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Correcting distortions of thin-walled machined parts by machine hammer peening

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Abstract Thin-walled aerostructural components frequently get distorted after the machining process. Reworking to correct distortions or eventually rejecting parts significantly increases the cost. This paper proposes a new approach to correct distortions in thin-walled components by strategically applying hammer peening on target surfaces of a machined component. Aluminium alloy 7475-T7351 was chosen for this research. The study was divided in two stages. First, the residual stresses (RS) induced by four different pneumatic hammer peening conditions (modifying the step-over distance and initial offset) were characterised in a test coupon, and one of the conditions was selected for the next stage. In the second stage, a FEM model was used to predict distortions caused by machining in a representative workpiece. Then, the RS induced by hammer peening were included in an FEM model to define two hammer peening strategies (varying the coverage area) to analyse the capability to reduce distortions. Two workpieces were machined and then treated with the simulated hammer peening strategies for experimental validation. Results in the test coupon showed that pneumatic hammer peening can generate high compressive RS (-50 to -350 MPa) up to 800 μm depth, with their magnitude increasing with a reduced stepover distance. Application of hammer peening over 4 % of the surface of the representative workpiece reduced the machining-induced distortions by 37 %, and a coverage area of 100 % led to and overcorrection by a factor of five. This confirms that hammer peening can be strategically applied (in target areas and changing the percentage of coverage) to correct low or severe distortions.

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1. Introduction

Cost reduction for aircraft purchase and operation is essential in many airline companies, and aircraft manufacturers compete to meet those demands.¹ The use of high strength and

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damage tolerant alloys enables the design of thin-walled aeronautical monolithic components to manufacture lightweight aircrafts with higher fuel efficiency.² Aluminium alloys have been extensively used since the 1980s for those monolithic parts because of their high specific strength, low cost and good forming properties.¹ However, these thin-walled aluminium parts have low stiffness and can easily get distorted during the manufacturing process, where up to 90% of the material is removed by machining.³⁻⁴ These distortions can induce important misalignment and tolerance issues,⁵ and consequently affect the assembly process and induce a pre-stresses assembly state that influences the functional performance of the structural components.⁶ To avoid this scenario, aircraft manufacturers establish tight tolerances, and out-of-tolerance distortions require correction processes which increase the cost of the component or eventually lead to a rejection of the part. For example, a study conducted by Boeing regarding the information on manufacturing of four different aeroplanes, estimated that scrap and rework of distorted machined parts cost the company over 290 million dollars.⁷ In this context, significant research studies have been conducted over the last 20 years to understand the causes of distortions and develop approaches to reduce part distortions.

Part distortion is defined as the form deviation of the shape of the final component with respect to the designed component once it has been released from the clamping system.² Particularly, the initial bulk residual stresses of the material induced in the preceding processes (IBRS) and the machining-induced residual stresses (MIRS) are the main factors affecting the distortions of thin-walled aluminium components.^{3,8} There is a general agreement that IBRS cause distortions when removing the material. The distortion is mainly generated by the release of the IBRS that remain inside the material rather than the removed material.⁹ The effect of MIRS is more relevant when wall thickness is below 5 mm¹⁰ and the magnitude of IBRS is low.¹¹ The influence of MIRS on component distortion depends on their sign, magnitude and the position of the machined surface with respect to the centroidal axis of the part.¹² Furthermore, shear residual stresses induced by machining are crucial since they can lead to torsional deformations significantly affecting the shape and magnitude of geometrical deviations of the component.¹¹ Consequently, controlling the magnitude and distribution of the IBRS and MIRS is the main approach to minimise the distortion of large aluminium parts.⁴

The most popular strategy to minimise distortions is to find an optimum position of the parts in the initial raw material using analytical, finite element model (FEM) or machine learning models. Chantzis et al.¹³ proposed a workflow that consists of characterisation of IBRS and optimisation of the part location in the bulk material through numerical modelling. Zhang et al.¹⁴ determined by FEM, and proved experimentally, the optimum position for T-shaped workpieces (12 mm high) within 30 mm thick 7050-T7451 blocks. Cerutti and Mocellin,¹⁵ only considering IBRS, found that an offset of 9 mm led to negligible distortions when machining a 68 mm thick ribbed aluminium AIRWARE 2050-T84 part from an initial workpiece of 90 mm thickness. Barcenas et al.¹⁶ also determined by FEM the optimum offset to prevent distortions of aluminium 7050 workpieces with high and low IBRS, but the effect of MIRS was not addressed in this work. Interestingly, Rodriguez-Sanchez et al.¹⁷ used Artificial Neural

Networks (ANN) that include IBRS to predict aluminium 7050-T7451 part distortion and optimum part location, leading to a reduction of 80% in a part representative of aeronautical components. The approach that finds the optimum position within the initial plate can be quite useful to minimise part distortions when IBRS are the main/only source and the initial plates are much thicker than the final part. However, the initial cost of thicker plates is higher, and energy consumption and machining time will also increase.¹⁸ Therefore, thickness of initial plates are minimised in industry to meet cost reduction demands and consequently do not have sufficient space to find an optimum part position that brings the final part into tolerance.¹⁹

With material cost considerations in mind, an alternative to minimise part distortions is to control the effect of MIRS by changing machining conditions or the tool path strategy. Denkena et al.²⁰ side-milled two different workpieces of Al 7449-T651 (400 mm × 400 mm × 76 mm initial dimensions) and found the lowest part distortions when machining at the highest cutting speed. Li et al.²¹ observed that the accuracy of thin-walled part is improved by controlling the depth of cut of the successive passes, which redistributes the residual stresses. They found that a reduction of the depth of cut minimises the MIRS that cause distortions. However, a severe reduction of the depth of cut dramatically reduces productivity. Madariaga et al.¹² employed FEM that includes IBRS and MIRS to analyse distortions in an inverted T-shaped 7175-T7351 aluminium part. They demonstrated that by strategically applying the MIRS located in the flange and web of the part, distortions could be reduced up to 40%. However, deeper and higher residual stresses than MIRS would be necessary to fully correct the distortion. In a recent work, Weber et al.²² changed the machining strategy from zig-zag to spiral and minimised the distortions of aluminium AA7050-T7451 parts by 50%-69% depending on the thickness of the part. The shear stresses induced by machining in the spiral strategy are self-balanced and its effect on distortions is minimised. Dong and Ke²³ developed a FEM model that considers the tool path, machining loads and initial residual stresses. This model could be used to define the optimum path and machining conditions, but the model is limited for single tooth cutting. Later, Denkena et al.²⁴ proposed a FEM model that takes into account the tool movements and different residual stress depth profiles for specific tool-process combinations. The model was used to change the tool path of the milling process by the inverted shape of the predicted distortion, so that distortions of the machined component were compensated. Weber et al.²² used the same approach to reduce by 77% the distortions of an aluminium component with high IBRS since the efficiency of controlling MIRS is lower in the presence of high IBRS. However, they highlighted that the contouring process for the inverted part is time consuming.

Despite some research successes in controlling the distortions induced by machining thin-walled components, these are not fully implemented in industry and corrective processes are still required. A range of post-processing strategies can be employed to improve the performance of machined components by modifying and enhancing the properties of the machining affected layer.²⁵ The most preferred method to correct distortions is the application of shot-peening since it does not induce tensile residual stresses.²⁶ It consists of gradually shot-peening a target area with controlled parameters to

flatten the component through several iterations. One of the main drawbacks is that the shot-peened surface is usually rough and requires smoothing to prevent fatigue failures from initiating at the surface. It also requires moving the distorted component from the machine tool to the shot-peening equipment. Beyond this context, Machine Hammer Peening (MHP) with guided tools is gaining more importance in industrial applications.²⁷ Interestingly, MHP can be applied in the same machine that is used to machine the thin-walled part. During continuous contact machine hammer peening process, the tool is initially moved down to contact the surface of the part, and then it moves in the main direction and impacts the surface with a hammering frequency. Unfortunately, there are few works analysing the effect of MHP on the properties of the treated surface in aluminium alloys. Lin et al.²⁸ showed that piezoelectric machine hammer peening can produce smooth surfaces ($R_a < 0.4 \mu\text{m}$) with increased hardness in 6016 anodized aluminium alloy. More recently, the authors of this paper²⁹ demonstrated that pneumatic hammer peening can induce significant compressive residual stresses (up to -350 MPa) within $\approx 0.8 \text{ mm}$ depth and produce smooth surfaces ($R_a < 0.3 \mu\text{m}$) in aerospace aluminium alloy A7050-T7451. Therefore, it seems to be a suitable approach to replace shot-peening to correct distortions of thin-walled aluminium parts, even in the presence of high IBRS. Furthermore, pneumatic hammer peening equipment has a low cost ($< 1/10$) compared to piezoelectric hammer peening tools, and the technology could be accessible for small/medium companies too. To the best of authors knowledge, there is no published work that proposes the application of machine hammer peening to correct distortions caused by machining in thin-walled parts.

