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Simulation of the coupling effect of bulk and induced residual stresses on machining distortion

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Abstract

During high performance machining of large thin walled aluminum aerospace parts, significant distortions become visible. These distortions are due to the effect of the residual stress redistribution, it is therefore critical to understand the influence of residual stresses on machining distortions. This paper presents the prediction of machining distortions on a demonstration part caused due to the combination of bulk and measured induced residual stresses using interpolation techniques into a FE software. The FE model was then compared with CMM data where the FE model predicted the trend and the magnitude with a small difference of around 3%.

Peer-review under responsibility of the scientific committee of the 9th CIRP Conference on High Performance Cutting.

Keywords: Machining distortions, Residual Stresses, Finite element Analysis, High Performance Machining, Aerospace

1. Introduction

The increased demands on aircraft fuel efficiency has led to the thickness reduction on aero structural components. In addition to this, there is an increased demand to keep up with the aircraft orders leading to many aluminum aerospace structural components to be manufactured faster and with very high precision [1]. High speed machining is one of the methods of increasing productivity especially for aluminum alloys although this comes with a penalty of non-conformance due to distortions [2]. Distortions during machining, is one of the products of the residual stress (RS) misfits within the component, and is one of the main cause of component rejection especially within the machining sector due the exceeding the tolerances imposed in high value components.

Machining distortion for aluminium alloys is highly influenced by the residual stresses carried forward from the heat treatment process; and also for the machining induced residual stress by plastic deformations for thin-walled components less than 3mm thickness [3]. In order to avoid distortion related problems, manufacturing companies sometimes increase the number of operations on a “trial and error” basis, change the work holding strategy, or “shot peen” the part to correct for distortion, all of which increase production costs and time [4]. The influence of the bulk and machining induced residual stresses (MIRS) on the distortions in aluminium specimens have been discussed by Madriana et, al. [5]. In their study a simple dry face milling operation was performed to investigate the distortions; and the bulk and MIRS were measured using the contour and incremental hole drilling techniques, respectively. They also developed a numerical model to interpolate the stresses for the simple case study.

In this research, an interpolation technique was implemented in a Finite Element (FE) software to integrate the bulk and MIRS to investigate impact of their coupling effect on the machining distortion for a complex representative ribbed aerospace aluminium component.

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This was done by experimentally performing bulk residual stress measurements on the initial billet of the size of the part; and taking the experimentally measured MIRS on small coupons, which were machined using the tool path strategy of the roughing and finishing operation of the representative component. In addition to this, Minimum Quantity Lubrication (MQL) was used for the trials to obtain the MIRS at this conditions that have not been considered in previous research.

2. Experimental study

High-speed milling trials were performed under minimum quantity lubrication (MQL) cutting conditions on a CNC machine, Scharmann Ecospeed. The material used in the cutting trials was aluminium alloy 7050 billet with a T7451 temper. This was to understand the effect of a set of machining parameters after roughing and finishing process on the induced residual stress responses in two rectangular coupons. Secondly, a demonstrative ribbed component was machined with a number of pockets to measure the distortions caused by the machining process, which was used to validate the FE simulations.

Bulk and near surface residual stress measurements were carried out in this project to investigate their effects on the machining distortion of a demonstration part. For the near surface residual stress measurements, the incremental hole drilling was used to measure the MIRS in coupons. For the bulk residual stress measurements, the contour method was utilized to map the residual stresses in the cross section of the billet.

2.1. Bulk residual stress measurements

For the bulk stress measurements, the contour method was used. This is a destructive measurement technique to determine the bulk residual stress in a component by cutting the component into two pieces, and measuring the deformations that are caused by the residual stress redistribution [6]. Once the data has been measured, the data is then smoothed to average the two sections and interpolated into a FE model. An inverse function is then used to predict the residual stresses normal to the cut surface. In this study, wire EDM cuts were performed on the workpiece through its longitudinal direction at the center line of the width of the billet to measure the bulk residual stresses. As a part of the bulk residual stresses calculations, the distortion data from CMM Crysta apex S series co-ordinate measuring machine was taken. The distortion measurement was repeated three times, which gave a repeatability of 1 µm. There are errors inherited from the bulk residual stress measurements are in terms of CMM uncertainty, and the smoothing of the displacement surfaces [7]. The estimated accumulated errors were around ± 4.6 MPa.

The calculated normal stress S33 contour maps of the cross section of the billet length (longitudinal) in Abaqus-Simulia is presented in Fig. 1. In this figure, the red color region represents the maximum tensile values, and the blue color corresponds to the maximum compressive values.

The contour method predictions show that the bulk stresses is compressive of -30 MPa and tensile of + 15 MPa.

Similar stress contours and magnitudes have been found by Madriana et, al. [5], and D' ALvise at al [6].

The residual stress comparison between the experimental data and the interpolated residual stresses onto the model is also shown in Fig. 1. It can be seen that the residual stresses were interpolated well at the edges of the billet with a difference of 3 % and 8 %, respectively. However, there was a variation of stress interpolation in the model in the section of the billet between a distance of 100 to 400 mm, and 600 to 900 mm with an average difference of stresses of 20 % and 23 %, respectively. This interpolation error may be due to the coarseness of the tetrahedral elements in those sections. Although this interpolation error, the model was reasoned useful to carry out the machining distortion study.

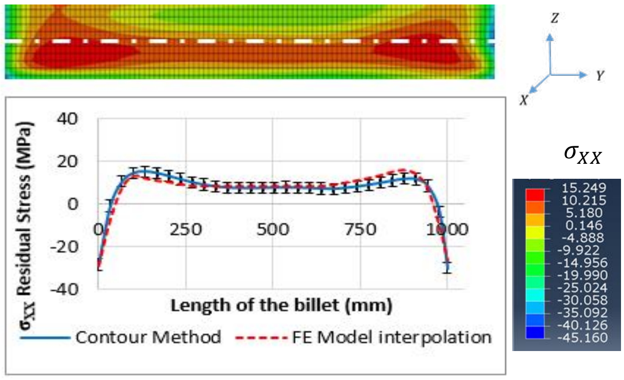

Fig. 1. Comparison between contour method measurements and the interpolated residual stresses.

2.2. Machining induced stress measurement

The aim of machining the coupons was to capture the induced residual stress profile from roughing and finishing operations. The coupons were designed with a large thickness to maintain high stiffness in the coupons to prevent any deformation due to stress relaxation; therefore the stresses could be effectively be measured. The coupons were machined according to the toolpath of the demonstrative part with the set of cutting parameters as shown in Table 1.

Table 1. Machining parameters

	Roughing Operation	Finishing Operation
Tool	Walter MB266-20.0A3X400B-WJ30UU	Kyocera SGS S-Carb APF 44753
Cutting Speed (v_c)	1178 m/min	1508 m/min
Feed/tooth (f_z)	0.1 mm	0.12 mm
Axial depth of cut (a_p)	19.75 mm	0.25 mm
Radial depth of cut (a_e)	6.6 mm	0.25 mm

For the MIRS measurements, the Incremental Hole Drilling (IHD) method works was used by drilling holes to set depths in the workpiece after the machining process. Fig. 2 show the geometry and measurement locations of the two rectangular coupons that were machined separately using the roughing and finishing operations in the demonstrative part.

Fig. 3 and Fig. 4 show the residual stress plots up to a depth of 224 µm after the roughing and finishing trials for the coupons at the point 2 since at this region showed large stresses.

It was observed that the residual stress profiles between the transverse and longitudinal direction within the same test were similar with small variations in magnitude. It was also noted that the residual stress magnitudes were tensile and greater in the finished process than the roughing process. This increase could be down to increase of the cutting speed and feed in the finishing operation than the roughing operation.

It was also observed that the uncertainty from the measurements were large which could be from the material, the drilling process, the strain gauge used or the strain indicator as defined by the National Physical Laboratory good practice [7].

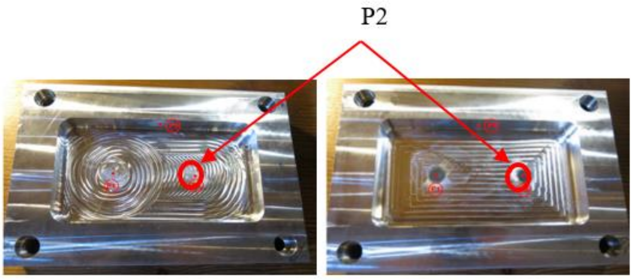

Fig. 2. Machining coupons: after roughing process; and after roughing and finishing process.

