Prediction and control of residual stress and distortion during machining of Al705 billets using modelling and in-process measurements

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Abstract. High value aluminium forgings develop their mechanical properties through intense heat treatments, which generate significant residual stresses, leading to severe distortions during machining. Heat treated AA7075 billets were milled using a typical machining strategy to benchmark Finite Element process models and use as a starting point to devise machining strategies to minimize distortion. Stresses were assessed with Contour method, while distortions were measured in-situ at different stages of the machining trial and ex-situ after completion of milling operations and unclamping of the part. Simulation results were in line with residual stress and distortion measurements, where the observed distortion was associated with the material removal sequence and the clamping conditions. Release and re-distribution of bulk residual stresses were directly correlated with the observed distortion, while the machining sequence affected the distortion magnitudes and profiles.

Introduction

Residual Stresses (RS) exist within metallic materials due to the thermo-mechanical processing route, which is required to develop the application specific microstructure and mechanical properties. These stresses are locked-in the material and though they can be reduced by thermal annealing, cold work, or other stress relief treatments, these stresses cannot be eliminated, and they can still cause significant challenges with distortion and dimensional tolerances in final products, particularly when very tight tolerances are required. A pertinent example is the case of machining distortion in large aluminium aerospace structural components. This is a multi-million problem of the manufacturing sector, but it is also one that can be addressed through a Design for Manufacturing approach, where the origins of RS and the generation and evolution of machining distortions are adequately captured with process models of the key stages of the manufacturing route.

Methodology

Two AA7075 rectangular billets, 150mm X 150 mm X 400mm, *Figure 1 (a)*, were heat treated as per AMS2770 [1]. The billets were quenched in water at 60ºC from the solid solution temperature of 477ºC, but they were not aged as per the standard, intentionally, to create a worst-case scenario for machining distortion. Then, one billet was sectioned for measurement of RS with Contour Method [2] to acquire information about the stress state of the material, while the other one was milled to an inverted T section with a standard machining strategy to investigate the generation and evolution of distortions, *Figure 1 (b) and (c)*. The machining strategy involved a very unbalanced material removal sequence from one side of the vertical wall before switching to the other and multiple clamps at either side of the billet. Distortion measurements were carried out in-situ the milling machine at key steps with a fully integrated, computer numerical controlled (CNC) touch probe system. After the unclamping of each part, the geometry of the finished part was scanned ex-situ with a non-contact optical system, GOM Atos [3], to capture the distorted shape in more detail and in the absence of all physical constraints. The generation of RS during the partial heat-treatment of the blocks was simulated based on the work of Koç et al. [4]. Then, the machining trial was simulated through a simplified model based on element suppression, ignoring the machining induced effects, to track down the generation and evolution of distortion. RS and distortion predictions were compared against the experimental data to benchmark these models and explore potential improvements or limitations of the modelling approach for machining, before attempting to further optimise the method of manufacture.

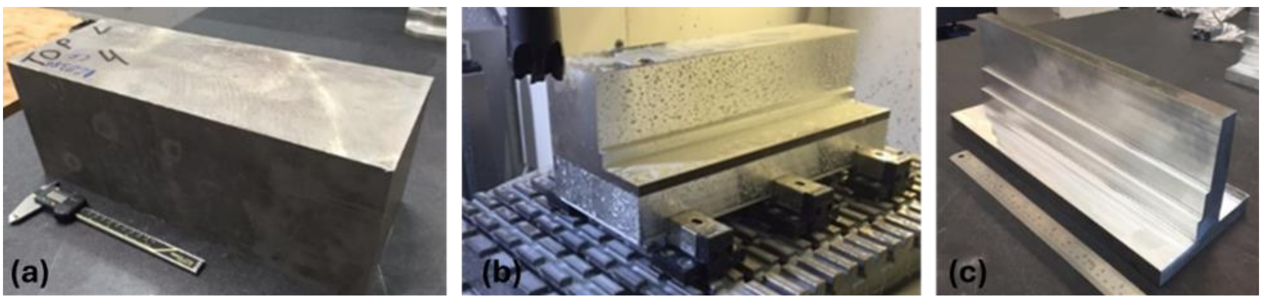

Figure 1 AA7075 billet; a) initial geometry, b) machining trial #01, c) final geometry