This paper is aimed at studying the feasibility of machine hammer peening process to correct distortions caused by machining in thin-walled parts. The aluminium alloy 7475-T7351 was chosen for this research. The study was divided in two stages. First, the residual stresses induced by four different pneumatic hammer peening conditions were characterised by the hole-drilling technique, and one of the conditions was selected for the next stage. In the second stage, the BIRS of the workpiece were characterised employing the slitting method. These were implemented in a FEM model to predict distortions caused by machining in a representative workpiece. Then, the residual stresses induced by hammer peening were included in the FEM model to define two hammer peening strategies (varying the coverage area) to analyse the capability of hammer peening to reduce distortions. Two workpieces were machined and then treated with the simulated hammer peening strategies for experimental validation. The distortions were measured in a Coordinate Measuring Machine (CMM).

2. Fundamentals of continuous contact machine hammer peening

Fig. 1 shows schematics of the Continuous Contact Machine Hammer Peening (CCMHP) process and the experimental set-up used in this work. To ensure the continuous contact between the head of the machine hammer peening tool (usually a sphere of diameter d) and the workpiece, the tool is initially moved down a distance z_0 (initial offset) into the surface. During the surface treatment, the head of tool advances in the desired direction at feed of v and impacts the surface of the

workpiece with a $f = \Omega/2\pi$ hammering frequency (Fig. 1(a)). To cover the target surface, the tool describes successive linear or curved tool paths, which are separated by a stepover distance s as shown in Fig. 1(b).

Each impact generates an indentation which features depend on the energy of the impact and the elastoplastic properties of the materials in contact. The distance between two successive indentations in the main motion direction depends on the feed rate and hammering frequency: $\lambda = v/f$. When the head of the tool impacts the surface, contact forces are induced which deform the material below the surface as shown in Fig. 1(c). If deformations cause yielding, compressive residual stresses are generated in the hammer peening affected layer. Note, although contact forces are predominant in the continuous contact machine hammer peening process, friction forces are also generated against the main motion direction.

3. New approach: Correcting distortions by Machine hammer peening

Machine hammer peening processes induce compressive residual stresses beneath the surface. Because of the compressive residual stresses generated in the surface layer, the part bends to balance the disequilibrium caused by compressive residual stresses. Therefore, if the link between the compressive residual stresses and balanced part deformation is understood, compressive residual stresses could be applied to a surface to shape or correct the distortion of the part.

The fundamentals of the distortions caused by residual stresses locked in surface layers in simple geometries were described in Literature.¹² Fig. 2 shows schematically the effect of these residual stresses on part distortion. It must be clarified that the drawing is not scaled. The surface layer i (grey area in Fig. 2) is affected by compressive residual stresses $\sigma_{RS,xi}$ induced by hammer peening, which are perpendicular to the cross section of the layer. The resultant force of the residual stress profile R_{xi} can be calculated using Eq. (1), where dA_i is a differential area of the cross section of the surface layer. The position of the resultant force with respect to the local axis system is given by Eq. (2), where n_i is the local axis perpendicular to the mechanically treated surface with its origin at the surface. The position of the resultant force in the global coordinate system is defined by z_j and can be determined employing Eq. (2) and Eq. (3) respectively. The position of the centroidal axis of the part is defined by z_c . The resultant force of the compressive residual stresses generates a bending moment M_{yi} on the right side of the cross section as shown in Fig. 2, which can be determined using Eq. (4). This bending moment causes a disequilibrium and as a result, the part is bent with a radius of curvature ρ in the opposite direction to restore the balance. For beams, the radius of curvature ρ can be determined using Eq. (5), where E is the Young's modulus of the material and I_{yy} is the second moment of area of the cross section of the part with respect to y (bending axis).

$$R_{xi} = \int \sigma_{RS,xi} dA_i \quad (1)$$

$$n_{ci} = \frac{\int \sigma_{RS,xi} n_i dA_i}{\int \sigma_{RS,xi} dA_i} \quad (2)$$

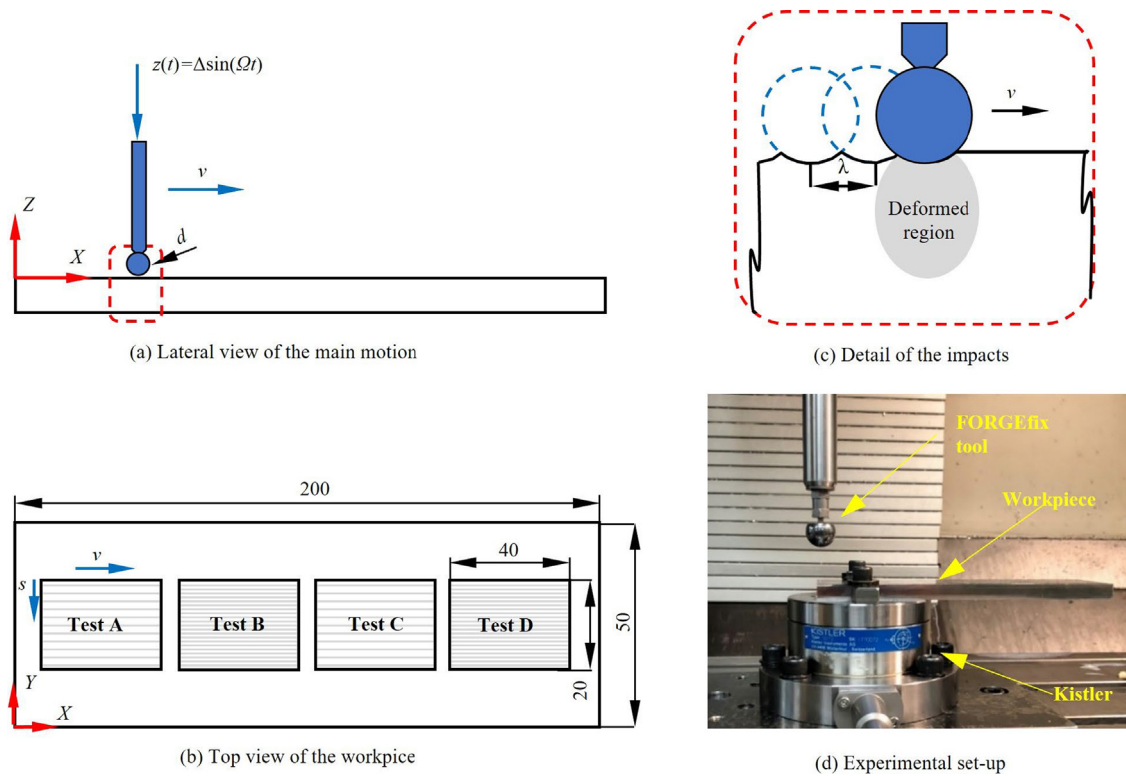


Fig. 1 Scheme of continuous contact machine hammer peening process and experimental set-up.²⁹

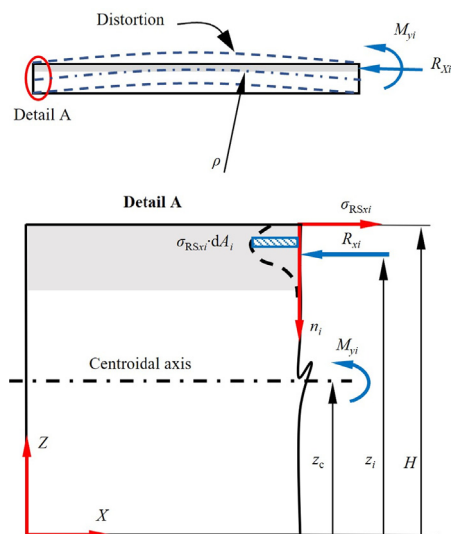


Fig. 2 Schematic description of distortions caused by compressive residual stresses locked in surface layer.¹²

$$Z_i = H - n_{ci} \quad (3)$$

$$M_{yi} = R_{xi}(Z_i - Z_c) \quad (4)$$

$$\frac{1}{\rho} = \frac{M_y}{EI_{yy}} \quad (5)$$

The shape and magnitude of the distortion caused by hammer peening fundamentally depend on the magnitude of compressive residual stresses, the dimensions and position of the

peened surface, and the bending stiffness of the part (inversely proportional to EI_{yy}). Thus, if we can measure or predict the distortions after machining a thin-walled part, we could apply hammer peening to target surfaces to generate the counter-shape of the distortion. As a result, the final geometry will have reduced distortions. Fig. 3 shows an example of the concept of the proposed innovative approach. At the first step the raw material has initial residual stresses generated in the preceding manufacturing step (usually rolling + heat treatment). During machining, these initial residual stresses will be relaxed, and surface residual stresses will be generated by the cutting processes. Consequently, the part will reach a new stress state and will be distorted as shown in the second step. As explained in the previous paragraph, the compressive residual stresses generated by hammer peening produce a radius of curvature ρ in the treated surface. To correct the distortions caused by machining, hammer peening should be applied to the bent surfaces as can be seen in the third step, while the surfaces that are not treated will be kept undeformed. It should be clarified that the third step of Fig. 3 only shows the effect of hammer peening. Ideally, the distortions generated by machining will be counterbalanced by the distortions generated by hammer peening and as result, the final geometry will be free of distortions, as shown in the fourth step.

