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Part Distortion Modeling on Aluminum Slender Structural Components for Aeronautical Industry

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Abstract

During the manufacturing of slender thin-walled aluminum components for the aeronautical industry, the appearance of part distortion once they are machined is a common problem, mainly due to the presence of residual stresses on the aluminum stocks. In this paper, the development of an agile analytical model for the calculation of the final distortions of machined components is proposed, accounting for different part geometries. The capability of the model to predict the final distortion in these pieces has been validated by comparing results of distortions of specimens obtained in experimental tests.

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Keywords: Machining part distortion; Residual stresses; Analytical modeling; Quality assurance

1. Introduction

The manufacturing of structural components for the aeronautical sector shows a considerable number of difficulties. The need for the maximization of load capacities, together with the minimization of the energy consumption in air transport systems, pushes the use of materials with high mechanical properties and less specific weights. Analogously, the design of structural components tends towards very slender ribbed structures (Figure 1), which optimizes the bending capacity of the components for a given component weight.

Fig. 1. Example for a structural component of the aeronautical sector.

On the other hand, safety aspects inherent in aeronautical components whose failure could result in the loss of human lives must be taken into account. In this sense, these types of parts have rigorous requirements in terms of structural and surface integrity of the component, dimensional tolerances or surface finishes. Aspects such as dynamic instabilities during the process, part distortions due to the presence of volumetric residual stresses on the stocks, thermal deformations and microstructural alterations due to the heat generated during the cutting process or the generation of layers with high residual stresses and mechanical deformations in the machined surfaces have been widely reported [1,2].

In the case of slender structural components manufactured on aluminum, in which up to 90-95% material is removed, the main manufacturing problems are related to the appearance of distortions in the machined parts due to the residual stress state in the stocks before the machining process [3,4]. Examples of such distortions can be seen in Figure 2.

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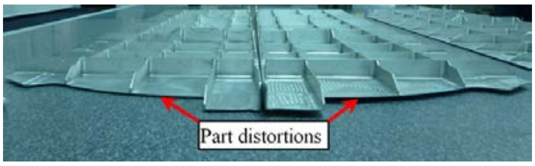

Fig. 2. Distortion problems appearing on slender ribbed parts: undesired curvature on the longitudinal direction of the part.

The stocks from which these types of slender parts are usually obtained show residual stress states coming from the processing phases (extrusion, heat treatment...) prior to machining [5]. The removal of the material required to obtain the final part generates the need to achieve a new force balance on the part; creating a deformation on the part after the release of the clamping forces [3,4]. This way, depending on the magnitude and distribution of the residual stresses as well as the geometry of the workpiece; a distortion that makes the part non-acceptable can appear, generating a considerable expense in materials, tooling and processing times.

Therefore, the correct planning of the machining process (machining strategy, phases, machining zones) is of great importance for obtaining the minimum distortion on the part so that it satisfies the requirements specified for it [6]. However, the resulting strategies usually show a large amount clamping phases, together with a reduced material removed on each phase. All this leads to high processing times for obtaining a component with minimal distortions.

The present work is focused on the development of a calculation model that, on the one hand, allows the identification of the stress state of a stock in a simple way. On the other hand, it must be able to calculate the final deformation of a part after a machining process. These developments will work as the foundation for a general tool that allows defining a machining strategy that, based on the initial state of the stock material, minimizes the final part distortion, as well as generates competitive machining times for slender structural ribbed components.

2. Development of the stress and distortion model

Most of the solutions reported in bibliography to perform calculations of distortions in machined parts are based on the use of the finite element method (FEM) [4, 6-13]. In spite of this, the present work has been focused on the development of an analytical tool coded in Matlab.

While analytical models are not able to represent a case study in such a detail as a model developed by a FEM tool, they allow for a greater agility on the modification of the geometries and initial conditions. Also, the computational requirements are considerably lower than those normally required for calculation programs based on the FEM. This way, it is considered that they are more suitable for the development of an agile tool for its use in an easy way in industrial environments.

For the development of the distortion model, some hypotheses have been defined based on observations made during the manufacturing of slender ribbed structural components on aluminum.

On the one hand, the curvature is usually uniform in the longitudinal direction of the parts (X direction in Figure 3), indicating stress uniformity in the longitudinal direction and a negligible effect of the transverse ribs on the final part distortion. On the other hand, the deformation achieved in the transverse direction is practically zero, having decided to remove the stresses in the transverse direction within the distortion model. In the case of the depth direction, the stresses have also been dismissed.

Since the stress components in the transverse and depth directions (Y and Z directions in Figure 3) are neglected, as well as the contribution of the transverse ribs to the bending behaviour of the machined component, it is possible to represent the bending behaviour of the whole geometry by a representative cross section for that geometry. Moreover, it is possible to reduce the complexity of this section by employing an equivalent section with the same flexing behaviour. The reduction procedure from the initial geometry to the equivalent section can be seen schematically in Figure 3. In this way, it is possible to define a simple calculation model with the ability to represent virtually a large number of real geometries.

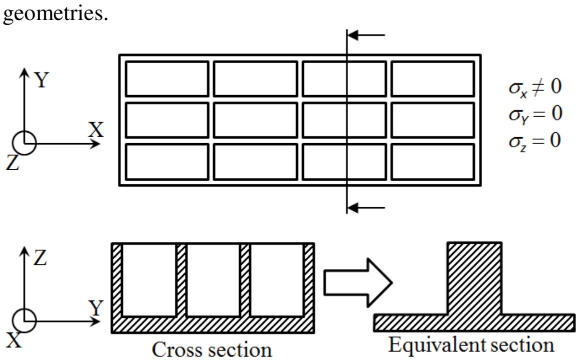

Fig. 3. Graphical representation of the hypotheses taken for the model, as well as the reduction of the whole geometry to an equivalent section.

Based on the above hypotheses and simplifications, a calculation model has been developed that allows obtaining the residual stress values from the curvatures obtained during layer removal tests, following the approach proposed in [14]. This way, after the removal of a material layer, the strain at the surface ε is calculated based on the curvature ρ on the part and the height of the part h:

$$\varepsilon = \frac{h}{-2 \cdot \rho} \tag{1}$$

Then, the stress σ on the removed layer is obtained employing the moment of inertia I of the part, the elastic modulus E, the leverage k of the machined layer to the neutral fiber and its cross-section A. On the layer removal tests, the effect of the previously removed layers on the new measurements is taken into account through the solution of the following equation system: