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FEM based investigation on thrust force and torque during Al7075-T6 drilling

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Abstract. As modern industry advances, the demand for more time and cost effective machining is rising. In order to achieve high levels of standard during machining it is necessary to employ sophisticated techniques for precise prediction of various important parameters that relate to the machining processes. Such technique is the implementation of finite element modelling (FEM) which can become a valuable tool for researchers and industry engineers alike. In this work, the 3D modelling of Al7075-T6 drilling process with solid carbide tooling is being presented. DEFORM3D™ finite element analysis (FEA) software was utilized for simulating the drilling process based on frequently used cutting conditions; cutting speed of 100m/min and feed of 0.15mm/rev, 0.20mm/rev and 0.25mm/rev respectively. In order to approximate the complex phenomena that occur during drilling, the most critical factors were considered in the presented model such as the developed friction, heat transfer and damage interaction between the tool and the workpiece. Additionally, a validation of the generated results for thrust force and torque was performed by comparing the simulated results with experimental data. Three drilling experiments were carried out with the aid of a CNC machining center and a four component dynamometer in order to acquire the experimental values of thrust force and torque. Most of the simulations yielded results in accordance to the experimental ones with the agreement percentage reaching 95% in most cases for both the thrust force and torque, confirming the validity of the models and the accuracy of the simulated results.

1. Introduction

Finite element modelling (FEM) of cutting processes is a relatively new area of research with an increasing interest. Especially, the investigation of standard machining processes such as turning, drilling and milling seems to benefit from the employment of FEM and the recent advantages.

Maranhão and Davim [1] investigated the thermo-mechanical behavior when machining stainless steel AISI 316 to determine the influence of the friction coefficient in the tool-chip interface on several parameters such as cutting and feed forces, cutting temperature, plastic strain, plastic strain rate, maximum shear stress and residual stresses. In addition, authors performed a number of experiments for validation of the numerical results. Maurel-Pantel [2] realized simulations of shoulder milling operations on AISI 304L stainless steel using commercial software. Moreover, authors carried out a number of experiments in shoulder milling configurations in order to study the machinability of the material and also to validate the results obtained from the developed 3D FE model. Attanasio et al. [3] simulated the tool wear in drilling of Inconel 718 to study its influence on tool life, on final part quality and on cutting force and power consumption. Dou et al. [4] developed a prediction model based on a new constitutive model for Al6063 to predict thrust force and torque in drilling, which involves in the volume fraction of the material reinforcement. Additionally, authors established a 3D finite element (FE) model for simulating the drilling process of SiCp/Al6063 by using the new constitutive model. Nan et al. [5] studied the three-dimensional FE modeling for simulating the small-hole drilling process of AISI 1045. The verification of the model was performed via drilling experiments with 3mm diameter solid carbide drills at different rotational speeds and feeds. Xiang et al. [6] worked on a universal method that can be used to determine whether the constitutive formalism is suitable to describe the material constitutive behavior by measuring goodness-of-fit. A quantitative comparison of different fitting strategies on identifying Al6063/SiCp's material parameters was made in terms of performance evaluation including noise elimination, correlation, and reliability. Lastly, authors developed a 3D FE model in small-hole drilling of Al6063/SiCp composites to compare with the experimental observations in thrust force, torque, and chip morphology. Tzotzis et al. employed 3D FEM for developing prediction models for the generated cutting forces during turning of AISI-4140 [7] and drilling of Al7075-T6 [8] respectively.

In the present study, a 3D FEA was realized with DEFORM3D™ for investigation purposes of the Al7075-T6 behavior during drilling. Furthermore, validation of the numerical results was performed via experimental testing. With the utilization of a rotating dynamometer, the thrust force and the generated torque were determined and compared to the numerical values obtained from the 3D FE model. The comparison indicates that the FE modelling of drilling is feasible and yields accurate results.

2. Materials and Methods

2.1. *Overview of the experimental process*

In order to acquire the experimental results, three drilling experiments were conducted. A CNC machining center was employed for improved accuracy of the experiments. A rectangular piece (150mm x 130mm x 15mm) of Al7075-T6 alloy was chosen to serve as the workpiece, whereas a solid carbide drill from Kennametal (product code: B041A1000CPG - KC7325 grade), was used as the tool for the drilling experiments. The used tool contains 10% cobalt and is double coated. Moreover, the outer layer of the coating is a layer of TiN with 15 micron thickness and the inner layer of the coating is a multilayer of TiN/TiAlN with 3.5 micron thickness. In addition, Table 1 presents the most important geometric aspects of the used tool.