4. Materials and experiments

4.1. Material

The specimens used in this study were extracted by water jet assisted machining from a 40 mm thick aluminium 7475-

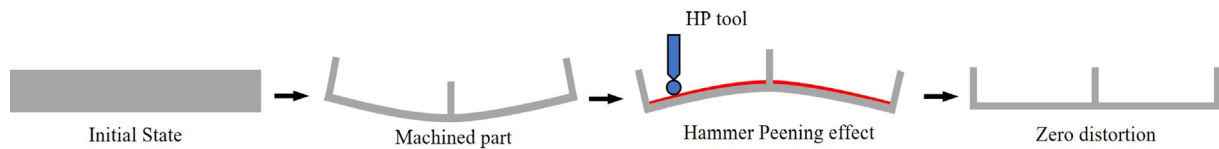


Fig. 3 Concept of manufacturing process to correct distortions by strategically applied hammer peening (HP) processes.

T7351 plate. The mechanical properties of the raw material at room temperature in both rolling and transverse direction were determined by standard tensile tests. Table 1 shows the Young Modulus (E), yield stress (σ_y), ultimate strength (σ_u) and maximum elongation (ΔL) of the aluminium 7475-T7351 plate. These mechanical properties are similar in both rolling and transverse direction.

As described in the introduction, two types of experiments were performed in this work: i) a test coupon to analyse the effect of hammer peening on residual stresses; and ii) the implementation of hammer peening to correct machining-induced distortions in a representative workpiece. To perform those experiments, different type of specimens and methods were used, and they will be explained separately in the following subsections.

4.2. Experiment I: Effect of hammer peening on residual stresses

A 200 mm long, 50 mm wide and 10 mm thick coupon was extracted from the plate to analyse the effect of hammer peening on residual stresses. The longest side of the specimen was parallel to the rolling direction of the original aluminium plate. Before the hammer peening tests, the upper and lower surfaces of the specimen were face milled in the CNC machine using an indexable face milling cutter with a diameter of 40 mm with four uncoated inserts. To avoid the generation of significant machining-induced residual stresses, the specimens were face milled at a cutting speed $v_c = 980$ m/min, feed per tooth $f_z = 0.08$ mm/tooth and depth of cut $a_p = 1.5$ mm, using a Minimum Quantity of Lubricant (MQL) supply.

Then, hammer peening tests were done in a CNC Kondia B1050 machine. For that purpose, a FORGEfix pneumatic hammer peening tool was fixed in the tool holder of the CNC machine. A total of four different hammer peening conditions were tested as depicted in Fig. 1b. The path of the hammer peening process was the following: i) the tool was moved down an initial offset (z_0), ii) then the tool advanced from the left to the right at feed v , iii) when reaching the end of the path, the tool was raised and moved back to the left position and iv) finally, the process was repeated after displacing by the stepover distance (s). Table 2 summarises the parameters of the hammer peening conditions. The stepover distance and initial offset were varied in the tests. By contrast, the feed, hammer-

ing frequency ($f \approx 250$ Hz), the diameter of the cemented carbide indenter ($d = 20$ mm) and the air supply (≈ 6 bar) were not modified. The specimen was fixed to a triaxial sensor Kistler dynamometer (9272) to measure the forces generated by the four hammer peening conditions in three orthogonal directions. The set-up used in these experiments can be seen in Fig. 1d.

The residual stresses generated by the face milling process and hammer peening tests were measured employing the hole drilling technique, following the procedure given in the ASTM-E357 standard. To accurately plot the variations of residual stresses near the surface, the fine increment hole drilling procedure developed by Grant et al.³⁰ was followed. Two types of target strain gauges supplied by Vishay Measurement Group were bonded in the centre of the treated surfaces. The surfaces were prepared for gauge installation following the instructions of the gauge supplier. The smallest EA-06-031RE-120 strain gauge was used to measure machining-induced residual stresses since they reach shallower depths than residual stresses induced by hammer peening. The largest strain gauge CEA-062UL-120 was employed to characterise the residual stresses generated by hammer peening. The tests were done using a Restan MTS3000 machine, employing a high speed air turbine and drill bits of 0.8 mm diameter for the EA-06-031RE-120 strain gauge and of 1.6 mm for the CEA-062UL-120 strain gauge respectively. The drill bit was aligned with the gauge before drilling the hole. The zero depth was identified by electrical contact between the drill bit and the workpiece surface. Then, the incremental hole drilling procedure was carried out at each gauge employing a total of 15 depth increments. For the EA-06-031RE-120 strain gauge we used: five initial increments of 10 μm , the next five increments were of 20 μm , and the final five increments had a depth of 50 μm . This sequence of increments produced a hole with a ≈ 0.9 mm diameter and a depth of 500 μm . For the CEA-062UL-120 strain gauges, larger increments were used: five initial increments of 20 μm , the next six increments were of 50 μm , and the final four increments had a depth of 100 μm . This produced a hole with a ≈ 1.8 mm diameter and a depth of 800 μm . Strains were acquired in a HBM data acquisition system after each increment. Finally, the residual stress profiles were determined by the procedure described in the ASTM-E357.

4.3. Experiment II: Implementation of hammer peening to correct machining-induced distortions in representative workpieces

This experiment aims assessing the implementation of hammer peening to correct machining-induced distortions. To conduct this analysis two representative workpieces of 400 mm long, 100 mm wide and 40 mm thick were cut out from the plate.

Table 1 Mechanical properties of 7475-T7351 aluminium plate.

Direction	E (GPa)	σ_y (MPa)	σ_u (MPa)	ΔL (%)
Rolling	74.2	427	530	9.5
Transverse	74.0	431	534	10.1

Table 2 Hammer peening parameters.

Test	$v(\text{m}\cdot\text{min}^{-1})$	$s(\text{mm})$	$z_o(\text{mm})$	$d(\text{mm})$	$f(\text{Hz})$
A	5	0.35	0.3	20	≈ 250
B	5	0.07	0.3	20	≈ 250
C	5	0.35	0.5	20	≈ 250
D	5	0.07	0.5	20	≈ 250

Table 3 Face milling conditions.

Operation	$v_c(\text{m}\cdot\text{min}^{-1})$	$f_z(\text{mm}/\text{tooth})$	$a_p(\text{mm})$	Coolant
Roughing	300	0.2	12	MQL
Finishing	400	0.2	1	MQL

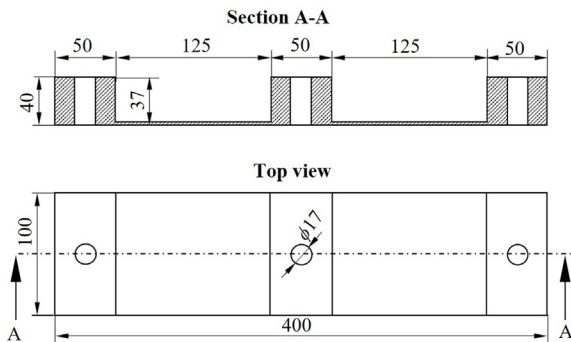
Table 4 Properties of uniKENAL 4302.60 tool.

Material	Diameter (mm)	Cutting length(mm)	Edge radius (mm)	Cutting edges(qty)
Uncoated, WC-Co	20	38	2.5	3

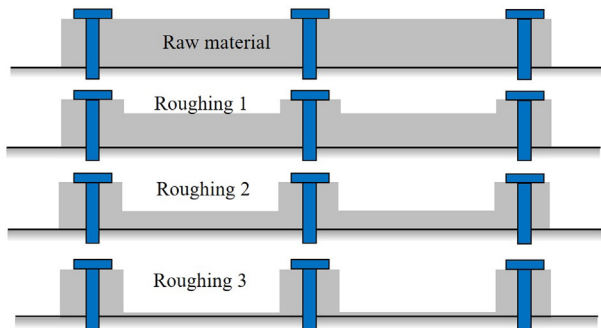
The longest side of the workpieces was aligned to the rolling direction of the plate. Those workpieces were initially slot milled in the CNC Kondia B1050 machine to obtain the final parts with the geometry shown in Fig. 4(a). The flow diagram of the machining process followed to generate the final parts is shown in Fig. 4(b). It consisted of three roughing passes and the finishing step, which is not included in Fig. 4(b) for simplicity. The workpiece was fixed with three screws. The conditions of the slot milling process and the properties of the uniKENAL 4302.60 tool of 20 mm diameter used in the machining can be seen in Table 3 and Table 4 respectively. The roughing passes used a cutting speed $v_c = 300$ m/min, feed per tooth $f_z = 0.2$ mm/tooth and depth of cut $a_p = 12$ mm. The cutting speed was increased up to 400 m/min in the finishing tests, while the depth of cut was reduced to 1 mm. All the face

milling passes used MQL supply. Finally, the distortions were measured in a Mitutoyo Crysta-Apex S 7106 CMM.

