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Methodology for aluminium part machining quality improvement considering mechanical properties and process conditions

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ABSTRACT

The manufacturing of structural aluminium alloy parts requires several steps of both forming processes and heat treatments. Before machining, which is usually the last step of the manufacturing, the workpiece has thus undergone multiple manufacturing steps involving unequal plastic deformations which are source of residual stresses. During machining, where up to 90% of the initial workpiece volume can be removed, the mechanical equilibrium of the part evolves constantly with the redistribution of the initial residual stresses. For thick, large and complex parts in highly alloyed aluminium, this redistribution of the residual stresses can leads to an unexpected behaviour of the workpiece and is the main reason for both workpiece deflections (during machining) and post-machining distortions (after unclamping). These two phenomena can lead to the nonconformity of the part with the geometrical and dimensional tolerance specifications and therefore to the rejection of the part or to additional conforming steps. As a consequence, the mechanical behaviour of the workpiece has to be considered during the definition of the machining process plan to improve the machining accuracy and the robustness of the process and thus to ensure the conformity of the machined part with the dimensional and geometrical specifications, i.e. to ensure the desired machining quality. In this paper, the numerical tool developed in [1] is used to conduct an analysis on the influence of the initial workpiece residual stress state, of the fixture layout as well as of the machining sequence on the machining quality. This analysis is performed on a part which has been specially designed and which can be considered as being representative of real aerospace parts. Several comparisons with experimental results are performed, one of them using digital image correlation (DIC) measurements. Results obtained show a good agreement, validating both the prediction of the behaviour of the workpiece during machining and the prediction of the machined part geometry. Based on the results of this analysis, a classification of the parameters has been performed depending on their influence on the machining quality. A first methodology allowing to define machining process plans adapted to the initial workpiece stress state has then been created based on the previous classification. This methodology is composed of a procedure and basic guidelines which are both presented in detail. An example of an application of this methodology is then introduced, demonstrating the benefits of the approach developed in this work.

1. Introduction

In aeronautics, several material processing steps are required to produce aluminium alloy structural parts. All these manufacturing steps involve plastic deformations resulting from mechanical and thermal loads which are source of residual stresses [2]. Residual stresses can thus not be avoided and have to be considered as unexpected outcomes of the manufacturing processes. Their magnitude and distribution vary according to the manufacturing steps used to produce the parts.

The manufacturing of structural aluminium alloy aerospace parts is usually described by alternating steps of thermal treatments and forming processes. Depending on the desired part, the ingot obtained after the casting of the melted mix of alloying elements is hot-rolled or hot-forged. The obtained workpiece is

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then heat-treated and quenched. During the quenching residual stresses are produced in the workpiece due to significant thermal gradients and associated plastic deformations. In the case of a rolled plate, a mechanical stress relief operation by stretching in the rolling direction is realised to decrease the residual stresses [3]. Precipitation strengthening is then performed by thermal ageing in order to achieve the desired physical and mechanical properties of the material. At the end of these steps the material with the desired properties is obtained but a nonuniform through-thickness residual stress distribution remains in the plate.

Aeronautical structural parts made from aluminium are often large and complex monolithic parts machined from these rolled plates [4]. Up to 90% of the initial volume of the workpiece can be removed during the machining of aerospace structural parts. Being the last manufacturing step allowing to obtain the final part geometry, machining is therefore an important process in the manufacturing of aerospace parts. The residual stress redistribution linked to the removal of material is one of the main issues in industry [4,5]. It can lead to workpiece deflections during the machining, resulting in overcuts or undercuts in some areas. Post-machining distortions can also be observed after the unclamping of the part. Both of these phenomena cause dimensional and geometrical deviations which can lead to the nonconformity and then the rejection of the parts. The part conformity is therefore strongly governed by the initial workpiece residual stresses. In addition, aeronautical part manufacturers have to cope with increasingly larger parts of complex geometries and with a rising need of productivity and quality (tight tolerance specifications). As a consequence, the aeronautical industry expresses keen interest in the mastery of the residual stresses and in the development of methodologies to improve the machining quality.

