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Numerical assessment of residual stress induced by machining of aluminum alloy

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Abstract. A numerical approach has been developed to predict the near surface residual stresses induced by turning in orthogonal cutting configuration of aluminum alloy AA7075-T651. This approach is based on a Lagrangian formulation using the finite element software Abaqus–Explicit. The calculated residual stress profiles were validated by experimental measurements using X-ray diffraction method on samples turned under different cutting conditions. Using this method, the effect of the cutting speed and the feed on the machining residual stress has been established.

1. Introduction

The tool–material interactions under machining conditions modify significantly the properties of metal near surface layers 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 to predict the in–service lifetime of machined components subject to cyclic loading or stress corrosion cracking.

For long time, the appreciation of the surface integrity and the properties of the near surface layers affected by machining were based on experimental approaches combining a variety of techniques and methods of mechanical and physicochemical investigations [1-3]. These approaches are expensive and lead to more or less significant uncertainties of surface properties. In fact, numerical approaches have been developed to reduce machining costs and improve product quality. The manufacturing industry recently addresses these issues by increasing the implementation of simulation tools for the specific operations included in their processing chain.

The numerical approaches found successful applications in recent years. They are mainly used to predict machining power or tool life by estimation of cutting forces and generated heat. Nevertheless, numerical models are rarely used to predict the properties of machined surface for the case of aluminum alloys.

Nevertheless, numerical simulation results are very sensitive to the used material behavior laws, friction model and mesh smoothness [4, 5]. In addition, simulated machining residual stresses are rarely validated by experimental measurements for different cutting conditions. The models validations are usually based on cutting forces measurements [6-8].

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 Lagrangian formulation using the commercial finite element code Abaqus–Explicit and experimental material behavior law and friction model. Experimental cutting tests are conducted on the AA7075-T651 aluminum alloy under different cutting conditions. Residual stresses fields, induced by machining, are evaluated by X-Ray diffraction method and used for calibration and validation of the finite element model. Experimentally validated approach is used to investigate the effects of cutting conditions on machining induced residual stresses.

2. Numerical approach:

The proposed numerical approach consists to simulate the thermo-mechanical phenomena acting in the cutting zone during turning of 7075-T651 aluminum alloy in orthogonal cutting configuration. In this approach a plane-strain coupled thermo-mechanical analysis was performed using the finite element code Abaqus-Explicit. For a better prediction of residual stress distribution induced by orthogonal cutting, a Lagrangian formulation is used to describe motions where material points are considered connected to the mesh nodes. The workpiece and tool geometries, thermo-physical properties, material behavior model, cutting conditions, and friction law are introduced in the finite element model to simulate machining operations. Then, cutting forces and residual stress retained as main machinability indicator were numerically determined and compared to those established experimentally on the 7075-T651 aluminum alloy to prove the numerical procedure efficiency. Once this procedure validated, these results were used to study the effect of cutting speed and feed on machining residual stress distribution (Fig.1).