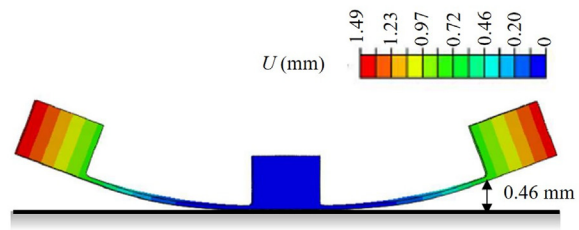
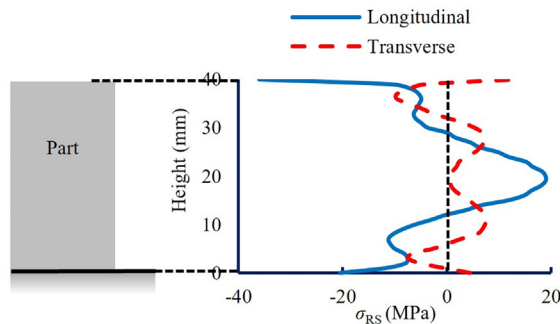
Simulations can be useful to predict distortions and take measures to minimise them. This is relevant for the proposed approach because if machining-induced distortions are correctly predicted, then the appropriate hammer peening strategy can be defined. For this reason, the distortion caused by machining in this case study was predicted by Finite Element



(a) Geometry of the workpiece



(b) Flow diagram of the machining process, and images of the initial and final workpiece



(c) Bulk residual stresses and predicted distortion of the machined part

Fig. 4 Geometry of workpiece, flow diagram of machining process, bulk residual stresses used in simulations and predicted distortion of machined part.

Modelling (FEM). The model used in this study follows the simulation strategy developed by Denkena and Dreier.³¹ This strategy consists of three main steps: i) introduction of bulk residual stresses in the initial workpiece, ii) deletion of the material removed during the machining process and, iii) adding the residual stresses induced by machining in the finished surfaces. For that purpose, the commercial Abaqus Standard software was employed. The Young's modulus of the 7475-T7351 aluminium was 74 GPa and the Poisson's ratio 0.33. The part was meshed using C3D8R type elements with a global nodal distance of 1 mm. The measurement of the distortions depends on the boundary conditions. In this case, contact was defined between the part and the flat surface (emulating the CMM measurement table) as can be seen in Fig. 4c.

In the first step of the simulation the bulk residual stresses of the original material were assigned to the workpiece employing the user-defined subroutine SIGINI in all active elements as function of coordinates, assuming a homogenous distribution throughout the workpiece. The bulk residual stresses are shown in Fig. 4(c). These were determined using the Slitting Method,³² following the experimental procedure in.³³ To characterise the bulk residual stresses 30 mm × 40 mm × 400 mm specimens with their longest side aligned with the rolling and transverse directions were extracted from the plate. In each specimen, a CEA-06-125UN-350 strain gauge from Vishay was glued and then coated at the opposite face of the slitting line. Then, the specimens were placed into a wire-EDM machine. The deforma-

tions were acquired during slitting of the specimens using a total of 38 increments of 1 mm. Finally, the strains were analysed in Matlab using the series expansion inverse approach³⁴ to determine the bulk residual stresses in both the longitudinal and transverse direction. Conservative estimates of the uncertainties on the measured stresses³⁵⁻³⁶ gave values of about ± 2–5 MPa, which are quite good considering the low stress magnitudes.

In the second step of the simulation, the elements corresponding to the machined section were removed using the MODEL CHANGE, REMOVE interaction. Finally, the machining-induced stresses should be added in the third step. In this study, they were not added in the model since their magnitude was low (< 50 MPa and within 100 μm depth), and their effect can be neglected. The simulation predicted a vertical displacement of 0.46 mm within the thinnest region of the part, as shown in Fig. 4(c).

Prior to performing the machine hammer peening tests to correct the distortions caused by machining, a series of FEM simulations were conducted. The results obtained in the test coupon (experiment I) will be explained in section 4, but the four hammer peening conditions led to similar residual stress profiles. The conditions used in Test A ($z_0 = 0.3$ mm and $s = 0.35$ mm) were selected because of higher productivity while introducing significant residual stresses. Subsequently a series of simulations were done in Abaqus to find the most effective hammer peening strategies. Fig. 5(a) shows the models of the two selected hammer peening strategies, with a cov-

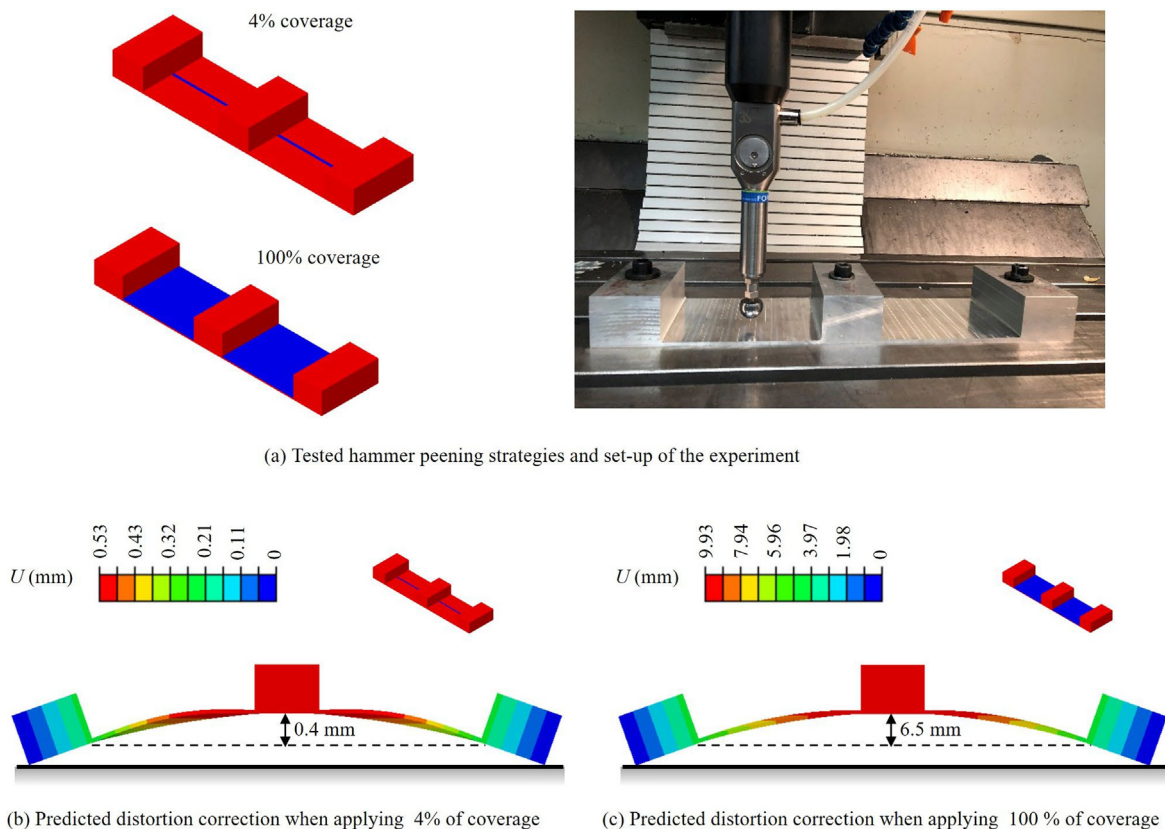
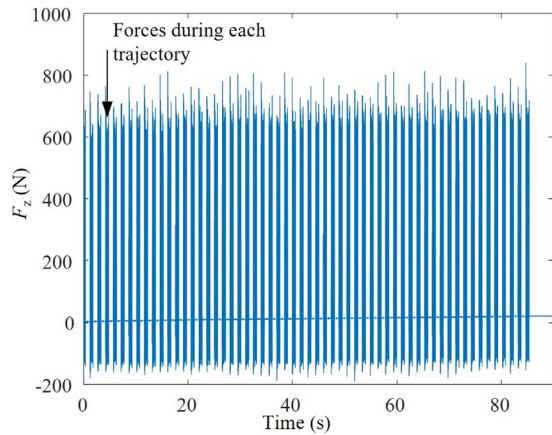
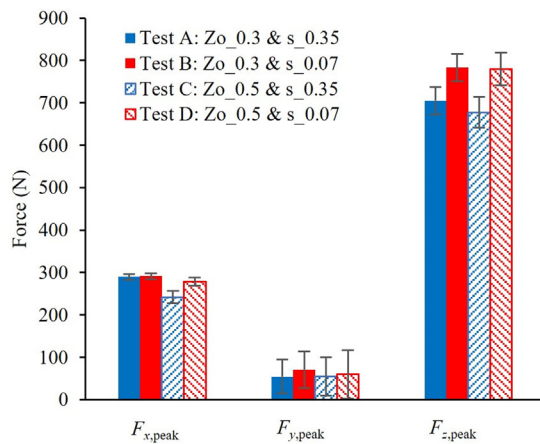


Fig. 5 Tested hammer peening strategies, set-up of experiment and predicted maximum distortion for different strategies (deformations are not represented in the same scale).