Table 1. Geometric parameters of B041A1000CPG drill.

Product code	Cutting diameter	Point angle	Helix angle	Chisel edge length	Point height
B041A1000CPG	10mm	140°	30°	0.35mm	1.71mm

A Kistler 9123C rotating four-component dynamometer was utilized to acquire both the thrust force and the produced torque during the experiments. The experimental values were monitored with Dynoware software (type 2825D-02) via a multichannel charge amplifier and a standard data acquisition system. Additionally, the sampling rate was set to approximately 10 kHz.

Figure 1 depicts the physical drill used in this study (a), the HAAS VF1 CNC machining center (b) and the setup of the tool – dynamometer – workpiece (c).

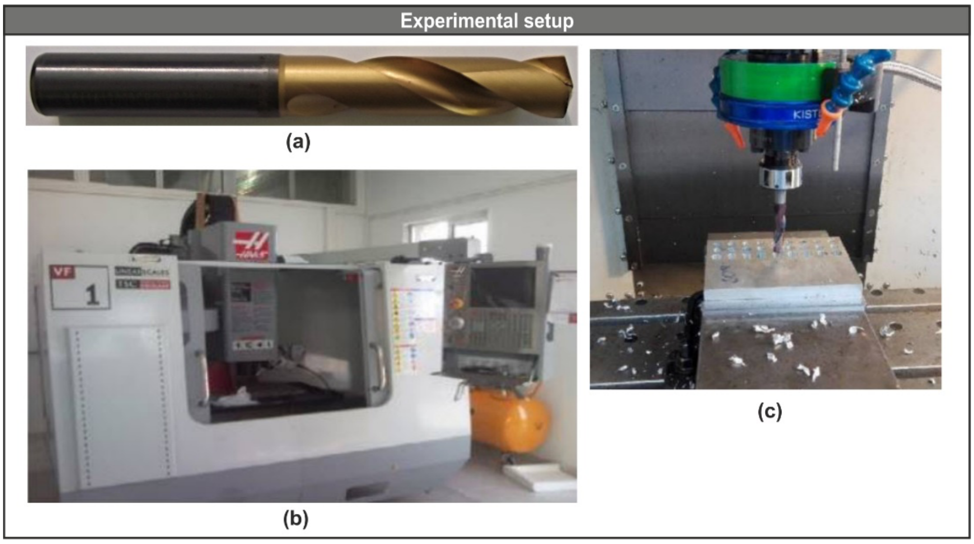

Figure 1. The setup of the experimental process.

2.2. *Overview of the simulation process*

The 3D cutting simulations of the drilling experiments were carried out with the commercially available finite element analysis software DEFORM3D™ ver. 11.3. To accelerate the process, the simulations were halted when the thrust force and thus the torque reached steady state. In order to simplify the workpiece model it was designed as a thin cylindrical piece. Due to the fact that the area of interest on the workpiece is located in the middle (based on the circular design), a spot according to the point angle of the tool was created (see Table 1). This design ensures that no time will be lost during the penetration of the drill bit to the workpiece. It was modelled as plastic and meshed with about 200000 elements. Moreover, a ratio of 10:1 was used for the localized meshing of the center spot, for increased accuracy (Figure 2b). On the other hand, the tool was modelled to be fully rigid and approximately 25000 triangles were used for the mesh. Figure 2a depicts the CAD model of the used tool. A 4:1 ratio was applied to the tip (Figure 2b) because most of the phenomena that occur during drilling are located in this area. Finally, Figure 2c illustrates the tool - workpiece model setup; to further simplify the problem only the tip of the drill was used.