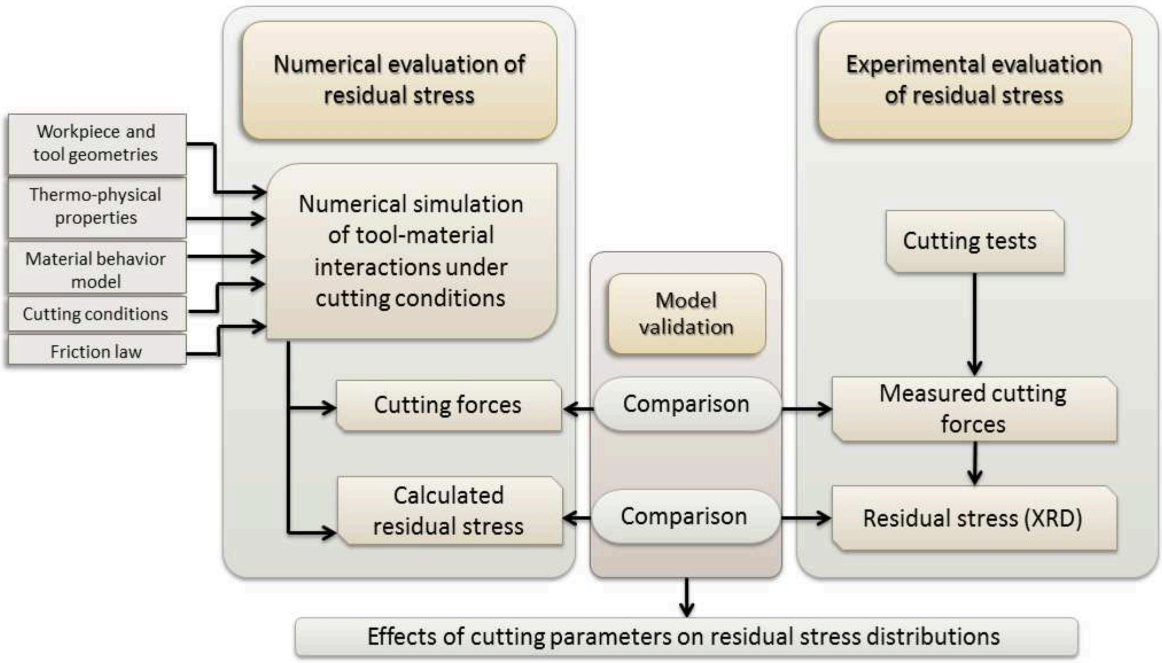


Fig.1 Proposed procedure for residual stress assessment

2.1.Finite element model description

The workpiece and tool geometries are introduced in the model and meshed with, respectively, 10650 and 721 isoparametric quadrilateral elements (CPE4RT) available in Abaqus element library (Fig. 2). In the current model, the mesh is extremely refined near the tool–workpiece and tool–chip interfaces until a length of 8 µm for the workpiece and 6 µm tool's elements. Two types of boundary conditions were introduced (mechanical and thermal) into the model for both workpiece and tool geometries (Fig.2).The workpiece is fixed on the bottom face while the cutting velocity was applied to the tool. The heat transfer between the part and the ambient air is controlled by air convection factor h2= 10 Kw/m2 K. thermal conductance coefficient (h1) of 1000 Kw/m2 K was used to characterize the heat transfer at the tool–chip and tool–workpiece interfaces.