(a) Forces induced in z direction during hammer peening when applying a feed of 5 m/min, a stepover distance of 0.35 mm and an initial offset of 0.3 mm



(b) Peak forces measured in the hammer peening tests of the coupon

Fig. 6 Example of forces induced in z direction vs process time, and peak forces measured in tests of coupon.

erage area of 4% and 100% respectively. The model consisted of the geometry of the final part and it was meshed with a general element size of 0.5 mm. The mechanical properties were

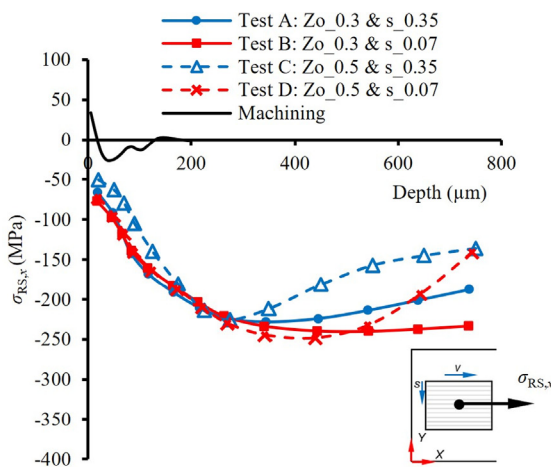
identical to the preceding model. To quantify the amount of distortion that hammer peening can correct, in the selected surfaces (blue colour) the residual stresses induced by Test A were averaged within a layer of 1 mm thickness. Fig. 5(b) shows the predicted results of both selected conditions. As mentioned above, due to the bulk stresses relief during machining, a distortion of 0.46 mm was predicted. If a coverage of only 4% is applied, the predicted correction was 0.4 mm in the same region of the part, and thus the final distortion should be almost negligible. To explore the capability of hammer peening to correct severe distortions, a coverage of 100% was chosen for the second model. This strategy will potentially correct a maximum distortion of 6.5 mm as can be seen in Fig. 5(c).

One of the machined workpieces was treated with a coverage area of 4% since it would correct the distortion based on the results of the simulations. The second workpiece was treated with a coverage area of 100% to study the maximum distortion that could be corrected. The FORGEfix pneumatic hammer peening tool was fixed in the tool holder of the CNC Kondia B1050 machine to do those experiments (Fig. 5 (a)). A video of the process is shared in the Supplementary material (S1). After the hammer peening tests, the final distortions were measured in the CMM machine, Mitutoyo Crysta-Apex S 7106.

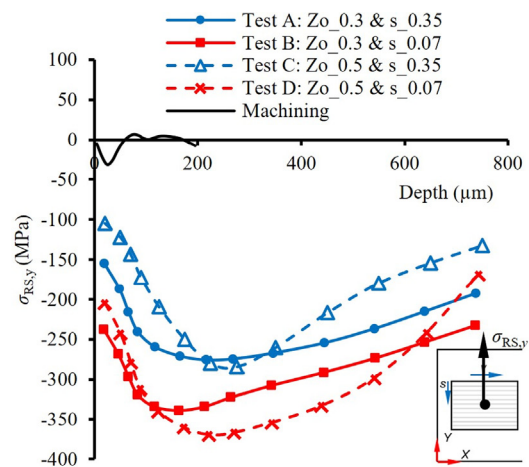
5. Experimental results

5.1. Hammer peening forces

The forces generated by hammer peening when impacting the surfaces were measured in the coupon test (experiment I). We initially studied the evolution of forces induced by hammer peening with respect to process time to verify the stability of the process. Fig. 6(a) shows the forces measured in the perpendicular direction to the surface (z) when applying a feed of 5 m/min, a stepover distance of 0.35 mm and an initial offset of 0.3 mm. Each segment of lines shows the forces induced during each trajectory. In all tested conditions, forces followed the same evolution and therefore it was confirmed that the process was stable.



(a) Residual stresses in the x direction (feed direction)



(b) Residual stresses in the y direction (stepover direction)

Fig. 7 Residual stresses induced by machining and hammer peening.

Fig. 6(b) shows the average of the peak forces in the feed direction (x), stepover direction (y) and perpendicular to the surface (z). As expected, the highest forces, ranging from 680 N to 780 N, were measured in the z direction, since it is directly related to the contact forces. The peak forces in the x direction varied from 240 N to 290 N. The forces in the x direction were fundamentally a consequence of the friction between the tool and workpiece in the main sliding motion. The forces in the stepover motion (y), were very low (below 100 N).

The effect of the initial offset z_o on the average of the peak forces was not significant for the tested conditions. However, the changes in the stepover distance affected the impact forces in the z direction. A reduction of the stepover distance from 0.35 mm to 0.07 mm caused an increase of 11% when using $z_o = 0.3$ mm and of 15% when using $z_o = 0.5$ mm. In fact, each impact plastically deforms and hardens the surface layer and when reducing the stepover distance the tool impacts more times on the hardened surfaces. As a result, contact forces increase when using lower stepover distances. The influence of the stepover distance on the forces in the x and y direction was not significant. Variations were within the uncertainty range.

5.2. Residual stresses induced by hammer peening

Fig. 7. depicts the residual stresses induced by the face milling process and hammer peening tests. It clearly shows that the selected machining conditions generated much lower residual stresses and thinner affected layer than the hammer peening tests. Therefore, the effect of machining-induced residual stresses on the final residual stress generated by the hammer peening tests could be disregarded.

All the hammer peening test produced compressive residual stresses in both the x direction (feed motion) and the y direction (stepover motion) reaching a depth >800 μm , fundamentally as consequence of plastic deformation from the highly localised contact forces. This can be interesting not only for the proposal of this work (to control distortions), but also to improve the fatigue strength or corrosion behaviour of structural components made by aluminium 7475-T7351. In fact, the magnitude and depth of residual stresses induced by hammer peening were comparable (or even more compressive) to those induced by laser shock peening in aluminium 7075-T7351 leading to a high cycle fatigue strength increase of 20%.³⁷ Compressive residual stresses were the lowest near the surface, around -60 MPa in the x direction and ranging from -100 to -240 MPa in the y direction. The maximum compressive residual stress peak in the x direction was located at a depth of 300 to 450 μm , with a value of ≈ 250 MPa in all cases. The maximum compressive peak was even more compressive in the y direction and its value increased up to -375 MPa (87% of the yield stress of the raw material) for the lower stepover distance. However, the position of the maximum compressive peak was closer to the surface than in the x direction. The shear residual stresses ($\tau_{RS,xy}$) generated by hammer peening, not shown here, were below 20 MPa near the surface, which demonstrates that x and y are almost the principal stress directions.

The magnitude and depth of residual stresses induced by hammer peening in aluminium 7475-T7351 tested in this study,

and those generated in aluminium 7050-T7351 in our previous study²⁹ were similar. In general, the differences in magnitude of residual stresses were below ~ 50 MPa. Both alloys were solution treated and artificially aged, leading to comparable mechanical properties (yield stress and rupture stress) which explains that similar residual stress fields were induced in both alloys when using identical hammer peening conditions. This finding suggests that hammer peening conditions used in this study will induce similar residual stress fields in solution treated and artificially aged 7000 series aluminium alloys.

5.3. Distortions caused by machining and hammer peening

Fig. 8 compares the distortions (vertical displacement) of the two representative workpieces after machining and applying the two hammer peening strategies. The FEM simulation of the machining process predicted a convex shape of the final part and a maximum distortion of 0.46 mm in the thinnest region of the part ($x = 50$ mm to 350 mm). The experimental measurements of both machined parts showed similar shapes, with a vertical displacement of 0.48 mm in the case of Machining I and 0.38 mm in Machining II, within the region $x = 50$ mm to 350 mm. Thus, the model predicted the distortion with an error below 20%. The application of hammer peening with a coverage of 4% only led to a correction of 0.17 mm (37% of correction), while the simulation predicted a correction of 0.4 mm. Interestingly, hammer peening showed the capability of correcting distortions up to 2.4 mm (522% of correction) when applying 100% of coverage, but this was overestimated by the predictions (6.5 mm). It should be noted that the latter results have not been included in Fig. 8 because they would require a larger scale, which would hinder interpretation of machining distortions and the small distortion correction when applying a coverage of 4%.

6. Discussion

The discussion is divided into three subsections. First, the relationship between the residual stresses generated by hammer peening and the forces is described. In the second subsection, the differences between predicted distortions and experimentally measured distortion are discussed and completed with a further analysis. The third subsection is aimed at providing guidelines for engineers and discusses the effect of thickness, width and length on the distortions corrected by machine hammer peening.

6.1. Effect of hammer peening parameters on residual stresses

The effect of process parameters on the residual stresses generated in the x direction (feed motion) was not significant. However, a reduction of the stepover distance caused more compressive surface and subsurface residual stresses (around 100 MPa for both initial offsets) in the y direction, as shown in Fig. 7. Correspondingly, the contact force F_z was $\approx 10\%$ higher when using the lowest stepover distance $s = 0.07$ mm than when employing $s = 0.35$ mm, which could lead to higher deformations and as a result, more compressive residual stresses. Nevertheless, the increase of F_z should have affected in both x and y direction, and the results clearly show that variations are more significant in y direction. This implies that

some other mechanisms related to the stepover distance s are relevant.

