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An industrial workflow to minimise part distortion for machining of large monolithic components in aerospace industry

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Abstract

Part Distortion due to inherent residual stresses has resulted in recurring concession, rework and possibly scrap worth millions of Euro in the aircraft development and manufacturing life cycle. The paper presented here outlines an industrial solution based on years of fundamental research dated back to as early as mid-1990 to the development of a practical industrial solution to optimise part distortion in large monolithic components in the aerospace industry. The developed system was designed to empower manufacturing engineers at the shop floor level to help with their day to day activities from characterising residual stress profile in materials to numerical simulation to arrive at an optimised solution. The industrial technology suite includes the following technologies: (i) characterisation of inherent material residual stresses by adapting the established layer removal method for implementation on an industrial CNC machining centre; (ii) generation of residual stresses profiles using displacement measurements; and (iii) optimisation of part location in the materials through numerical modelling. The machine operator can characterise the bulk residual stresses in the materials on a standard CNC machining centre . The residual stresses profiles will subsequently be used as inputs via a user-friendly GUI, which will drive the numerical calculation to be performed remotely in supercomputers, in order to deliver an optimised solution.

Keywords: residual stresses; residual stresses measurement; part distortion; modelling; simulation

1. Introduction

Part distortion is a common problem in manufacturing life cycle and is defined as the deviation of part shape from original intent after released from the fixture. This is not caused by dimensional inaccuracy, machining tolerance or over/under-machined. Distortion is a major challenge in airframe industry [1] which costs billion of losses in profit every year. A study by Boeing, based on four aircraft programmes, estimated the rework and scrap costs related to parts distortion comes to in excess of 290 million dollars [2]. Moreover, it is estimated that distortion from heat treatment the machine tool, automotive and power transmission industries in Germany is costing an economic loss of €850 million [3]. It is known that distortion comes from several variables such as the type of material, residual stresses in bulk material [4], machining induced residual stresses, part design [5], the location of the part in the billet of which it was machined [4] etc. In aerospace industry, aero structure components are generally made up of large thin wall or web components. These components are often machined from rolled plate, forgings, extrusion or casting and up to 90 to 95% of the materials could be removed. The dominant factor of part distortion in aerospace industry is the inherent residual stresses in the part. These inherent residual stresses

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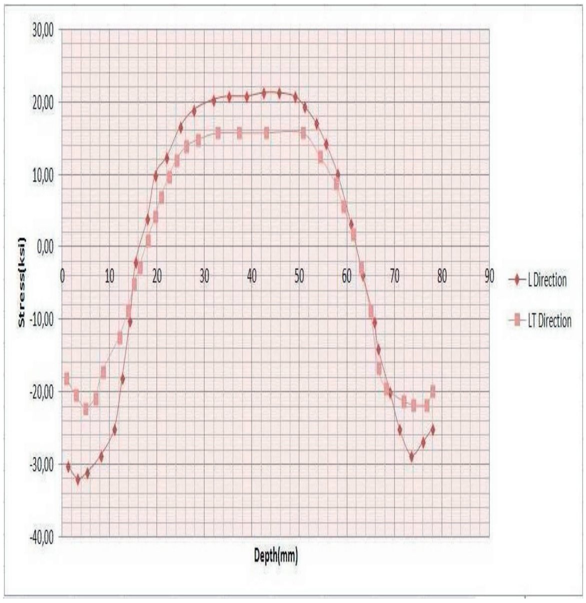
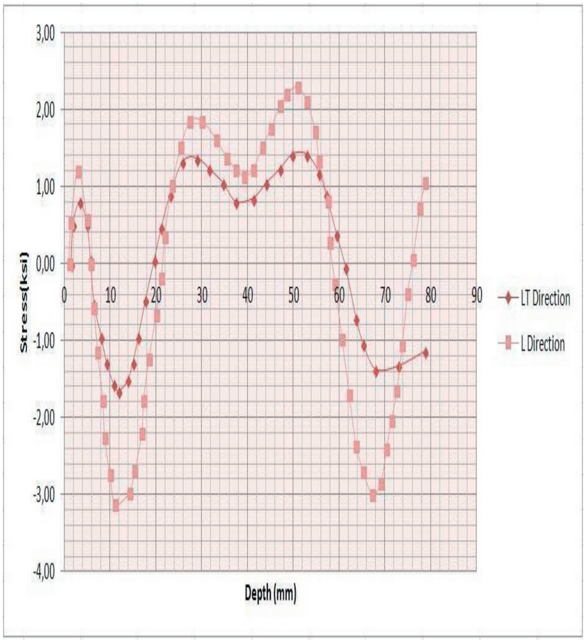
usually come from different manufacturing processes, i.e. quenching, stretching forging, extrusions, casting, welding, machining, forming, and etc [6]. These processes are complex combinations of heat transfer, mechanical deformation and metallurgical changes.