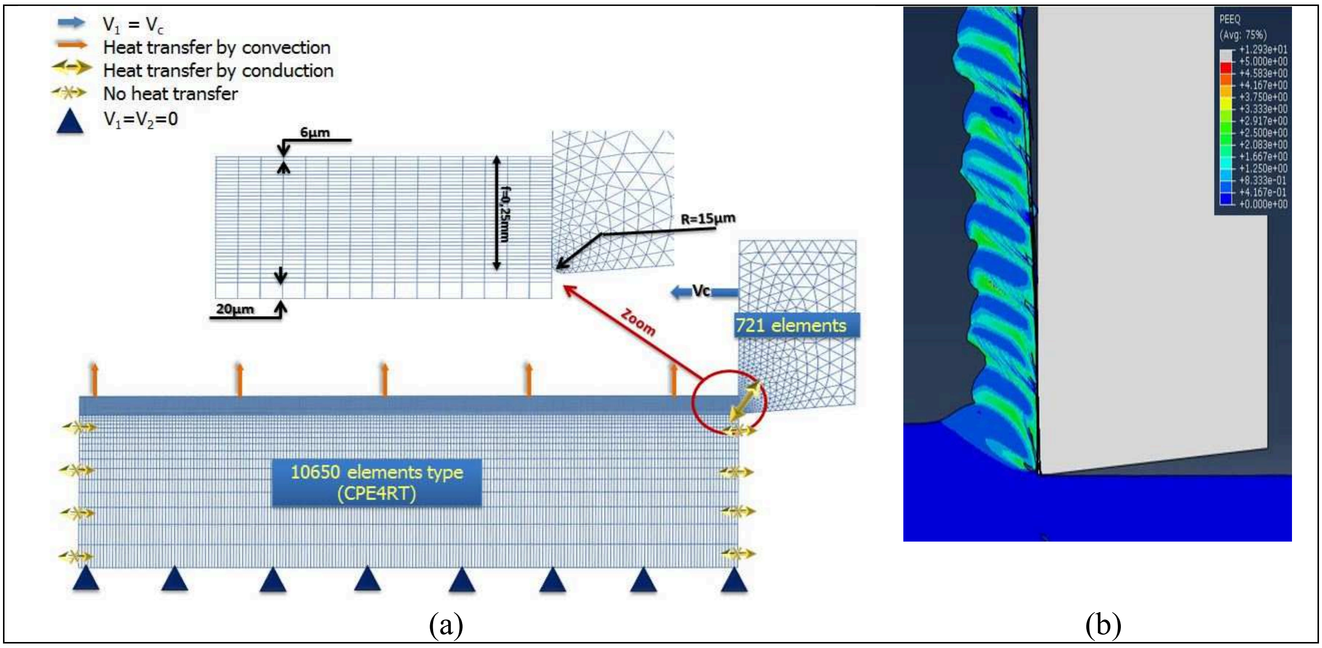


Fig.2 Numerical simulation,a: Mesh, boundary and initial conditions, b: Numerical result

The AA7075-T651 thermo–mechanical properties are introduced in the finite element code as function of temperature to describe the material behavior of the workpiece during orthogonal cutting, a Johnson-Cook thermo-visco-plastic model has been used [9]. This law, expressed by Eq. 1, provides a good behavior description of material subjected to large strains, high strain rates and thermal softening.

$$\sigma = (A + B(\bar{\varepsilon})^n)(1 + C ln\dot{\bar{\varepsilon}}^*)(1 - (T^*)^m) \qquad (1)$$

where: $\dot{\bar{\varepsilon}}^* = \frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_0}$ and $T^* = \frac{T-T_0}{T_m-T_0}$

In Eq.1, σ is the material flow stress, $\bar{\varepsilon}$ is the equivalent plastic strain, $\dot{\varepsilon}_0 = 10^{-3} s^{-1}$ is the reference plastic strain rate, $\dot{\bar{\varepsilon}}$ is the plastic strain rate, T_m and T_0 are the melting and the room temperatures, respectively. The coefficients (A, B, C, n and m), listed in Table1, are obtained from [10].

Table1 Johnson-Cook behavior law parameters of AA7075-T651

A (MPa)	B (MPa)	C	n	m
527	676	0.017	0.71	1.61

The contact between tool and workpiece is defined by simple Coulomb law (Eq.2) on the whole contact zone where the frictional stress τ depends on the normal stress σ_n acting on tool rake surface and carbide-aluminum alloy friction coefficient µ approximated to 0.2.

$$\tau = \mu . \sigma_n \qquad (Eq.2)$$

In this work to assess the numerical approach prediction capabilities, calculated residual stress must be validated by experimental measurements curried out on aluminum AA7075-T651 samples.

2.2.Evaluation of turning residual stress tests using the X-ray method

In the current work, the samples used for cutting tests are disks with a thickness of 15 mm obtained from a bar of AA7075-T651with a diameter of 80 mm (Fig. 3). The orthogonal cutting tests were conducted on a numerical controlled lathe (RealMeca T400), using an uncoated carbide tools with a rake angle γ of 0°, a clearance angle α of 7° and a cutting edge radius Rn of 20µm.