Considering that the contact force $F_z \gg F_x$ and F_y , we can assume that the main mechanism involved in the generation of subsurface residual stresses is the Hertzian contact between the indenter of the tool and workpiece. The forces generated during sliding of the tool along the x direction could also contribute to the generation of residual stresses near the surface, but to a lower degree. Based on classical Hertzian Contact theory, if two elastic spheres of radii R_1 and R_2 are subjected to a contact force P , they have a circular contact area of radius a , that can be determined using Eq. (6).³⁸ E_m is the contact modulus and can be obtained using Eq. (7), where E_1 , ν_1 , E_2 and ν_2 are the Young modulus and Poisson ratio of spheres 1 and 2 respectively. R represents the reduced radius of curvature and can be calculated by Eq. (8). An ideal Hertzian contact produces a maximum pressure p_0 on the axis of symmetry, that can be determined by Eq. (9).

$$a = \left(\frac{3PR}{4E} \right)^{1/3} \quad (6)$$

$$\frac{1}{E_m} = \frac{1}{E_1} + \frac{1}{E_2} \quad (7)$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \quad (8)$$

$$p_0 = \frac{3P}{2\pi a^2} \quad (9)$$

In this study, we pressed a flat specimen, and therefore the reduced radius R is R_1 . Table 5 shows the radius a of the contact region and the maximum pressure p_0 in each impact, taking into account the maximum contact force F_z for each working condition (see Fig. 6). Therefore, the dimensions of the contact region were not significantly affected by the tested conditions, since it varies from $a = 0.44$ mm to 0.46 mm. The changes in the maximum pressure p_0 are also very little, with a maximum difference of 5%.

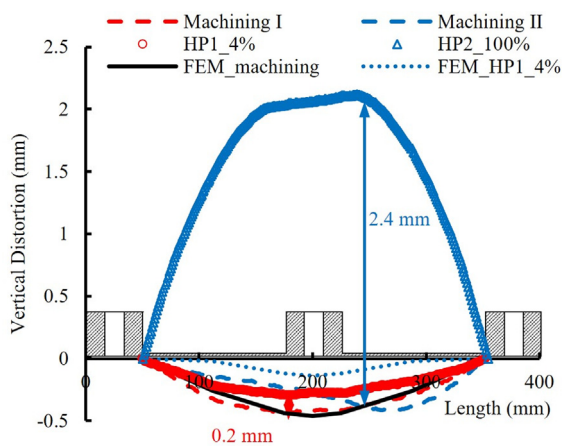


Fig. 8 Simulated and experimentally measured vertical distortion across length of parts after machining and applying two different hammer peening strategies, as well, as the amount of corrected distortion.

As explained in the methodology Section 4.2, residual stresses generated by hammer peening were measured using the hole-drilling technique, where a hole with a diameter of 1.8 mm was drilled. Therefore, residual stress measurements average the residual stress field generated by several impacts. The distance between successive impacts in the x direction is $\lambda = v/f$, approximately 0.33 mm in all tested conditions. This means that the region affected by an impact, will be impacted 2–3 times by the subsequent impacts since the circular contact region has a diameter of $2a = 0.9$ mm. Nevertheless, the distance between successive impacts in the y direction is defined by the stepover distance s . The maximum stepover distance $s = 0.35$ mm was similar to λ , and therefore similar residual stress fields were generated under those conditions (Test A and C) in both x and y directions. However, when reducing the stepover to 0.07 mm, the region affected by one impact, was later impacted by ≈ 12 impacts, which caused an accumulation of deformation in the y direction leading to more compressive residual stresses than in the x direction.

6.2. Correcting distortions by hammer peening

The results provided in Fig. 8 demonstrate that machine hammer peening can correct the distortions caused by machining in thin-walled parts. Unfortunately, the predictions overestimated by $\approx 50\%$ – 60% the correction of the distortion in both tested cases. The main hypothesis for this significant deviation is that the residual stresses induced by hammer peening in the representative workpiece differed compared to the test coupon. To verify this hypothesis the residual stresses induced by hammer peening in the final part were measured using the hole-drilling technique as described in Section 4.2.

Fig. 9(a) compares the residual stresses generated in the test coupon of Fig. 1(b) (Test A) and the representative workpiece of Fig. 4(a). The magnitude of maximum compressive residual stresses induced in Test A was almost 3 times higher and reached higher depths than in the representative workpiece, confirming the hypothesis. These differences are a consequence of the clamping system and the stiffness of the specimen. In Test A, the specimen was smaller and thicker, and therefore stiffer than in the case study. Furthermore, the region to be treated (Zone A) was tightened to the Kistler dynamometer ensuring a high-quality contact. Consequently, the energy of the impacts was efficiently converted into deformation energy of the treated surface, leading to high compressive residual stresses. By contrast, the part from the case study was distorted after the machining process, and when clamping to the table with three screws (see Fig. 4), a perfect contact between the part and the table was not ensured. Thus, a percentage of the energy of the impacts elastically deformed the part, while the remaining caused the plastic deformation of the surface. This explains the lower efficiency of the hammer peening in the generation of compressive residual stresses in the case study and consequently a reduced correction of the distortion. This observation suggests that large thin-walled parts must be correctly clamped to the table (for instance using a vacuum system) to ensure the efficiency of the hammer peening process, since deformation response depends on the energy input introduced by peening.³⁹ It also suggests that a configuration of the test coupon to calibrate the residual stresses from the hammer

Table 5 Radius of circular contact region and maximum pressure in each impact.

Test	v ($m \cdot min^{-1}$)	s (mm)	z_o (mm)	a (mm)	p_o (MPa)
A	5	0.35	0.3	0.44	1702
B	5	0.07	0.3	0.46	1763
C	5	0.35	0.5	0.44	1679
D	5	0.07	0.5	0.46	1760

process must be carefully designed to precisely match the conditions seen by the real part.

Then, we adjusted the value of surface residual stresses induced by hammer peening and corrected the predictions of final distortions after applying hammer peening with 4% and 12% as shown in Fig. 9(b). This comparative confirms that predictions are accurate if correct values of residual stresses are assigned to the surface layer affected by machine hammer peening.

Finally, the results of the new measurement were used to recalculate the machine hammer peening strategy. Based on simulations (procedure described in 4.3), a 12% coverage area was now predicted to be optimal. It should be noted that this treatment with 12% coverage was applied to the workpiece that initially was treated at 4%. Fig. 10 compares the experimentally measured distortion after machining and final hammer peening treatment with a coverage of 12%, as well as the deformation predicted by the simulation. The correction of the distortion was improved to 0.25 mm from 0.17 mm with respect to the coverage of 4%. There is still a remaining distortion of 0.2 mm within the range $x = 50$ to 350 mm. The simulations with a coverage of 12% predicted a higher correction (0.5 mm) as shown in Fig. 10. The difference could be because: i) the residual stresses introduced by the hammer peening did not accurately represent the residual stress profile adjusted in preceding simulations (results shown in Fig. 9(b)), or ii) due to the uncertainty of the experimental process (the part was

unclamped and clamped several times and treated over the same process). Nevertheless, these results demonstrate that hammer peening could be strategically applied to correct distortions.

6.3. General guidelines

This paper has assessed the application of machine hammer peening to correct distortions caused by machining in thin-walled parts. The results suggest that same hammer peening conditions induce comparable residual stresses in aluminium alloys with similar mechanical properties. Therefore, the residual stress profile measured in this study could be used as reference when applying hammer peening to solution treated and artificially aged 7000 series aluminium alloys with mechanical properties comparable to alloy 7475-T7351.

The geometry of the workpiece was fixed and only the effect of coverage area and magnitude of residual stresses on distortions was studied. However, the thickness and length of real components affect their stiffness and therefore, corrected distortion can vary significantly depending on the geometry of the part for the same residual stress field induced by machine hammer peening. This subsection is aimed at giving some general guidelines to consider the effect of part thickness and length.

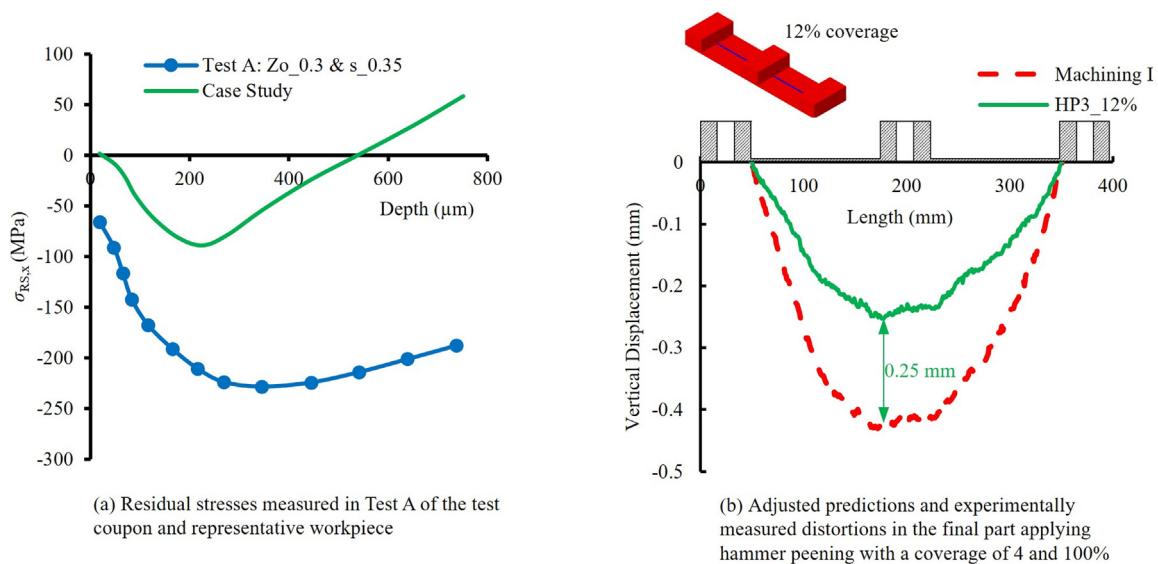


Fig. 9 Comparative of residual stresses measured in test coupon and representative workpiece (case study), and adjusted predictions and experimentally measured distortions in the final part applying hammer peening.