(a)



(b)

Fig. 1 Residual stress distribution before (a) and after (b) stretching

The industrial solution detail in the paper focus on part machined from rolled plate. Different alloying elements are mixed, melted and casted into an ingot and cooled. The cast ingot is then heated, rolled, quenched or rapidly cooled to achieve desirable physical and mechanical material properties. However, quenching also induces undesirable high levels of residual stresses because of the large surface heat fluxes and high temperature gradients near the surface and between intermediate layers of the materials. These conditions usually induce thermal residual stresses at yield stress magnitude, which causes high residual stresses in the half-product and may even cause distortion or cracking [7]. The plate is then mechanically stretched in the rolling direction to 1.5 to 3% plastic deformation at room temperature to relieve these high quench-induced residual stresses [8].

The paper presents an industrial solution to minimise distortion in the following ways: (i) determination of bulk residual stresses in rolled plate; (ii) data processing to create residual stress profiles; (iii) numerical simulation to determine optimised part location for minimal distortion.

2. Residual Stresses Measurement

Residual stresses play a critical role in failures due to fatigue, stress corrosion cracking, fracture buckling and more [9]. Due to this fact, knowledge of residual stresses is important for aerospace industry where liberal safety factors are impractical.

However, it is difficult to measure residual stresses in a structure or a part. Most of the times, certain physical quantities have to be extracted from which the kinds of residual stresses can be derived, but this may compromise the structure's integrity. Residual stresses measurement techniques is categorised into non-destructive and destructive testing.

Both of these techniques have their advantages and disadvantages. In general, non-destructive methods such as X-ray diffraction (XRD) or Neutron diffraction (ND) can non-destructively measure residual stress up to a maximum measurement depth of 0.05mm. Measuring to a greater depth requires layer removal. ND can measure to depths of many centimetres but it is constrained to measure a volume no smaller than a cube 1 to 2 mm on a side. This constraint makes it difficult or impossible to resolve residual stress variations over distances less than 1mm. Moreover these techniques require dedicated equipment and skilled workers with specific knowledge. Therefore it is difficult to use them in an industrial environment.

On the other hand, destructive measurement methods require material removal from the structure which sometimes it is not feasible, but they can extract results through all the thickness of it. The basic principle of these techniques is that the deformation is measured after the material removal comes from residual stress release. Then, residual stresses are estimated by using analysis based on linear elasticity. Another disadvantage of destructive methods is that dedicated equipment such as strain-gauges are needed, something that makes them inappropriate for practical industrial exploitation. The most common methods of this category are hole drilling, ring core, layer removal and wide slot techniques.

To cope with the complexity problems of these measurement techniques and the specific knowledge requires, a method has been developed which can be performed in a conventional CNC machining centres using only displacements measurements from high resolution linear transducer. For the residual stresses profiles extraction of a rolled plate two specimens are required; one cut from the longitudinal (L) direction and one from the lateral (LT). The method has the same principles as the Layer Removal Method (LRM) [10]. The basic assumption is that the state of internal stresses, varying with the thickness, producing mechanical potential energy. The accumulated mechanical energy results in the addition of elementary particle energies. When energy is released from a layer of metal removed, it is carried to the remaining materials and results in residual stress redistribution, producing the part bending.

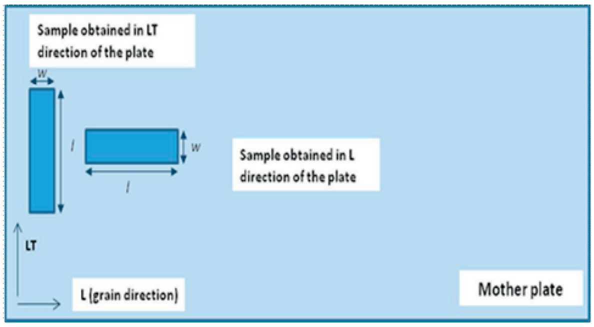


Fig. 2: Test Specimens for Modified Layer Removal Method

The method consists of making successive displacement measurements after every gradual thin layer of material removed. If the stress profile is assumed to be symmetrical because of the process, the incremental milling can be stopped at half of the initial thickness. Then, the measurements are being processed through a model which extracts the residual stress magnitude in each step.

