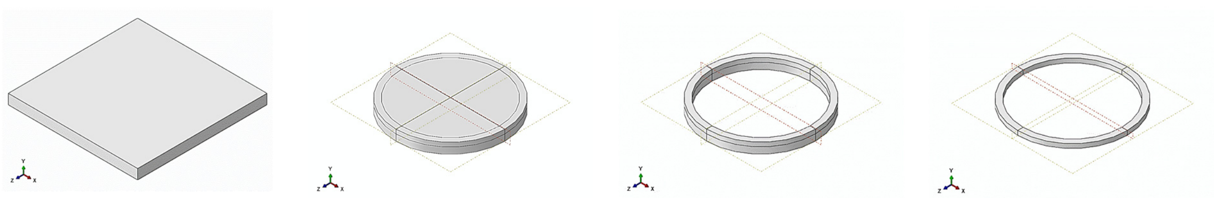
three-dimensional model was constructed according to the machining process as shown in Fig.10. First, an aluminum blank material with original thickness was applied with proper material constants and stress profile assignments in both L- and C-directions. Next, the outer part was removed, following by the removal of the inner disk. Finally, the thickness was reduced to half of its original dimension.

The deformed geometry of the model at each material removal step is shown in Fig.11. During the first and second steps in Fig.11(a) and 11(b), the flatness still remains in good condition due to the symmetrical stress profile. However, as the stress distribution lost its symmetricity, it starts to deflect vertically after the thickness was reduced at the final step as illustrated in Fig.11(c).

A closer examination of the final product as depicted in Fig.12. shows how much the work piece deforms exactly after the residual stress is released. The released stress effectively pulls the ring shape along the *y*-axis, resulting in a larger diameter D_1 illustrated in Fig.12(a) by scaling up at 250X. The difference in diameter (D_1-D_0) is around 0.5mm, which is close to the actual deformation as seen in Fig.2. The elliptical shape can also be identified by tracing the displacement around θ, the Ux and Uy curves as shown in Fig.12(b).

4. IMPROVEMENT OF THE LEVELING PROCESS

It was found in the previous section that the greater residual stress in the C-direction expands the diameter



(a) (b) (c) (d)

Fig.10. The modeling of the machining process. (a) Original plate. (b) Outer material removal. (c) Inner material removal. (d) Thickness reduction.

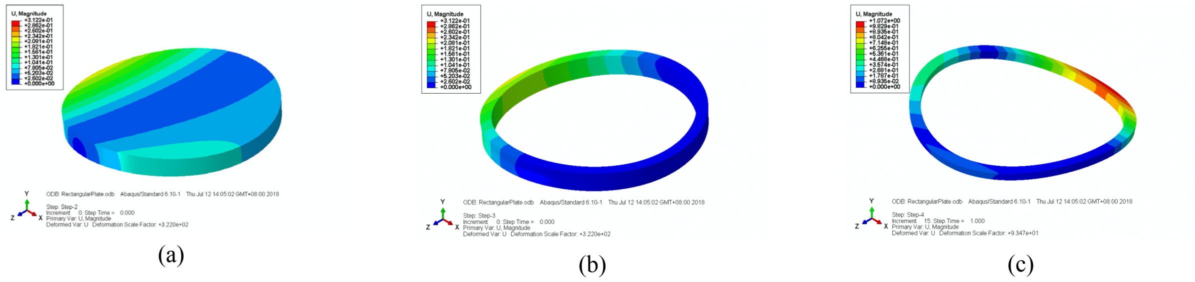


Fig.11. Simulation results of deformed geometry at each stage. (a) Outer material removal. (b) Inner material removal. (c) Thickness reduction.

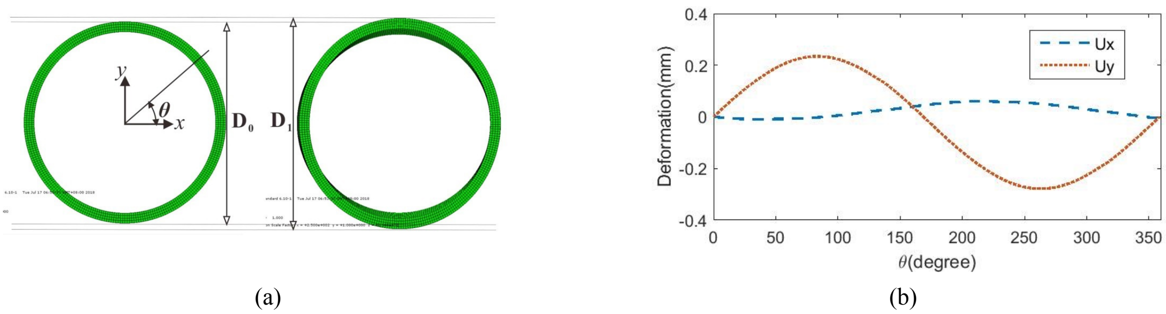


Fig.12. Dimension inspection of distorted part. (a) Changes in diameter (b) Displacement of the ring shape in both axes.

more obviously than L-direction. The only way to further reduce residual stress is through a stretch leveling process. The principle of stretch leveling is explained in Fig.13. Suppose the curvature of the aluminum plate is deformed by uneven cooling due to the quenching process. The fast cooling side has larger compressive stress and higher tensile elongation, while the slower cooling side has lower values. The original strain-stress state on the top, middle and bottom surface is denoted by 1, 2 and 3 respectively. The stretching is illustrated by two steps. First, the plate is pulled until it becomes flat, meaning that all three states are transferred to 1' and 2' and 3' all with the same length. In the second step, the process continues such that the material is stretched to exceed its

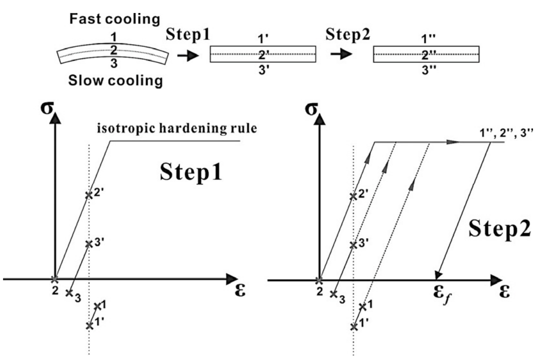


Fig.13. Improvement of plate flatness and residual stress by stretch leveling.

elastic limit, and further plastically deformed to the same state. Finally, the stress was released and then the plate spring back to ε_f. As the stretching process pushes all the strains to a uniform state ε_f, there would be no more mismatch in plastic deformation, resulting in virtually zero residual stresses.

Ideally the residual stress is zeroed as long as the elongation is large enough. However, significant residual stress still remains in the material due to two reasons that obstruct sufficient deformation. First, the deformation caused by stretch leveling in L-direction is several times larger than C-direction. A small-scale experiment was performed using a tensile machine to investigate the strain in both directions(14). The images during the deforming process were recorded and the whole strain field were obtained by processing the displacement map $U(x,y)$ and $V(x,y)$ generated by DIC method (Fig.14). It was demonstrated that the strain in C-direction is only 35% of L-direction. The ratio of C-direction to L-direction strains depends on the material anisotropy. Another on-site measurement discovered this C/L-ratio had dropped to 28% by applying strain gauges directly onto the plate surface(15). The insufficient deformation in C-direction is the primary cause of the undesired flatness and residual stress. The second reason for insufficient deformation is due to the unsupervised quality of the stretch leveling process. The stretch machine controls the strain by incorporating encoders to monitor the displacement of the gripper. However, as the displacement

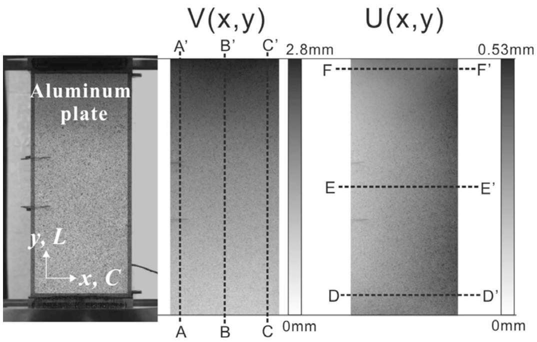


Fig.14. Deformation measurement of stretching test by DIC.

of the gripper includes the elongation of the plate and the elastic deformation of the gripper itself, the control of plate elongation could not be precise without the compensation of the gripper deformation. Furthermore, the elastic spring back of the aluminum plate is not considered in the control program. As a result, the plate is not sufficiently deformed due to these uncompensated errors.