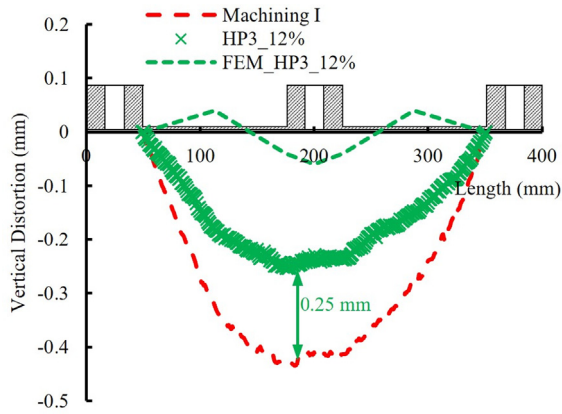


Fig. 10 Predicted and experimentally measured distortions in the final part after machining and applying hammer peening with a coverage of 12%.

Numerous thin-walled parts have two dimensions smaller than the third dimension, and therefore beam elasticity theory could be used to estimate shape corrections produced by machine hammer peening. As described in section 3, the effect of residual stresses induced by machine hammer peening on corrected distortions can be estimated by the bending moment M_y , which depends on the magnitude and depth of residual stresses, and the position of the surface layer with respect to the centroidal axis of the beam. This bending moment can be calculated using Eqs. (1) to (4). The curvature induced by the residual stresses also depends on Young’s modulus E of the material and the second moment of area of the cross section I_{yy} as defined in Eq. (5). However, the corrected curvature is independent of the length of the part. The thickness of the part affects both the value of the bending moment M_y , because the position of the surface layer with respect to the centroidal axis is changed, and the second moment of area I_{yy} .

Fig. 11(a) shows the effect of thickness on a 100 mm wide plate (same width of the case study). To calculate M_y , we used the adjusted values of residual stresses of the case study, and

we applied it for different percentages of coverage area. We modified the thickness from 1 mm to 6 mm, since these are representative of real aerostructural components. The curvature $1/\rho$ induced by machine hammer peening increases significantly when reducing the thickness below 2 mm. In fact, a reduction of the thickness dramatically reduces the second moment of area I_{yy} since they have a third-degree relationship, but this is slightly compensated because the bending moment M_y is linearly increased when increasing the thickness.

An increase in the length L of the beam, leads to a reduction of the stiffness of the part, and consequently for the same field of residual stresses induced by hammer peening the maximum displacement increases. Fig. 11(b) shows the effect of length on a simply supported beam subjected to a constant bending moment M_y caused by the residual stresses induced by machine hammer peening. The maximum displacement occurs in the centre of the beam and it is given by $\delta_{max} = 8M_y L^2 / (EI_{yy})$. The displacements were calculated for 100% coverage, in a 100 mm wide beam and different thickness.

In actual production bending deformation will undergo in multiple directions. This is even more relevant when the width is not negligible compared to the length (plate shape). The approach described in section 3 is equally valid for plates and similar equations can be found in Literature.⁴⁰ In order to define some guidelines regarding the effect of width as well as the hammer peening path on the distortions of plates, we conducted complementary simulations in 400 mm × 200 mm × 3 mm aluminium plate. In all simulated conditions we applied a coverage area of 25% using the adjusted residual stresses of this work, but five different hammer peening paths were tested. The results of the simulations are shown in Fig. 12. For the same magnitude of residual stresses and percentage of coverage, the shape of the deformed plate and its magnitude change. The magnitude of the corrected distortions and the gradient of the deformation is lower when applying hammer peening in the length direction (Cases I, III) than in the width direction (Case II, IV). If hammer peening is applied in two (or several) separated paths, the region between two paths will remain quite flat, but there will be a higher deformation from the direction of the path to the edge. Finally, if ham-

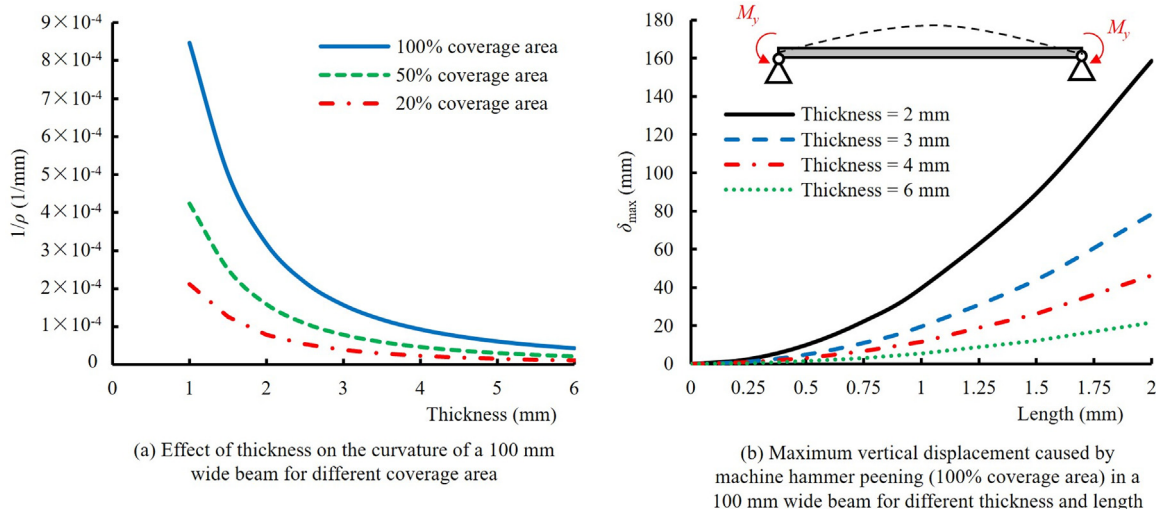


Fig. 11 Effect of thickness and length of a 100 wide beam on the curvature and maximum vertical displacement caused by machine hammer peening.

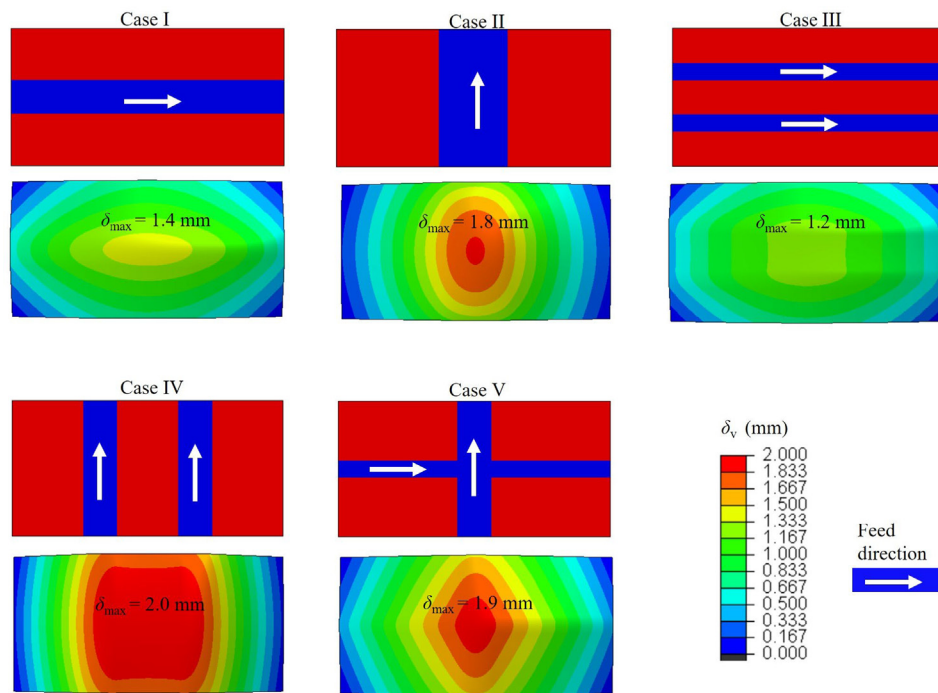


Fig. 12 Effect of different machine hammer peening strategies with a 25% coverage on the vertical distortion of a 400 mm × 200 mm × 3 mm aluminium plate (Hammer peening region is shown in blue, and the arrow represents the feed direction).

mer peening is applied in both directions (Case V), the magnitude of the corrected distortion is similar than when applying hammer peening along the width direction. These results of these simulations can be used by engineers/manufacturers as guidelines when deciding the best path to correct the distortion.