For the implementation of this method in a CNC machine, a jig has been designed and manufactured. The design philosophy behind it was to provide a tool for the industrial engineer in order to easily characterise the material. The choice of using a CNC machine has been made due to the fact that an engineer in the shop-floor environment is familiar using it. This jig is easy to assemble, easy to handle and helps the industrial engineer to take the displacement measurements, which are needed for the residual stresses profiles, within 50 minutes for both directions.

Fig. 3 Residual stresses measurement system for a conventional CNC machine

The modified LRM consists of the following steps:

i. Coupon clamping
ii. Layer removal
iii. Coupon un-clamping on one side
iv. Displacement measurement
v. Step i again

Before the measurement step, some amount of time is needed for the coupon to cool from possible induced heat during cutting. Lubrication can also be used in order to counteract the heating effect. The linear displacement sensor should be an IP 65 one, in order to withstand any oil. Moreover, in this case, the accuracy of the probe, which was used, is 0.07 μm, its resolution less than 0.01 μm and its range 20mm. Finally during the tests, feed per tooth parameter should be below of 0.05 mm/tooth in order to minimise the machining induced residual stresses during the process.

Based on experimental results, only a deflection probe is used for material characterisation. The current Layer Removal method uses both deflection probe and strain gauge. However, strain gauge requires certified and qualified skills and it is too sensitive for industrial environments. Previous benchmark work shows a good agreement between results from linear probe and strain gauge. The result is shown in Fig. 4.

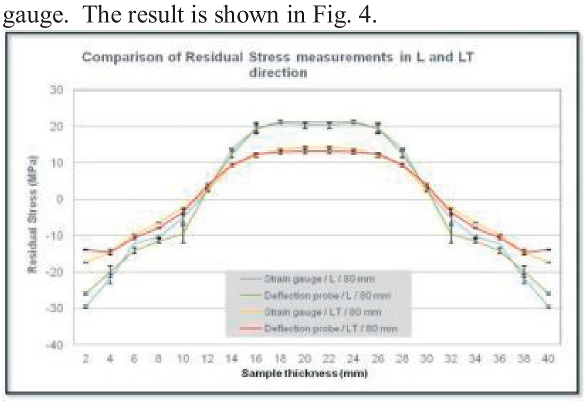


Fig. 4: Results' comparison between MLRM and LRM

3. Data Processing

At this stage, the industrial engineer has gathered all the measurement data using the jig. Firstly, the displacement data has to be converted to residual stress datapoint. For this purpose an analytical elastic model has been developed which can deliver residual stresses using displacement data. Secondly, in order to obtain a complete, through plate thickness, residual stress profile from discrete residual stress values a fitting script has been developed. This script takes into account the discrete residual stresses values and fits a cosine function as in (1) to these datapoints:

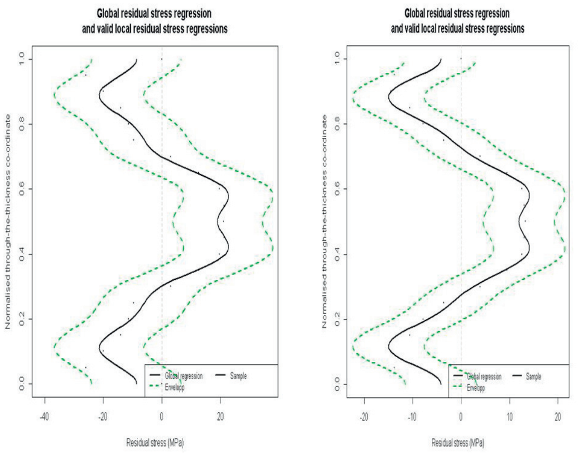
$$\sigma = c_0 + \Sigma c_n * \cos(2\pi * n * \xi) \text{ [MPa]},\ n = 1 \text{ to } 5 \qquad (1)$$

Equation 1: Cosine fit function

In the above equation σ is residual stress, ξ is the normalised through-thickness coordinate of the plate, i.e. x = 0 at the bottom of the plate and x = 1 at the top surface.

