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# Three approaches for modeling residual stresses induced by orthogonal cutting of AISI316L

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ABSTRACT

Different to model the orthogonal cutting process methods can be found in the literature. Each approach has its advantages that make it more appropriate for modeling particular cutting cases than others. In this work, three finite element models of the orthogonal cutting process are developed: (i) Lagrangian (LAG), (ii) Arbitrairy Lagrangian and Eulerian (ALE) and (iii) hybrid model. The purpose of this paper is to improve these models in order to predict machining induced Residual Stresses (RS). A critical assessment of the applicability of each method is presented and their efficiency in the prediction of RS profiles is discussed. The absence of the damage criterion and consequently the absence of suppressing mesh elements makes the ALE model more reliable than the LAG one when predicting the RS curves. However, even though the hybrid model presents similar performances in the numerical prediction, the RS profiles are closer to the experimental results, owing to the accuracy of its input data.



## 1. Introduction

The fatigue phenomenon generally initiates from free surfaces. In fact, the superficial layers of manufactured components can be submitted to the highest load and exposed to environmental effects. In this context, the investigation of the machined surface integrity constitutes an interesting objective of several studies. The surface integrity is described generally by three main characteristics; (i) metallurgical (microhardness), (ii) geometrical (roughness) and (iii), mechanical (residual stress). For the identification of these characteristics, the Finite Element Model (FEM), based on numerical approaches, seems to be a better alternative to the experimental and analytical techniques. This is basically because it overcomes the high cost and significant uncertainty of experimental methods and the several assumptions of the analytical method. FEMs are then used to better understand the cutting process and therefore to properly predict machining induced surface integrity, allowing the combination of different cutting parameters. In fact, various models are set up to predict the machining performance in terms of cutting forces [1], temperature [2], phase transformations [3], tool geometries [4], chip morphologies [5–6] and especially surface integrity [7–8]. Since the Residual Stress (RS) represents the key parameter in controlling surface performances [9], the majority of numerical studies investigating surface integrity have been focused on it. The use of an appropriate numerical formulation, when developing a FEM of cutting, is very important to improve the RS prediction reliability. Indeed, three different techniques have been used for the metal cutting simulation: Eulerian, Lagrangian (LAG) and Arbitrary Lagrangian–Eulerian (ALE). Each of these formulations has its own advantages and drawbacks. For example, both the LAG and the ALE models have been widely used to investigate surface integrity [10-11]. However, the Eulerian formulation cannot be used in the RS prediction, since the material elasticity is not taken into account [12]. Lastly, a hybrid model of cutting was carried out by Valiorgue [13–14] and subsequently developed by Mondelin [15–16]. In the latter approach, both the chip and the tool are replaced by equivalent thermo-mechanical loadings based on heat transfer data, friction coefficients and cutting forces. The hybrid would FEM combine analytical and numerical aspects to model the cutting process in different configurations such as milling and turning. This method makes it possible to avoid the mesh distortion problems, especially in the contact areas between the chip and the tool and between the workpeice and the tool in both 2D and 3D machining models.

As a result, the complexities of the cutting process make the numerical simulations particularly difficult. Consequently, the choice of an appropriate FEM for a given problem of cutting requires being aware of how such a method may influence the estimate of the effective process-output (chip morphology, cutting forces and surface integrity).

In this study, three orthogonal cutting patterns, corresponding to three numerical approaches are developed; (i) thee LAG model, (ii) the ALE model and (iii) the hybrid model. The aim of this paper is to im-

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**Table 1**
Johnson Cook parameters [18].

| $A$(MPa) | $B$(MPa) | $n$ | $C$ | $m$ | $\dot{\varepsilon}_0$ |
|---|---|---|---|---|---|
| 514 | 514 | 0.508 | 0.042 | 0.533 | 0.001 |

**Table 2**
Thermo-physical properties of AISI 316 L steel and WC-Co cutting tool AISI [19].

| | |
|---|---|
| AISI 316 L steel | Density (kgm$^{-3}$): 7921–0.614 T + 0.0002 T$^2$ |
| | Young's modulus (MPa): 197,845 + 140,76 T–0.5714 T$^2$ + 0.000T$^3$ |
| | Poisson ratio: 0.3 |
| | Specific heat (J kg$^{-1}$ K$^{-1}$): 440.79 + 0.5807 T–0.001 T$^2$ + 7 10$^{-7}$ T$^3$ |
| | Inelastic fraction heat: 0.9 |
| | Thermal conductivity (W/m °C): 14.307 + 0.0181 T–6 10$^{-6}$T$^2$ |
| WC-Co | Density (kgm$^{-3}$): 13,000 |
| | Specific heat (J kg$^{-1}$ K$^{-1}$): 243 |
| | Inelastic fraction heat: 0.9 |
| | Thermal conductivity (W/m °C): 62.7 |

prove these FEMs in order to predict realistic RS curves induced by the orthogonal cutting process. A comparison between the different models is evaluated. Finally, a critical assessment of the relevancy of each technique is presented and their applicability and limitations in the surface integrity prediction is discussed.