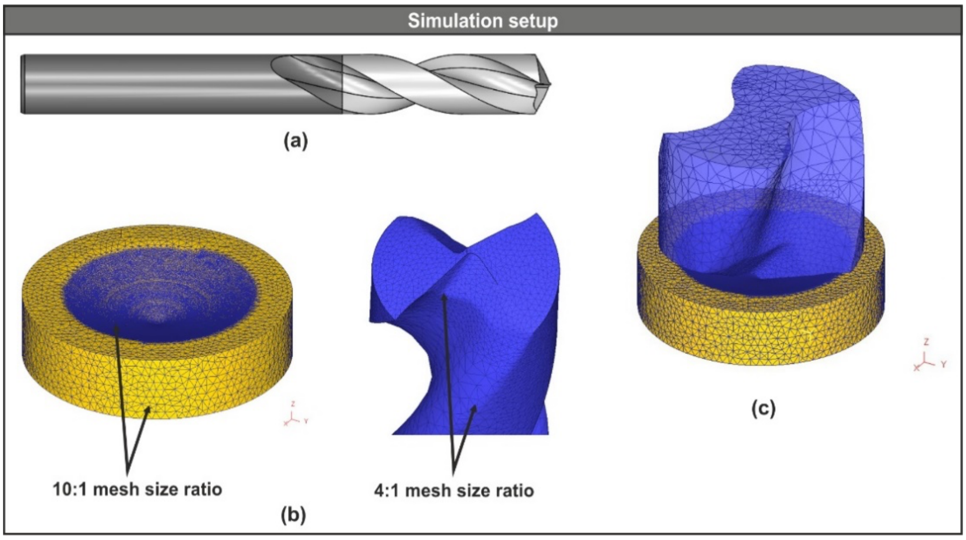

Figure 2. The setup of the simulation process.

The Johnson-Cook flow stress model is widely adopted when the problem involves high strain, strain rate and temperatures, therefore it was used in the present numerical study. In addition, the material constants have been determined for a large number of materials that exist in current literature. Equation 1 describes the aforementioned model [9], whereas Table 2 includes most of the important material properties of the Al7075-T6 alloy, as well as the constitutive model parameters.

$$\sigma = \left(A + B\varepsilon^n\right)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right] \quad (1)$$

Table 2. Basic thermo-mechanical properties [10] and model constants of Al7075-T6 [11].

Al7075-T6 properties				
Young's modulus [GPa]	Density [kg/m^3]	Poisson's ratio	Thermal expansion [μm/m°C]	Thermal conductivity at 20°C [W/mK]
71.7	2810	0.33	2.2x10^{-5}	130

Constitutive model						
A [MPa]	B [MPa]	C	n	m	T_0 [°C]	T_m [°C]
546	678	0.024	0.71	1.56	20	635

In equation 1 A is the initial yield stress, B is the strain hardening modulus, C is the strain rate dependence coefficient, ε denotes the plastic strain, n is the strain hardening exponent, m represents the thermal softening coefficient, $\dot{\varepsilon}$ is the plastic strain rate, $\dot{\varepsilon}_0$ is the reference plastic strain rate, T is the reference temperature, T_0 is the bulk temperature of workpiece material and finally T_m stands for the melting temperature of workpiece material. In the present numerical study, a reference strain rate of 1/s was used.

In order to approximate the physics of material separation that occur in the deformation zones, the damage model of Cockcroft and Latham was selected [12]. This model depends on the maximum principal stress. The contact pressure at the tool-workpiece interface generates frictional forces that can be determined with the aid of a hybrid model [13]; the constant shear friction coefficient is $m = 0.7$ for the sticking zone and the constant Coulomb friction coefficient is $\mu = 0.6$ for the sliding zone.

The boundary conditions and the movement controls were set in such a manner that the workpiece remained fixed and the tool could rotate around Z axis based on the given cutting speed. In addition, linear motion along –Z axis was applied to the tool so that it could travel towards the workpiece with the given feed. Furthermore, the heat exchange between the workpiece and the environment was defined, as well as the heat exchange between the tool tip and the workpiece (contact region). The default coefficient values for heat transfer were applied to the model for both convection and conduction.

3. Results and discussion

The cutting conditions that were applied to both the experiments and the simulations are: cutting speed of 100m/min combined with three different feeds (0.15mm/rev, 0.20mm/rev and 0.25mm/rev respectively). The produced numerical results of thrust force and torque and the equivalent diagrams versus time were exported for further study. To avoid any unrealistic values for thrust force and torque due to remeshing, the first order exponential smoothing was applied to the simulated results. Figure 3a depicts a sample thrust force diagram, whereas Figure 3b illustrates a sample torque diagram. It is pointed out that both the thrust force and the torque for the given conditions increase rapidly until the point where steady state occurs (at approximately 0.01 sec). Moreover, this trend was noticed in all three simulations.