A sum-of-cosines fitting has been selected because it has been observed that most of the residual stress profiles follow this trend, and also to enforce symmetry about the mid-thickness plane. Normality of residuals is checked, as well as static equilibrium of the fitted stress function. The tool is particularly useful for finding the best quality data in a large number of measurement datasets and fitting the average residual stress profile of that data cloud. Finally the output is 6 coefficients which represent a cosine fitted residual stress profile and are going to be used in the next step of the workflow.

There is also the capability to combine stress data from more than one coupon of a material alloy. This way a representative stress curves can be derived from a library of stress data.



(a) (b)

Fig. 5: Cosine Fit Residual Stresses profiles in L (a) and LT (b) direction

4. Simulation

The last step of the proposed workflow is simulation. With simulation it is possible to predict distortion which comes from bulk material residual stresses [11]. The result from the simulation process will be a proposed optimised part location in the rolled plate for minimum distortion Figure 6 shows the schematic of part location in a rolled plate.

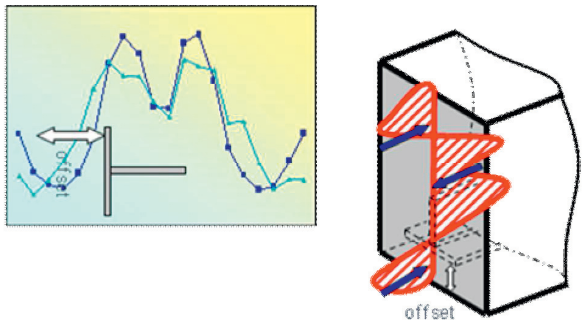


Fig. 6: Part location into the mother plate

Figure 7 shows the developed user-friendly GUI. The required inputs from the users are:

- Poisson ratio (ν) and Young's Modulus (E) of the material;
- Dimensions of the billet;
- Residual stresses fitting coefficients;
- Offsets range; and
- Meshed model of the examined part;

The basic assumption behind the simulation strategy is that residual stresses are homogenous in the plane of product. This means that if we measure residual stresses on one end of the plate, it should be exactly the same as the other one. This assumption is generally true for rolled plate but not also for forgings. Additional attention must be taken to measure residual stress outside of the homogenous zone near stretcher jaws.

Secondly, the choice of finite element meshing strategy has been done under the criteria of ease of use and time efficiency.

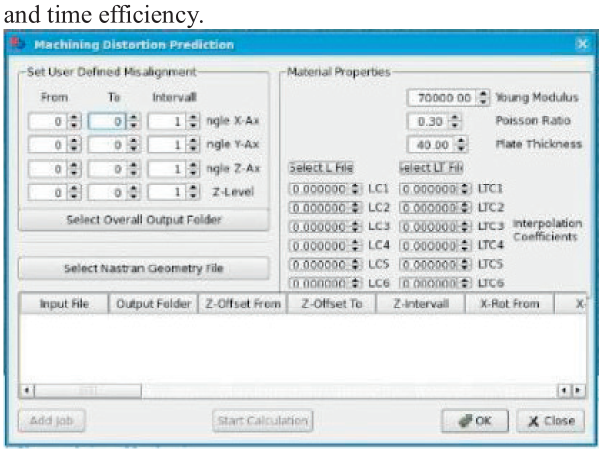


Fig. 7: GUI of simulation tool

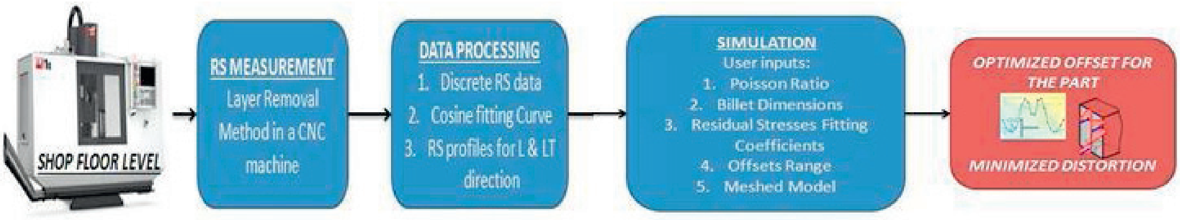


Fig. 8: Proposed Workflow for minimized distortion

The geometry is filled with second order tetrahedron elements. The element choice also favours automated meshing. Once the geometry of the part has been finalised, the part will be automatically meshed. Therefore, the industrial engineer will only have to characterise the residual stress and use the pre-defined meshed geometry in order operate the workflow to propose an optimized offset. Tetrahedron elements may not give the best results in terms of accuracy but make the entire system more efficient and pragmatic.

