

Paper:

Numerical Analyses of Turning-Induced and Mapped Ti6Al4V Residual Stresses for a Disc Subjected to Centrifugal Loading

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The paper investigates the effects of turning-induced and mapped Residual Stresses (RSs) for a Ti6Al4V disc subjected to centrifugal loading. The turning-induced RSs are predicted in orthogonal cutting using the Finite Element Method (FEM). The FE predicted RSs are validated after performing face turning followed by hole drilling and x-ray diffraction measurements. Numerical analyses are carried out at different Cutting Velocities (CVs) to obtain the RS profiles. The results show that the compressive RSs increase by increasing the CV and the depth of cut. A disc subjected to a centrifugal load is modelled using the FEM where the turning-induced RSs are introduced as an initial condition using mapping techniques. The predicted CV-dependent RS profiles are incorporated into the mapping techniques using the shape function approach. It is observed that the stress amplitudes at the points at which failure occurs are lower when the mapped turning-induced RS profiles are considered in the disc FE model. The lower stress amplitudes are related to prolonging the disc life due to fatigue.

Keywords: mapping surface residual stresses, turning of Ti6Al4V, disc under centrifugal load, finite element analysis

1. Introduction

The turning process is widely used for material removal and involves a large amount of plastic deformations where the material is removed in the form of chips. The process can induce either tensile or compressive near-surface RSs depending on the material and cutting conditions. The compressive RSs have a beneficial effect on the fatigue life and corrosion because they delay crack initiation and propagation. On the other hand, the tensile RSs can significantly increase service stresses, which can lead to premature failure of the components [1]. Afazov et al. [2] have investigated the effect of the tensile and compressive RSs on the fatigue life of a notched beam subjected to three-point bending. The FEM has been used and the RSs have been mapped around the notch. Low and high cycle fatigue life calculations have been performed using

different loading conditions. It has been concluded that the compressive RSs increase the life, especially in high cycle fatigue.

In the last decade, many FEM-based studies have appeared in the literature, and nowadays, the FEM is widely used as the preferred method to model RSs in metal cutting processes. Liu et al. [3] have investigated the impact of sequential cuts and tool-chip friction on the RSs. Movahhedy et al. [4] have studied the influence of the cutting edge geometry on the chip removal process by simulating sharp, blunt and chamfered tools using FEM. Sasahara et al. [5] have proposed a process model for the prediction of surface RSs caused by machining. The proposed model combines an orthogonal cutting simulation using FEM and a tool corner's indentation model. Hua et al. [6] have proposed a hardness-based flow stress model which has been incorporated into an elastic-viscoplastic FE model of hard turning to analyse the process variables which affect the RS profile of the machined surface. Salio et al. [7] have presented a FEM model for turning of Inconel 718 alloy. The model has been validated through comparison with experimental measurements. Valiorgue et al. [8] have presented an idea which consists of disconnecting the chip formation process on one hand and modelling the mechanisms leading to the RSs on the other hand. This approach necessitates quantifying the thermo-mechanical load induced by the cutting tool onto the machined surface. A FE model has been developed to simulate the movement of the thermo-mechanical load on the machined surface and predict the induced RSs. Jacobson [9] has investigated the effects of tool parameters and the depth of cut on the RSs of M50 steels. It has been found that both the effective rake angle and the tool radius affect the RS generation. Dahlman et al. [10] have conducted an experimental study of the influence of the rake angle, feed rate and the depth of cut on the RS in hard face turning.

The reviewed numerical models can simulate mainly 2D and 3D orthogonal cutting where the RS profiles can be predicted. Simulating the cutting processes on complex geometries, considering the tool-workpiece interaction in order to obtain the RS state, remains a challenge. Recently, Afazov et al. [11,12] developed a new approach for modelling the RSs of complex 2D and 3D geometries induced by different manufacturing processes

(e.g. shot-peening, machining, roller burnishing, etc.). The approach consists of mapping RS profiles onto complex surfaces and sub-surfaces. It has been demonstrated how the shot-peening RS profile can be mapped onto an aero-engine component using the developed mapping algorithms and formulations. Based on these mapping techniques, Afazov et al. [2] have investigated the effect of compressive shot-peening and tensile machining RSs of Inconel 718 aerospace alloy on the fatigue life. Furthermore, the mapping techniques have been implemented on different linear and quadratic axisymmetric elements where sensitivity studies have been performed [13]. Also, the mapping techniques have been used for applications of the turning process where the RS profiles have been mapped into an axisymmetric FE model of a shaft. In that model, the turning process has been performed by controlling the spindle speed to achieve a constant CV at the cutting tool tip in order to apply the mapping techniques [14, 15].