The obtained numerical results were compared to the experimental ones for validation purposes. Comparison study shows a good agreement between the numerical results and the experimental ones for both the thrust force and the torque. The relative error for F_z was calculated 0.81% for the first combination of cutting conditions (V_c = 100m/min and f = 0.15mm/rev), whereas for the other two (V_c = 100m/min and f = 0.20mm/rev, f = 0.25mm/rev) was found to be −3.4% and −4.7% respectively. Similarly, the relative error for M_z was determined 2.1%, 1.2% and −3.3% accordingly for each of the three aforementioned cases. Furthermore, the value of standard deviation of F_z for the three simulation tests was calculated 47.9N, 28.4N and 64.6N accordingly. On the other hand, standard deviation for M_z was determined 132.9Nmm, 146.8Nmm and 164.3Nmm for each of the cutting conditions combination. Finally, it is noticed that the maximum value of simulated thrust force (F_z = 751.6N) and torque (M_z = 3269Nmm) was found to be in the test with the highest value of feed (f = 0.25mm/rev), similarly to the experiments. This fact indicates that the increase of feed from 0.15mm/rev to 0.25mm/rev rises F_z by 31% and M_z by 46.7%.

Figure 3c presents the comparison between the numerical and the experimental results for thrust force Fz, in the same way, the chart of Figure 3d illustrates how the simulated values of torque M_z correlate to the experimentally acquired values.

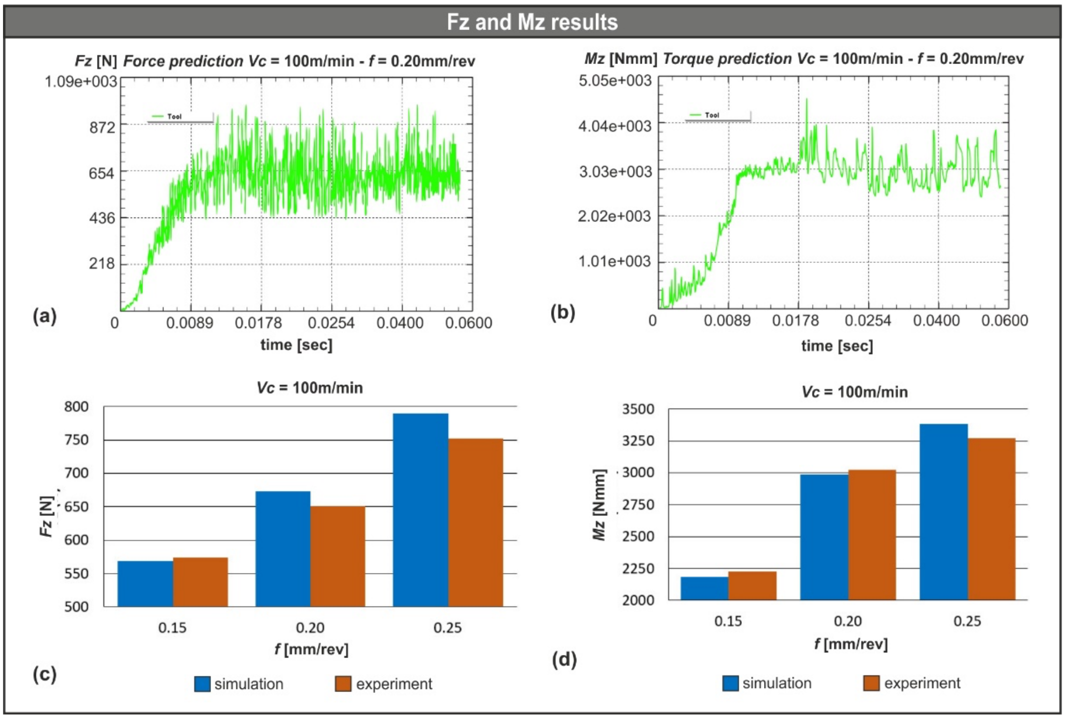

Figure 3. Comparison between the simulated and the experimental results.

4. Conclusions

In the present study, three drilling simulation tests were performed with the implementation of 3D FE modelling. The selected workpiece material is Al7075-T6 alloy and the used tool a solid carbide drill of 10mm diameter. Moreover, the chosen cutting conditions are a combination of cutting speed of 100m/min and feed of 0.15mm/rev, 0.20mm/rev and 0.25mm/rev respectively. The generated numerical results for thrust force and torque were verified via experimental testing, the comparison study showed that the simulated results are in good accordance with the experimental ones. Eventually, the findings of the numerical study lead to the following conclusions:

- Feed strongly affects the produced thrust force and torque. Specifically, an increase in feed from 0.15mm/rev to 0.25mm/rev and for the same cutting speed, increases thrust force by 31% and torque by 46.7% correspondingly.

- The relative error for both thrust force and torque was found to be relatively low which proves the accuracy of the 3D FE model.
- Moreover, the standard deviation values for F_z were determined between 28.4N to 64.6N and for M_z between 132.9Nmm to 164.3Nmm which further proves the validity of the 3D FE model.

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