The machining quality is defined here as the capability of a machining process plan to produce parts with the desired geometrical characteristics. "Quality" refers thus to the deviation between the part after the machining and the geometry initially desired and given by the designed one (CAD). The machined part quality is characterised by micro- (e.g. surface roughness) and macro-geometrical properties. In this work, since the machining of large structural aeronautical parts made of aluminium alloy is considered, we only take into consideration the macro-geometrical properties to characterise the machining quality. More specifically, these properties are the accuracy of dimensions, the form and the position of the geometrical elements [6].

Significant work has already been carried out on the determination of the residual stresses, on their influence on the machining process as well as on the prediction of the workpiece behaviour and the final part geometry. Several techniques have been developed to determine the residual stress profiles in rolled plates. Among these techniques, the layer removal method based on strain gauge measurements is nowadays the most commonly used [7–9]. Using the experimentally determined residual stress profiles, several authors have studied the redistribution of residual stresses during machining and developed finite element models to predict machining quality [10,11]. It is worth noting that only the post-machining distortion (curvature of the part) is predicted with these models, in other words, no information related to the dimensional deviation is obtained. Furthermore, these models rely on the elements deactivation as material removal method, which reduce the model versatility. Indeed, prismatic parts with relatively simple machining process plans (one machining step) are usually studied and the fixture-workpiece contact is often modelled by restricting the degrees of freedom in the clamping areas.

Fixture has also been the subject of several studies [12–15]. The influence of the fixture on the machining quality due to the part location errors and the deformation of the workpiece under clamping has notably been analysed. Among others, these articles emphasise the importance to consider the fixture-workpiece contact when dealing with the machining quality prediction.

More recently, the authors of [16,17] developed a numerical tool allowing to predict the behaviour of the workpiece and the post-machining distortion considering both the fixture-workpiece contact and the thermo-mechanical loads linked to the tool-workpiece interaction. This approach is particularly well adapted to the simulation of thin-walled parts. However, the same deactivation method is used to perform the material removal and no prediction of the dimensional deviations is obtained at the end of the simulations.

In industry, the influence of the initial workpiece residual stresses and of the machining process parameters on the machined part quality is often neglected. It thus leads to several costly machining trials to validate a machining process plan, to rejects and to unexpected extra conforming steps after machining to obtain a conforming part. There is therefore a need of methodologies and of tools to help in the definition of machining process parameters allowing to reach the desired machining quality.

In order to study the workpiece behaviour during machining and to predict the final part geometry, a specific numerical tool has been developed [1]. Here, this software is used and it allows a thorough analysis of the influence on the machining quality of (i) the initial residual stresses, of (ii) the fixture layout and of (iii) the machining sequences (tool path). This analysis is performed for parts machined from an AIRWARE®2050-T84 alloy rolled plate. This alloy is an aluminium–lithium alloy which has been specially developed for aeronautics and space and combines strength, lightness, durability and recyclability [18]. The work presented in this paper revolves around three principal steps, defined as follow.

First, the study and its objectives are presented. The numerical approach and the associated main assumptions are then recalled. In addition, the part geometry and the measurements performed at the end of each machining step to evaluate the machining quality are also introduced.

Second, the influence analysis is performed and the related results are shown. In some cases, experimental machining tests have also been conducted, one of them using a full-field measurement technique, namely the digital image correlation (DIC). Comparisons between experimental and simulation results are performed and a good agreement between the predicted and the measured final part geometries is observed.

Finally, a novel procedure improving the machining quality is introduced. It relies on the developed numerical tool and optimises the machining process plans by taking into consideration the initial residual stress state of the workpiece. Basic guidelines for the definition of machining process plans are also determined based on the observations that are made.

2. Presentation of the study

A machining process plan is required for manufacturing by machining. It is a detailed plan with instructions specifying how a product has to be machined depending on the characteristics of both the part and the available machining facilities.

The machining quality is strongly governed by the machining process plan parameters, which are the initial workpiece and its initial residual stresses, the fixture, the machining sequence (tool path) and the cutting loads (dependent on the cutting conditions). The cutting loads and the related residual stresses induced during the machining of aluminium alloy parts generally affect a depth of only approximately 250 μm under the machining surface [19]. They have therefore a small impact on parts without thin walls. In [20], the authors have also demonstrated that when dealing with aluminium alloy parts, the initial residual stresses are