## 2. Material constitutive law and friction model

### 2.1. Material constitutive law

In this study, the finite element analyses of the orthogonal cutting of stainless steel AISI 316 L with a carbide cutting tool are investigated. The isotropic constitutive material law of Johnson–Cook [17] has provided a good description of the material behaviour when subjected to large strains, high strain-rates and thermal softening. This law is incorporated in the three numerical models to describe the material response:

$$\overline{\sigma} = \left(A + B(\overline{\varepsilon_p})^n\right)\left(1 + C\ln\left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right)\right)\left(1 - \left(\frac{T - T_0}{T_f - T_0}\right)^m\right) \tag{1}$$

where $\bar{\sigma}$ is the equivalent flow stress, $\overline{\varepsilon_p}$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}_p$ is the equivalent plastic strain rate, $\dot{\bar{\varepsilon}}_0$ is the reference equivalent plastic strain, $T$ is the workpiece temperature, and $T_f$ and $T_0$ are the material melting and room temperatures, respectively. *A, B, C, n* and *m* are constitutive constants. The material constants and the thermo-mechanical properties are summarized in Tables 1 and 2, respectively.

### 2.2. Friction model

A friction model describing the interaction between a carbide pin and the AISI 316 L steel was carried out in the study of Valiorgue [20]. As a result, it was proved that the friction coefficient depended mainly on sliding speeds. Valiorgue et al. also developed this friction model for the cutting process. Thereby, the friction coefficients $\mu_1$ corresponding to the tool-chip contact and $\mu_2$ corresponding to the tool-machined surface contact was expressed as a function of both the sliding speed of the chip, $V_{chip}$ (m/min), and the cutting velocity, $V_c$(m/min), as follows:

$$\mu_1 = 0.39 - 0.002V_{chip} \tag{2}$$

$$\mu_2 = 0.39 - 0.002V_c \tag{3}$$

$$V_{chip} = \frac{V_c h}{b} \tag{4}$$

Where '*h*' is the undeformed chip thickness and b is the chip thickness.

## 3. Finite element models of orthogonal cutting

### 3.1. LAG model

The present section aims to develop a FEM model based on the LAG formulation. In this approach, the mesh follows the material deformation with the same velocity. A damage criterion is then required in order to separate the chip. In the current work, the ductile damage criterion available in Abaqus software, adapted to the AISI 316 L, is used. This criterion is a phenomenological model for predicting the damage initiation due to nucleation, growth, and coalescence of voids [21]. This model assumes that the equivalent plastic strain at the onset of damage $\bar{\varepsilon}_D^{pl}$ is as a function of the stress triaxiality and the strain rate: $\bar{\varepsilon}_D^{pl}(\eta, \dot{\bar{\varepsilon}}^{pl})$. where $\eta = \sigma_H/\sigma_{VM}$ is the stress triaxiality, $\sigma_H$ is the hydrostatic stress of the applied stress tensor, $\sigma_{VM}$ is the Von Mises equivalent stress, and $\dot{\bar{\varepsilon}}^{pl}$ is the equivalent plastic strain rate. The criterion for damage will be met when the following condition is satisfied:

$$\omega_D = \int \frac{d\bar{\varepsilon}^{pl}}{d\bar{\varepsilon}_D^{pl}\left(\eta,\ \dot{\bar{\varepsilon}}^{pl}\right)} = 1 \tag{5}$$

where $\omega_D$ is a state variable that increases monotonically with plastic deformation. The damage criterion parameters of the AISI316L steel are identified using the experimental data carried out by Lee et al [22–23].

Fig. 1 shows the geometric model as well as the boundary conditions of the proposed FEM. A long surface (12 mm) is simulated in order to achieve the steady state conditions which are necessary to predict the RS profiles. The cutting speed is applied to the tool and the workpiece is fixed. A multi-part model is used to optimize the contact management [24]. Indeed, the workpiece is composed of three parts: Part-1: the machined workpiece, Part-2: the tool–tip passage zone and Part-3: the chip. The assembly of the various parts numbered 1–3 is done by setting a constraint type (Tie constraint). A linear quadrilateral continuum plane strain mesh element CPE4RT with reduced integration is used . The mesh is refined (5 μm) in the first layers of the machined surface in order to enhance the model accuracy.

### 3.2. ALE model

ALE is a combination between LAG and Eulerian formulations. In fact, the mesh can be fixed in some regions (Eulerian) and can follow the material movement in others (LAG). The mesh can also move arbitrarily regardless the material in order to decrease deformation of elements, update free surfaces and produce chip geometry without using a damage criterion. Nevertheless, an initial form of the chip must be predefined in the model design in order to avoid mesh distortion, especially arising in the beginning of the cutting simulation. The main concern of this method is the implementation of Boundary Conditions (BCs). Based on the choice of these BCs, ALE models are classified in two main categories: ALE with a Eulerian trend and ALE with a Lagrangian trend [4].

In the present work, an ALE model with the Lagrangian trend is developed. A new implementation of the BCs is set up to approach to the real situation of the process. Figure 2 depicts the geometric model and the BCs implementation. In fact, The workpiece is split into four regions. Zones 1, 3 and 4 are lagrangian regions with a continuous remeshing which is applied so as to reduce mesh distortion during simulation. In these areas the mesh follows the material deformation which leads to produce free surfaces. Zone 4 presents the initial geometry of the chip, which does not affect both the final chip morphology after simulation and the physical mechanism of the process. The upper surface of the chip is free (Lagrangian boundary) enabling the chip formation until reaching the steady state conditions. A mesh constraint (Eulerian boundary) is applied on the left boundary of the workpiece in order to simulate a long machined surface. Zone 2 is a Eulerian region where the mesh is fixed in the space and the material flows through this grid as a fluid. In this area a refine mesh is utilized (4 μm with elements type CPE4RT) in