Building on the mapping techniques reported in [14, 15], one of the main objectives of the current paper is to develop a new methodology for mapping CV-dependent RS and equivalent plastic strain profiles for a disc subjected to turning at constant spindle speed where the CV varies across the machined surface. FE prediction and validation of the RS generation at different cutting conditions are also investigated. Another objective is to investigate the effect of turning-induced RSs on a disc subjected to centrifugal loading in terms of stress amplitudes which are used for the estimation of the fatigue life.

2. Overview of Methodology

The proposed methodology (see Fig. 1) includes FE modelling of orthogonal cutting where turning-induced RSs are predicted. The FE predicted RSs are validated for two depths of cut within an experimental programme including face turning and measurements of RSs using the hole drilling and x-ray diffraction methods. After validation of the FE predicted RSs, the FE model of orthogonal cutting is used to investigate the influence of the CV on the RS and equivalent plastic strain profiles. The RS and equivalent plastic strain profiles are mapped as initial conditions into a FE model of a disc subjected to centrifugal loading and the results are analysed for centrifugal loads up to 1600 rev/min.

3. FE Models and Mapping Techniques

Two FE models are presented in this section. The first FE model is developed to simulate orthogonal cutting process and predict the near-surface RS profiles at different depths of cut and CVs. The second FE model is developed to simulate a disc subjected to centrifugal loading where CV-dependent turning-induced RS and equivalent plastic strain profiles are introduced as initial conditions

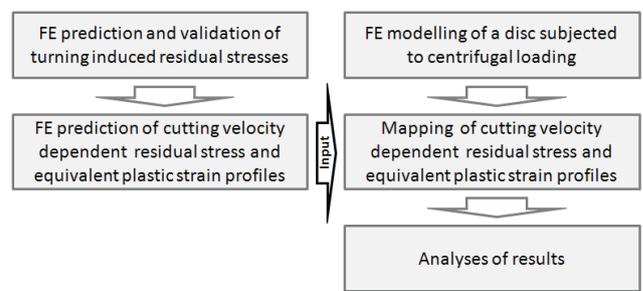


Fig. 1. Methodology diagram.

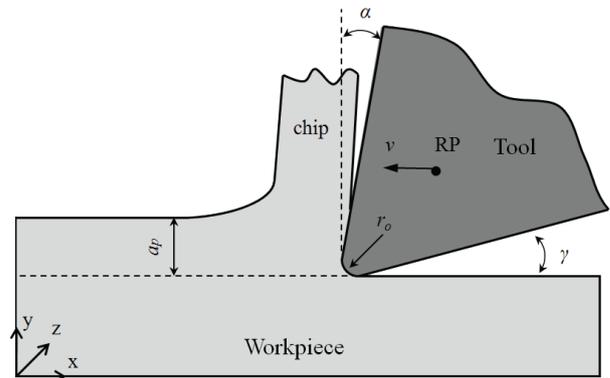


Fig. 2. Schematic of an orthogonal cutting process.

using mapping techniques. The mapping techniques are also presented and discussed in this section.

3.1. FE Model of Orthogonal Cutting and Experimental Programme

Figure 2 shows a schematic of an orthogonal cutting process. The ABAQUS/Explicit FE code is used to model the orthogonal cutting [16]. The geometry of the tool is created based on dimensions of the CCMT09T302-F2 HX inserter used in the experimental programme. The inserter edge radius (r_0) is $8 \mu\text{m}$. The rake angle (α) and the clearance angle (γ) are 0° and 7° , respectively.

Plane strain conditions are used within the FEA in this model. The workpiece is modelled as a rectangular block and meshed with 12,000 four-node bilinear temperature-displacement elements with reduced integration and hour-glass control (CPE4RT in ABAQUS/Explicit). The feed rate is represented by an element thickness of 0.1 mm in the plain strain conditions. Arbitrary Lagrangian Eulerian (ALE) adaptive meshing is used to avoid element distortions due to the large deformations in the cutting process. The tool is modelled as a rigid body represented by a reference point. Boundary conditions are applied to allow tool movement only in the x direction. CV (v) is applied at the reference point in the x direction. A room temperature of 20°C is applied to the workpiece as an initial condition. The tool-workpiece friction, conversion of the plastic work into heat, heat generation due to the contact