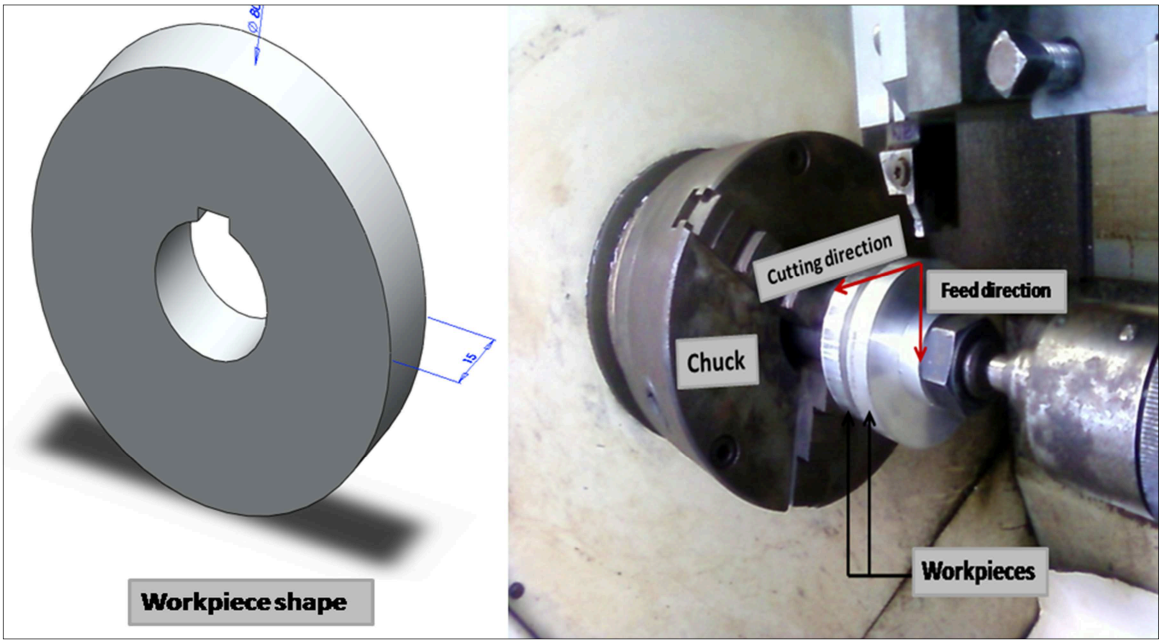


Fig. 3 Experimental setup used for orthogonal turning and cutting force measurement

Residual stress profiles were evaluated by the ψ tilt X-ray method using a SET-X-type diffractometer. The in-depth residual stress and peak half width profiles were measured after performing an incremental electrochemical etching.

3. Results and discussion:

3.1. Validation of numerical procedure:

To evaluate the efficiency of the numerical procedure, the calculated cutting forces (Fig.4) and residual stresses (Fig. 5) are compared to those measured experimentally. These results show a good agreement between numerical and experimental data proving the satisfactory capability of the suggested procedure to predict the gradients of properties induced by machining.