In order to achieve precise estimation of plate elongation, a piecewise model was proposed as shown in Fig.15, which comprises of three parts, namely elastic deformation, plastic deformation, as well as linear spring back. The signal output from the control system enables parameters calculations for the first two stages through a self-developed numerical method. The stiffness of the elastic part m and the yield strength YS can be accurately identified. The elongation of the plate ε_f can be obtained by tracing the final state of the σ-ε curve along the slope m to the stress released condition σ=0. Fig.16. shows a typical estimation result of a 5083 plate. The strain setting was 1.55% in the leveling control program. By following the tracing rule, the real elongation of the plate was found to be 1.22%. In other words, the setting value should be increased by at least 0.33% to achieve the desired elongation.

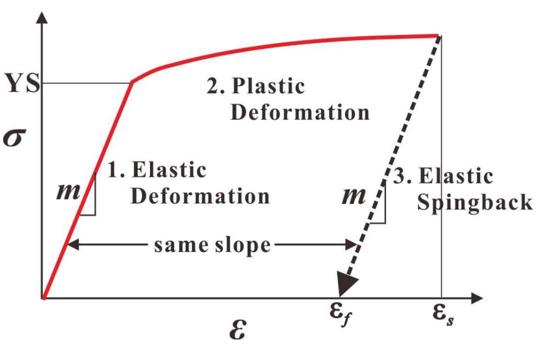


Fig.15. Proposed stretch leveling model for error compensation.

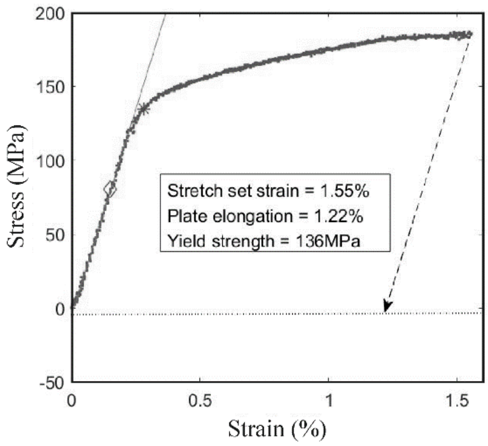


Fig.16. An example of calculating true plate elongation.

The method was applied to different alloys and various dimensions to obtain compensation values for the increment of settings. A new 7075 plate is manufactured with an increase of 1.3% strain setting and a compensation of 0.7% spring back error is applied during the leveling process. After leveling, the plate was sampled again to obtain the residual stress. The improvement on residual stress as seen in Fig.17. is quite impressive, showing a 65% reduction of amplitude from 70MPa to 25MPa. The simulation of the machining process was performed again by incorporating the new stress distribution, and the resulting deformation is reduced to around one-third of the original value.

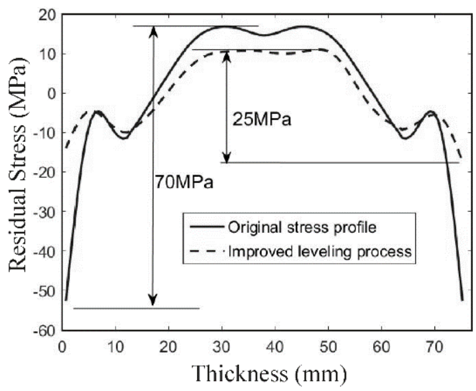


Fig.17. The residual stress of the newly manufactured plate reduced to 25MPa.

5. CONCLUSIONS

Deterioration of dimensional accuracy due to residual stress is an important issue in the area of precision manufacturing. This research opens an opportunity to estimate such deformations as a quality evaluation method before real production. The 7075 plate manufactured by CSAC experienced unacceptable deformation after machining into a ring shape work piece. Residual stress measured by slitting method shows a magnitude of 70MPa in C-direction. By taking the stress profile as the pre-existing knowledge, the machining process can be simulated by finite element modeling. The calculated deformation shows the ring deformed into an elliptic shape with the deviations similar to that of the real case. In order to reduce the distortion and dimension errors, new stretch settings were scheduled by increasing the elongation by the amount of spring back displacement. Finally, the residual stress is reduced to 25MPa and the estimated deformation of the ring piece diminished to one-third of its original values. Future work includes better residual stress management during the plate manufacturing steps including quenching, stretch leveling and even during the roll leveling process.

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