7. Conclusions

This paper has studied the effect of pneumatic hammer peening on near-surface residual stresses and confirmed the feasibility of this technology to correct distortions caused by machining in thin-walled aluminium parts. The main conclusions are:

- (1) Pneumatic hammer peening produced significant near-surface compressive residual stresses, ranging from -50 to -350 MPa, in both the x direction (feed motion) and the y direction (stepover motion) reaching a depth > 800 μm . The magnitude of compressive residual increased in the stepover direction when reducing the stepover distance since the same surface is subjected to more impacts. The effect of the initial offset was negligible.
- (2) The main mechanism involved in the generation of near-surface residual stresses is the Hertzian contact between the indenter of the tool and workpiece. The forces generated during sliding of the tool across the feed direction also contribute to the generation of residual stresses near the surface, but to a lower degree.
- (3) A hammer peening coverage of 4% was able to correct machining distortions by 0.17 mm (37% of the post-machining distortion of 0.46 mm) in aluminium 7475-

T7351 workpieces. Application of 100% of coverage led to correction of 2.4 mm, an overcorrection by a factor of over 5. These corrections were below the magnitudes predicted by FEM. Further characterisation of (sub)surface residual stresses induced by hammer peening showed that lower residual stresses were generated in the workpiece compared to a test coupon because a percentage of the energy is used to elastically deform the distorted machined part and the rest of it to plastically deform the treated (sub)surface. Importantly, to increase the efficiency of the hammer peening process the workpiece should be correctly fixed in the machine table. Using the residual stress profiles measured in the workpiece, a new hammer peening strategy was proposed (coverage of 12%) and distortion was corrected by 54%.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cja.2023.10.023>.

References

- Dursun T, Soutis C. Recent developments in advanced aircraft aluminium alloys. *Mater Des (1980–2015)* 2014;**56**:862–71.
- Sim WM. Residual stress engineering in manufacture of aerospace structural parts. Filton, UK: Airbus SAS. [Internet] 2009 [cited 20-09-2017]. Available from: <http://www.transport-research.info>.
- Wang ZJ, Chen WY, Zhang YD, et al. Study on the machining distortion of thin-walled part caused by redistribution of residual stress. *Chin J Aeronaut* 2005;**18**(2):175–9.
- Li JG, Wang SQ. Distortion caused by residual stresses in machining aeronautical aluminum alloy parts: recent advances. *Int J Adv Manuf Technol* 2017;**89**:997–1012.
- Costa MI, Leitão C, Rodrigues DM. Parametric study of friction stir welding induced distortion in thin aluminium alloy plates: a coupled numerical and experimental analysis. *Thin-Walled Struct* 2019;**134**:268–76.
- Zhang L, Wang H, Li S. Simulating assembly geometric and stress variation considering machining-induced residual stress. In: *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*; 2014 August 14-17; Buffalo, USA: ASME. 2014.
- Bowden DM, Halley JE. Aluminium reliability improvement program-final report 60606. Chicago, IL: The Boeing Company, 2001. Report No.: 60606.
- Li Y, Gan W, Zhou W, et al. Review on residual stress and its effects on manufacturing of aluminium alloy structural panels with typical multi-processes. *Chin J Aeronaut* 2023;**36**(5):96–124.
- Yang Y, Fan L, Li L, et al. Energy principle and material removal sequence optimization method in machining of aircraft monolithic parts. *Chin J Aeronaut* 2020;**33**(10):2770–81.
- Akhtar W, Lazoglu I, Liang SY. Prediction and control of residual stress-based distortions in the machining of aerospace parts: a review. *J Manuf Process* 2022;**76**:106–22.
- Weber D, Kirsch B, Chighizola CR, et al. Investigation on the scale effects of initial bulk and machining induced residual stresses of thin walled milled monolithic aluminum workpieces on part distortions: experiments and finite element prediction model. *Procedia CIRP* 2021;**102**:337–42.
- Madariaga A, Perez I, Arrazola PJ, et al. Reduction of distortions in large aluminium parts by controlling machining-induced residual stresses. *Int J Adv Manuf Technol* 2018;**97**:967–78.
- Chantzis D, Van-der-Veen S, Zettler J, et al. An industrial workflow to minimise part distortion for machining of large monolithic components in aerospace industry. *Procedia CIRP* 2013;**8**:281–6.
- Zhang Z, Li L, Yang Y, et al. Machining distortion minimization for the manufacturing of aeronautical structure. *Int J Adv Manuf Technol* 2014;**73**:1765–73.
- Cerutti X, Mocellin K. Influence of the machining sequence on the residual stress redistribution and machining quality: analysis and improvement using numerical simulations. *Int J Adv Manuf Technol* 2016;**83**:489–503.
- Barcenas L, Ledesma-Orozco E, Van-der-Veen S, et al. An optimization of part distortion for a structural aircraft wing rib: an industrial workflow approach. *CIRP J Manuf Sci Technol* 2020;**28**:15–23.
- Rodríguez-Sánchez AE, Ledesma-Orozco E, Ledesma S. Part distortion optimization of aluminum-based aircraft structures using finite element modeling and artificial neural networks. *CIRP J Manuf Sci Technol* 2020;**31**:595–606.
- Li X, Li L, Yang Y, et al. Machining deformation of single-sided component based on finishing allowance optimization. *Chin J Aeronaut* 2020;**33**(9):2434–44.
- Aurrekoetxea M, Llanos I, Zelaieta O, et al. Towards advanced prediction and control of machining distortion: a comprehensive review. *Int J Adv Manuf Technol* 2022;**122**(7–8):2823–48.
- Denkena B, De León-García L, Köhler J. Influence of high performance cutting operations on the residual stresses of aluminum structural work-pieces. In: Grant I, editors, *25th International Congress of the Aeronautical Sciences*; 2006 September 3-8; Hamburg, Germany: International Council of the Aeronautical Sciences (ICAS); 2006.
- Li B, Jiang X, Yang J, et al. Effects of depth of cut on the redistribution of residual stress and distortion during the milling of thin-walled part. *J Mater Process Technol* 2015;**216**:223–33.
- Weber D, Kirsch B, Jonsson JE, et al. Simulation based compensation techniques to minimize distortion of thin-walled monolithic aluminum parts due to residual stresses. *CIRP J Manuf Sci Technol* 2022;**38**:427–41.
- Dong HY, Ke YL. Study on machining deformation of aircraft monolithic component by FEM and experiment. *Chin J Aeronaut* 2006;**19**(3):247–54.
- Denkena B, Kaddour R, Dreier S. Methoden zur Simulation und Kompensation von eigenspannungsbedingtem Bauteilverzug. *Zeitschrift für wirtschaftlichen Fabrikbetrieb* 2013;**108**(4):208–11 [German].
- La Monaca A, Murray JW, Liao Z, et al. Surface integrity in metal machining-Part II: functional performance. *Int J Mach Tool Manu* 2021;**164**:103718.
- Munthe S, Munthe M. The method of corrective shot peening: how to correct the distortion on the machined parts. In: Champagne J, editors. *Proceedings of the 11th International Conference on Shot Peening*. South Bend, Indiana, USA. [Internet] 2011, Available from: <https://www.shotpeener.com/library/pdf/2011063.pdf>.
- Schulze V, Bleicher F, Groche P, et al. Surface modification by machine hammer peening and burnishing. *CIRP Ann* 2016;**65**(2):809–32.
- Lin XH, Huang HB, Zhou CS, et al. Research on surface modification of anodized aluminum alloy using piezoelectric machine hammer peening. *Int J Adv Manuf Technol* 2019;**104**:1211–9.
- Madariaga A, Cuesta M, Dominguez E, et al. Enhancing surface integrity of A7050-T7451 aluminium alloy by pneumatic machine hammer peening. *Procedia CIRP* 2022;**108**:317–22.
- Grant P, Lord J, Whitehead P, et al. The application of fine increment hole drilling for measuring machining-induced residual stresses. *Appl Mech Mater* 2005;**3**:105–11.
- Denkena B, Dreier S. Simulation of residual stress related part distortion. In: Denkena B, editors. *New Production Technologies in Aerospace Industry: Proceedings of the 4th Machining Innovations Conference*; 2013 September; Hannover, Germany. Berlin: Springer International Publishing; 2013. p. 105-13.
- Hill MR. The slitting method. In: Schajer GS, editor. *Practical residual stress measurement methods*. New York: John Wiley & Sons, Ltd.; 2013. p. 89–108.
- Prime MB. Experimental procedure for crack compliance (slitting) measurements of residual stress. Los Alamos: Los Alamos National Laboratory; 2003, Report No.: LA-UR-03-8629.
- Cheng W, Finnie I. A method for measurement of axisymmetric axial residual stresses in circumferentially welded thin-walled cylinders. *J Eng Mater Technol* 1985;**107**(3):181–5.

35. Prime MB, Hill MR. Uncertainty, model error, and order selection for series-expanded, residual-stress inverse solutions. *J Eng Mater Technol* 2006;**128**(2):175–85.
36. Beghini M, Grossi T, Prime MB, et al. Ill-Posedness and the bias-variance tradeoff in residual stress measurement inverse solutions. *Exp Mech* 2023;**63**:495–516.
37. Pan X, Zhou L, Wang C, et al. Microstructure and residual stress modulation of 7075 aluminum alloy for improving fatigue performance by laser shock peening. *Int J Mach Tool Manu* 2023;**184**:103979.
38. Williams JA, Dwyer-Joyce RS. Contact between solid surfaces. *Mod Tribol Hand* 2021;**1**:121–62.
39. Wang T, Wang JB, Zhang XJ, et al. A study on bending deformation behavior induced by shot peening based on the energy equivalence. *Thin-Walled Struct* 2023;**184**:110519.
40. Gulpak M, Solter J, Brinksmeier E. Prediction of shape deviations in face milling of steel. *Procedia CIRP* 2013;**8**:15–20.