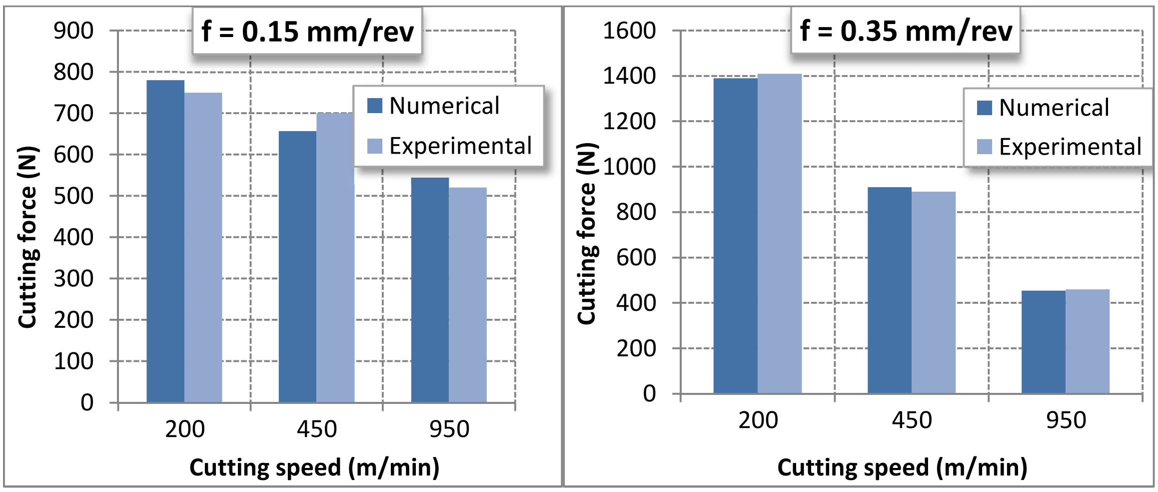


Fig. 4 Calculated and measured cutting forces during turning of the AA 7075-T651

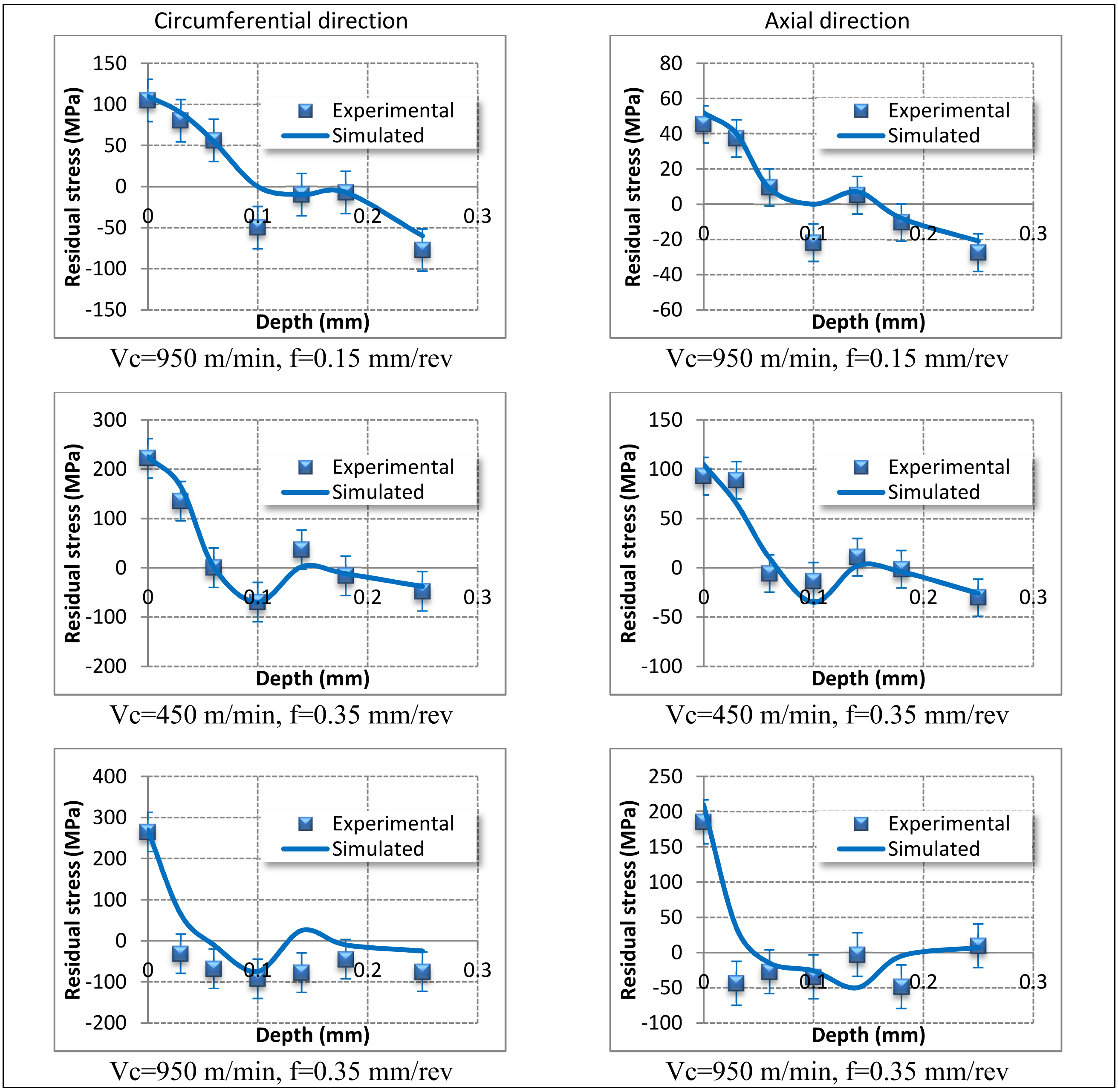
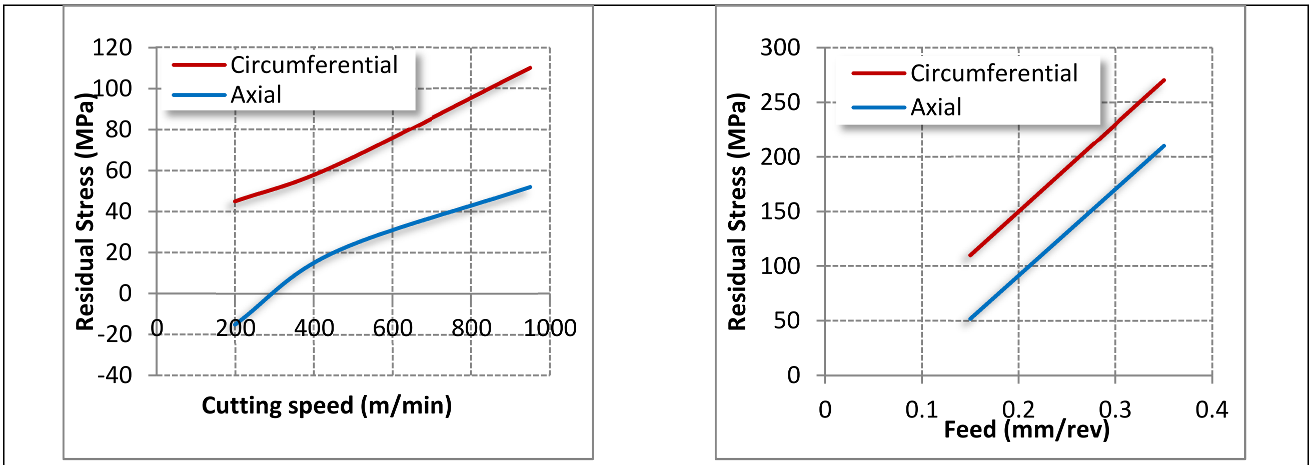


Fig. 5 Calculated and measured residual stresses induced by turning of the AA 7075-T651

3.2.Numerical results and discussion

The numerical simulation procedure established and validated in this study will be used to reveal the impact of cutting conditions on AA7075-T651 surface properties. Fig.6 shows that residual stresses in cutting direction (circumferential) and axial are mostly tensile and varies from -20 to 270 MPa and they are much higher in first direction. It can be seen from numerical result that the cutting speed and the feed have a significant influence on the surface residual stresses. In fact, the increase of cutting speed (Fig. 6a) or feed (Fig. 6b) leads to an increase of surface residual stress in both directions. These results can be explained by the contribution of the thermal effect generated by plastic strain during metal cutting. Thermal effect can be explained by an increase of heat fraction transferred to workpiece from cutting zone. Indeed, two sources of heat are assumed to generate the temperature rise in the cutting zone: plastic deformations in shear zones and friction between the tool and the workpiece. The created heat is transferred to chip, to tool and to workpiece in proportions depending on tool and material properties and cutting conditions. A higher quantity of heat is then transmitted to the workpiece surface causing an increase of tensile residual stress.



(a) (b)

Fig. 6 Effect of cutting conditions on surface residual stress, a: effect of cutting speed, b: effect of feed

4. Conclusion

In this study a numerical approach was developed to predict machining induced residual stresses in orthogonal cutting configuration. The simulated machining residual stresses are experimentally validated by X-ray diffraction in different cutting conditions and supported by an assessment of residual strain which is the basis of their generation. The good agreement between experimental and numerical results proves the efficiency of the proposed procedure to investigate the influence of cutting parameters on the gradient of properties of machined surface. The model has been applied to predict the residual stress and plastic strain induced by machining the AA7075-T651 aluminum alloy with different levels of cutting speed and depth of cut. Numerical results show that a reduction of tensile stress level in machined subsurface was obtained when a low cutting speed and depth of cut are used. This result was confirmed by experimental investigations. The proposed methodology can be extended for other materials and cutting processes.

References

[1] B. Ben Fathallah, N. Ben Fredj, H. Sidhom, C. Braham, Y. Ichida, International Journal of Machine Tools & Manufacture, 49 (2009) 261-272.

[2] Ben Moussa N., Sidhom H., Braham C., International Journal of Mechanical Sciences, 64 (2012) 82-93.

[3] Z. Al-Adel, N. Ben Moussa, H. Yahyaoui, H. Sidhom, Design and modeling of mechanical systems, (2013) 485-492.

[4] K.C. Ee, O.W. Dillon, I.S. Jawahir, International Journal of Mechanical Sciences, 47 (2005) 1611-1628.

[5] M.N.A. Nasr, E.-G. Ng, M.A. Elbestawi, International Journal of Machine Tools & Manufacture, 47 (2007) 401-411.

[6] Z.C. Lin, Y.Y. Lin, Journal of Materials Processing Technology, 115 (2001) 313-325.

[7] C.R. Liu, Y.B. Guo, International Journal of Mechanical Sciences, 42 (2000) 1069-1086.

[8] C. Maranhao, J.P. Davim, Simulation Modelling Practice and Theory, 18 (2010) 139-156.

[9] G.R. Johnson, W.H. Cook, Proceedings of the Seventh International Symposium on Ballistics, The Hague, The Netherlands, 54 (1983) 541-547.

[10] N.S. Brar, V.S. Joshi, B.W. Harris, AIP Conference Proceedings, 1195 (2009) 945-948.