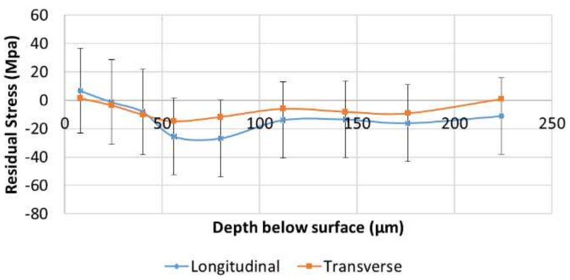

Fig. 3. MIRS measurement after roughing process from point location 2.

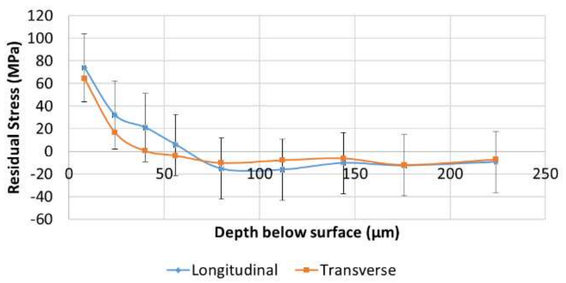

Fig. 4. MIRS measurements after finishing process from point location 2.

2.3. Part demonstrator machining

A representative ribbed component with nine pockets was machined as shown in Fig. 5 to investigate the distortions caused due to the coupling effect of bulk and induced machining stresses as per the cutting parameters in Table 1. The chosen pocketing machining order (3, 2, 6, 4, 5, 1, 7, & 8) for the material removal is also illustrated in the same Fig. 5.

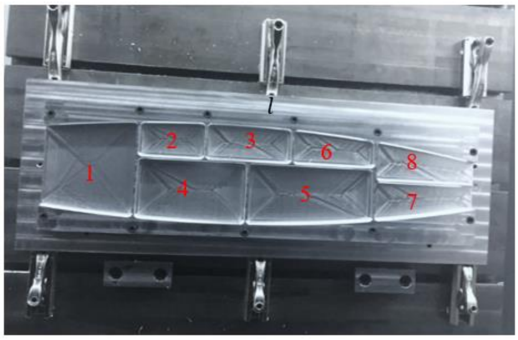

Fig. 5. Representative ribbed component.

3. Methodology for modelling

In this research, a hybrid model has been implemented to predict the effect of the induced and bulk residual stresses on the machining distortion. The simulation consisted in the application of experimentally measured stresses, which were interpolated in a Finite Element (FE) model. The FE software that was used for this study was DEFORM 3D V11.1 due to its proven use for the prediction of machining distortions in aluminium alloys as presented by Bilkhu et al (2019) [1]. DEFORM has also been found to have greater flexibility when it comes to importing or editing material properties and interpolation of data when compared to other FE methods.

The simulation was carried out as follows for bulk residual stresses: Interpolation of the bulk residual stresses from the contour method onto a 2D FE model; extrusion of 2D FE model into a 3D FE model to carry out the machining distortion simulations.

The methodology of the simulation steps of the machining process done on a pocket by pocket basis as follows: application of contact interaction between the fixture and workpiece simulation; Boolean operation to subtract the pocket geometry with the workpiece to replicate the pocketing sequence (Fig. 6 (a)); interpolation of machine induced residual stress on the floor and the wall (Fig. 6 (b)).

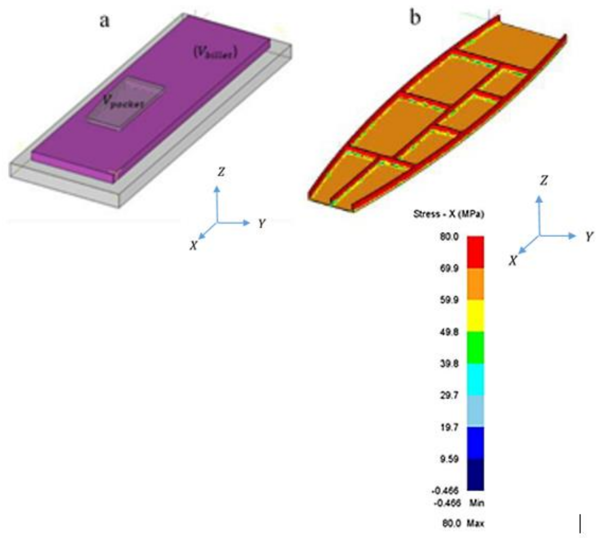

Fig. 6. Material removal set up: (a) Subtracted billet volume Interpolation of the Longitudinal MIRS on the pocket floor and wall; (b) demonstrator one, (c) demonstrator two.

