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Numerical and experimental analysis of residual stress and plastic strain distributions in machined stainless steel

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ABSTRACT

In this study, a numerical approach has been developed to predict the near surface residual stresses and plastic strain resulting from turning in orthogonal cutting configuration. This approach is based on the Arbitrary Lagrangian–Eulerian (ALE) formulation using the commercial finite element code Abaqus–Explicit. The coefficients of the used material behavior law and friction model required for the simulation are identified experimentally in this study. The simulated results are validated by experiments carried out on AISI 316L stainless steel. Using this method, the effect of the depth of cut (*Doc*) and the cutting speed (*Vc*) on the surface properties has been established. The simulated residual stress gradient resulting from machining has been experimentally validated by X-ray diffraction measurements. The simulated plastic strain gradient has been validated by an experimental microhardness–strain relationship established in this study.

1. Introduction

The tool–material interactions under machining conditions appreciably modify the properties of near surface layers of metal and subsequently their behavior and durability. The nature and the extent of the modifications depend on the types of tool–workpiece interactions. The identification of these modifications is extremely useful for a better prediction of the in-service life time of machined components subject to cyclic loading or stress corrosion cracking. For a long time, the identification of the properties of the near surface layers affected by machining was based on experimental approaches combining various techniques and methods of mechanical and physicochemical investigations [1]. These approaches are expensive and lead to more or less significant uncertainties of surface properties. For this reason, analytical approaches, based generally on geometrical considerations, have been developed. These approaches have recognized continuous development since the beginning of the previous century [2]. Nevertheless, the developed analytical models were mainly used to predict machining power or tool life by estimation of cutting forces and generated heat and are rarely used to predict the properties of machined surface. This is attributed to the large number of the involved and coupled physical phenomena as contact mechanics, thermal transfer, metallurgical transformations, dynamics of machining, etc.

The numerical approaches found successful applications in recent years. Three different approaches were commonly used to simulate metal cutting: Lagrangian, Eulerian and Arbitrary Lagrangian–Eulerian. The main advantages of each formulation are summarized in Table 1.

However, the numerical investigations were focused commonly on cutting forces and chip morphology prediction [3,4].

The Lagrangian formulation has been used in several works to investigate the effect of machining parameters on residual stresses distribution. These works focused commonly on analyzing the effect of cutting speed [5–10], depth of cut [6,8,10–12], number of passes [8,13,14] and cutting tool geometry and coating [8,15–20]. Nevertheless, the drawbacks of Lagrangian models cited in Table 1 reduce the profitability of these models.

Despite the advantages of the ALE formulation, its use in metal cutting simulation was very limited. Nasr [21] and Munoz [22] have presented an ALE finite element model to simulate the residual stresses induced by orthogonal dry cutting of the austenitic stainless steel AISI 316L. The works were limited to the study of the effect of tool edge radius on machining residual stresses.

Examination of the main numerical investigations of material cutting process can lead to the following comments:

- The numerical simulation results are very sensitive to the used material behavior laws [23], friction model [13,17,24] and mesh smoothness [14,21].

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Table 1
Comparison between different formulations used in metal cutting simulation.

Formulation	Advantages	Drawbacks
Lagrangian	• Simulation of discontinuous chip	• Mesh related to material=> excessive distortion • A separation criterion must be used • Dependence of the calculated residual stresses and plastic strains on separation criterion • High computing time of remeshing
Eulerian	• Reduced computing time • No separation criterion to use	• Initial chip shape must be introduced • Do not consider the material elastic behavior ≥ no residual stress prediction
Arbitrary Lagrangian–Eulerian (ALE)	• No mesh distortion • Distinction between the mesh and material evolution=> no mesh distortion • No separation criterion to use	• Initial chip shape must be introduced • No simulation of discontinuous chip

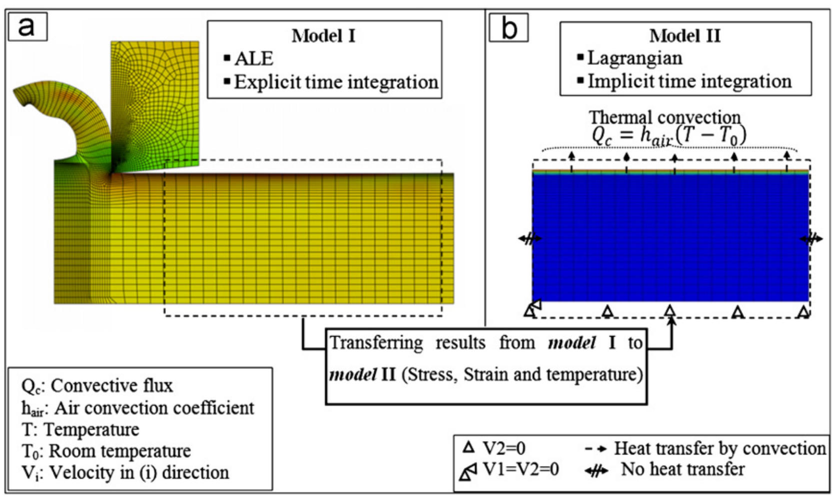

Fig. 1. Numerical simulation description.

- The explicit integration scheme is more efficient for applications involving high nonlinearities such as metal cutting simulation [21,22].
- The machining residual stress is very sensitive to the friction condition of the tool–chip interface. Nevertheless, the coulomb model with a constant coefficient was usually used to describe friction in metal cutting simulation [8,14,16,17,25].
- The simulated machining residual stress distributions are characterized by high tensile value near the surface in both directions (circumferential and axial) for austenitic stainless steels [8,11,19–22]. Moreover, in cutting direction (circumferential) the tensile residual stress is higher. In all cases, their levels are mainly controlled by the selected machining parameters which affect the generated heat flux.
- The simulated machining residual stresses are rarely validated by experimental measurements for different cutting conditions. The models validations are usually based on cutting forces measurements [7,13,20].
- The simulated residual stresses were never been confirmed by an assessment of plastic deformation fields which is the bases of their generation.

For these reasons, we propose, in this study, a numerical approach to predict the surface residual stress and strain gradients resulting from cutting material process. This approach is based on the ALE formulation using the commercial finite element code Abaqus–Explicit and pre-defined experimental material behavior laws and friction models. The finite element model is calibrated by residual stresses and plastic strains measured on AISI 316L stainless steel samples machined in different cutting conditions. The effects of cutting condition on surface residual stress and strain distribution are investigated.

2. Numerical approach

2.1. Numerical simulation procedure

The approach adopted to predict the near surface residual stresses and strains induced by turning consists of reproducing the generation mechanisms of residual stress and strain in metal cutting by simulating separately:

- The phase of tool/material interaction, in a kinematic of cut, that consists of simulating the viscoplastic flow of the material on the tool cutting face (model I Fig. 1(a)).
- The phase of unloading and cooling of the workpiece until reaching mechanical equilibrium and room temperature in the workpiece (model II Fig. 1(b)).
  In this procedure, the friction coefficient and material behavior law are provided from experimental data (Fig. 2).

2.1.1. Simulation of tool/material interaction (model I)

In a first step, an ALE model is used to simulate the viscoplastic flow of the material at the tool cutting face that is considered as fixed.