Results and Discussion

Contour Method provided a two-dimensional map of the axial stress component, i.e. in the direction along the length of the billet, with a typical tension-compression stress field, as expected from water quenching, *Figure 2 (a)*. This RS measurement was in good agreement to the predicted stress field, except for the outer compressive layer, *Figure 2 (b)*, which allowed the subsequent prediction of distortions during the machining trial. The evolution of the distortion of the part, as predicted by the simplified machining model, followed very close the peak values and deflection profiles measured in-situ the milling machine and ex-situ with the GOM ATOS system at key locations of the part, i.e. transverse and vertical deflection of vertical wall and side flanges, *Figure 2 (c)*. Thus, despite the inaccuracies of the RS field, the exclusion of machining induced effects and cutting forces, and material removal block by block, it was still possible to predict how a part will likely move and distort during machining. This outcome was expected due to adequately capturing the key factors of distortion, i.e. the bulk RS with a reasonable degree of accuracy and resolution, the clamping conditions, and the sequence of material removal.

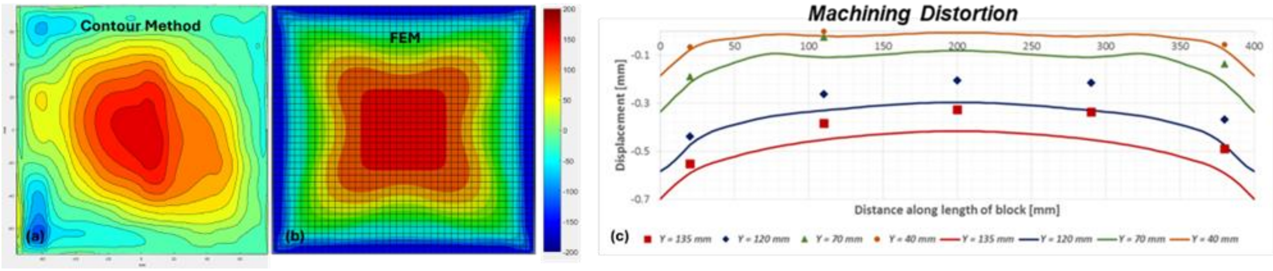

Figure 2 Experimental and modelling results: a) 2D map of axial residual stresses from Contour Method, b) 2D map of axial residual stresses from FEM of heat-treatment, and c) machining distortion measurements and predicted profiles from trial #01 at different heights of the vertical wall after material removal from the stepped side of the vertical wall.

Since the machining strategy involved heavily unbalanced cuts, severe distortions were observed in the transverse direction along the top side of the vertical wall. This in return resulted in significant deviations from the target geometry, not only in terms of straightness but also in local dimensions, i.e. thicknesses and widths, because of the net effect of distortions and nominal cutting paths. In addition, the part also moved within the clamps, and it was tilted along its length, as the clamps failed to fully constrain the part and prevent its uplift when the stepped side of the vertical wall was machined. Though the transverse deflection was reduced upon removal of material from the other side of the vertical wall, the vertical deflection of the inverted T part increased further, with the flanges distorting severely after unclamping. Based on these findings, it can be safely deduced that a more balanced material removal scenario could reduce significantly observed distortions and the stock material required to achieve final tolerances, or design a near-net-shape preform which would increase the sustainability and productivity without any machining distortion issues.

Conclusions

Understanding and prediction of the generation and evolution of Residual Stresses is the first step towards management and mitigation of distortions during machining. Bulk residual stresses are the key factor for machining distortion in higher stiffness parts, but machining induced effects and cutting forces may also contribute towards distortions in lower stiffness parts. Modelling can provide engineers with the information of how a part will move and distort, enabling them to design more robust and intelligent methods of manufacturing, optimising the sequence of material removal, improving clamping configuration, and reducing the number of machining set-ups and stock material for final machining. The most pressing objective is to eliminate rejections, but huge improvements can be made on material and resource utilisation, machining consumables and wastes, and lead times.

References

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