4. Results

Post machining geometric inspection using CMM were performed at the locations shown in Fig. 7. The CMM was executed three times before and after machining on the demonstrator, and the repeatability were as follows: demonstrator one was 6 µm and 5 µm. Also the uncertainty of the CMM was approximately ± 6.8 µm at the maximum length of the specimen.

The influence of the bulk RS and the combination of the bulk RS with the MIRS on distortion, at measurement locations illustrated in Fig. 8. It can be seen that the magnitude and profile between the two profiles are different, emphasizing the importance of MIRS for machining distortion FE predictions.

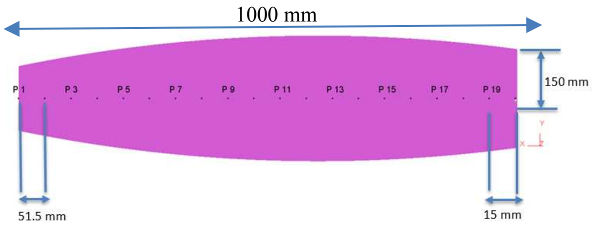

Fig. 7. CMM distortion measurement locations on pre and post machining in the part demonstrator (plan view)

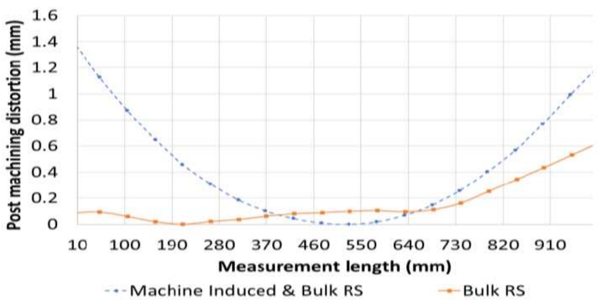

Fig. 8. Influence of residual stress on post machining distortion prediction.

The comparison of the FE model and the CMM results are shown in Fig. 9; it can be seen that the FE model predicts the trends in both parts, but with some variation in magnitudes. The difference may be attributed due to the: i) The clamping forces induced was not included in the model during the material removal simulation; ii) The lack of refined mesh during the last pocketing stages affecting the data interpolation (from the bulk and machine induced stresses) from the previous stage to the next stage; which would in turn affect the accuracy of the model.

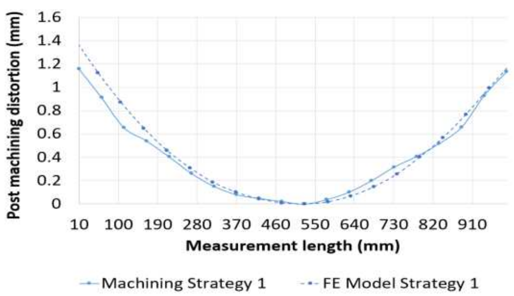

Fig. 9. Influence Post machining distortion prediction

5. Conclusions

Bulk residual stress measurements were made in billets of the same size of the demonstrator, which had an interpolation error to the FE model less than 8 % providing a good initial model for analysis of the distortion study. The MIRS was taken in a coupon level to characterize the induced stresses from a set of cutting parameters in roughing and finishing process, which were also successfully implemented by using interpolation techniques into a FE software. The distortion results of the hybrid FE model then were compared with the CMM distortion data of the demonstrative part; and it was found that the trend and the magnitude between them had a small difference of around 14 %. This demonstrated that the coupling technique of the FE interpolation of bulk and the MIRS was able to predict the distortion in a complex representative ribbed component using stress inputs from a small coupons.

Further work

To accurately determine the MIRS, repeat measurements would need to be performed to understand the repeatability and accuracy of these measurements. The determination of the MIRS analytically by calculating the thermal and cutting forces could be also be implemented in future work.

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