As for the applied boundary conditions are just sufficient to block rigid body motion. This means that real boundary conditions, which are applied during milling, are not reproduced in the solving code. In these circumstances, this is not necessary a problem because all the material removal is being done in just one pass and real milling process is not simulated.

The workflow is developed in FreeCAD, an open source 3D CAD environment. The simulation is performed using CalculiX, an open source finite element solver, together with an in-house developed script. This gives the required flexibility which is needed to encapsulate the code into a user interface, tailored to shop-floor use. Moreover the post-processing capabilities of the software provide good 3D representations of the results and summarised graphs.

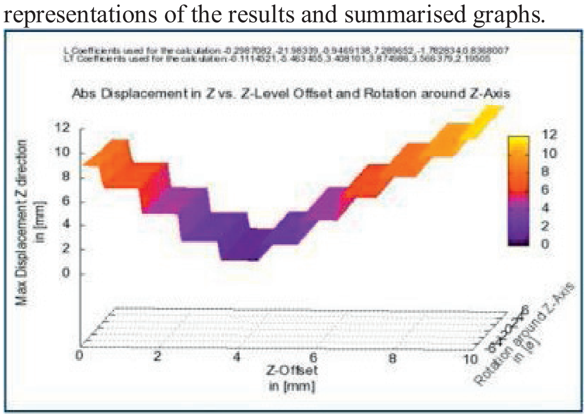


Fig. 9: Simulation Results

Finally, from the hardware point of view, the simulation is performed remotely on a centralised transnational high performance grid of computers and use up to 8 processors simultaneously. As a result, the average computational time for one large monolithic aerospace part such as panels, spars or stringers with 1 million elements and 10 different offsets, is about 20 minutes.

5. Conclusions

Distortion is a common manufacturing challenge in aerospace industry because of the length to thickness ratio of the parts. As it is widely known distortion can come from different reasons, from part geometry, symmetric or asymmetric design, bulk material residual stresses, or even from machining induced residual stresses. In order to minimise, or even eliminate distortion, a holistic view on residual stress distribution in the part based on the entire manufacturing history is needed. Shot peening is today's downstream solution to introduce compressive residual stresses to correct the distortion. Unfortunately, this added manufacturing costs and lead time to the manufacturing lifecycle.

As for the simulation strategy, further research needs to be done so realistic boundary conditions, progressive material removal and superficial residual stresses could be integrated because the resulted distortion is very conservative. For example, during milling, depending on the clamping, the part may distort and a subsequent milling pass will compensate.The proposed workflow will empower the manufacturing engineers to address the distortion at the shop floor prior to machining. Residual stress can be determined much earlier using the new jig and part location calculated to minimise distortion. This will lead into a more efficient resource planning, decrease of manufacturing lead times and costs and avoid rejected parts. The time for this workflow to propose an optimised offset is minimal compared to the time needed for one shot peening cycle and can be further decreased if an automated clamping system will be developed.

Moreover, it can be used as a 'Design against Distortion' tool in the design and development of new aerospace parts as it will be possible to predict the distortion behaviour of a new concept part through simulation. Therefore, decision on plate thickness and material specification to procure can be determined earlier at the design stage.

6. Further Research

The proposed workflow has been designed and tested for parts which come from aluminium rolled plates. However the challenges of the problem extend far beyond this. Titanium alloys are being more and more used in aerospace industry. Moreover many parts are not being made of rolled plates but also from extrusions or forgings.

On the other hand, fuel efficiency issue of aircrafts have pushed the industry to use composite materials in order to decrease the weight and in extension fuel consumption. Parts made of composite materials also do not lack distortion problems. Residual stresses which cause distortion can be induced in different manufacturing steps, such as curing, forming, trimming and coupled with the anisotropic nature of these materials can cause unpredicted distortion problems. Moreover, except from “new” materials, new manufacturing processes are being introduced. Additive manufacturing processes are a wide field of research in aerospace today but the distortion behaviour of these processes it is not known.

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