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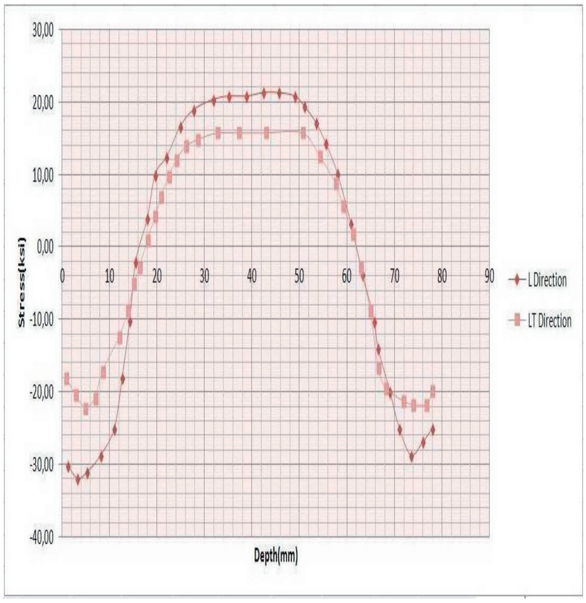
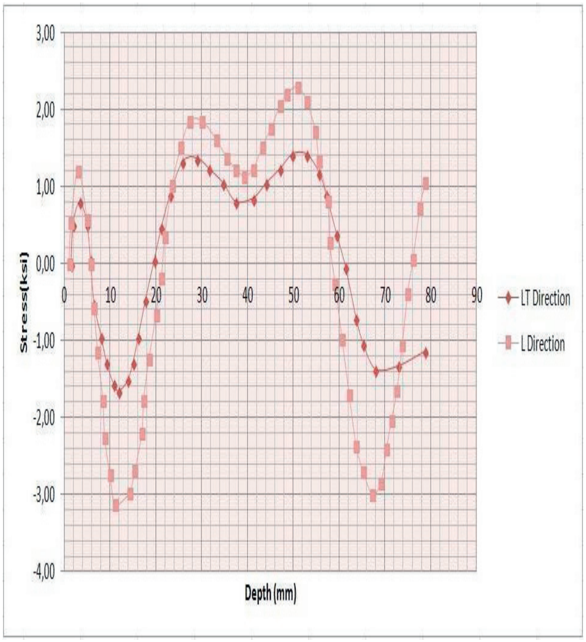
usually come from different manufacturing processes, i.e. quenching, stretching forging, extrusions, casting, welding, machining, forming, and etc [6]. These processes are complex combinations of heat transfer, mechanical deformation and metallurgical changes.



(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