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A STUDY ON SIMULATION OF METAL CUTTING PROCESS BASED ON LS-DYNA

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ABSTRACT

Metal cutting is one of the most important processes in the manufacturing industries for fabricating a particular product or a mechanical part. It was very difficult to research the performance of a cutting process because the complex physical phenomenon of the cutting operation makes it a challenging task in research. This paper presents numerical simulations of the metal cutting Smoothed Particle Hydrodynamics (SPH) method. In this paper, the two cutting metal models were built by using SPH technique. The results obtained using the model assures the exactness of the proposed method and prove that the SPH method is a practical approach for eliminating metal cutting problems.

1. INTRODUCTION

Metal cutting machining is one of the most important processes in the manufacturing industries for fabricating a particular product or a mechanical part. In the cutting processes, the material is removed from the workpiece surface by the cutting tool to achieve the desire product. Metal cutting processes such as turning, drilling, and milling are one of the most widely-used procedures in the manufacturing. However, although all the effort that has been expended, it is still difficult to predict the performance of a cutting process because the complex physical phenomenon of the cutting operation makes it a challenging task in research.

During the operation procedure heat generation, friction, chipformation, cracking, and large deformation of the workpiece surface layers arise due tocutting tool intervention. The experimental method is an ideal approach for understanding results and research the metal cutting. However, the experimental approach is very complex, costly and time-consuming. For example, T. Augspurger et al. [1] presented an experiment to investigate thermal boundary conditions at characteristic regions of metal cutting process. Kumar et al. [2] used an experiment to demonstrate influence of cutting speed with constant depth of cut on cutting force and surface roughness through turning of Al2219 alloy and AMMHCs. Puls et al. [3] presented an experimental test to analyze friction phenomena within the tool–chip interface in metal cutting. Zhang et al. [4] determined the lubrication performance of MoS2/CNT nanofluid for minimal quantity lubrication in Ni-based alloy grinding based on experimental results. Artozoul et al. [5] proposed an analytical thermal model of metal cutting based on experimental approaches. In their work, Karmiris-Obratanski et al. [6] conducted experiments on AWJ machining of Al7075-T651 in order to study the correlations between process parameters and its outcomes such as the depth of penetration, kerf width and kerf taper angle. Yadav et al. [7] carried out an experiment to investigate chip formation and shear localization phenomena in cutting.

Therefore, the numerical models were used by many researchers in order to investigate the metal cutting process. The finite element method (FEM) is the most popular method to constructing the numerical model of metal cutting [8-16].

However, the FEM has some difficulties in modelling problems involvinghourglass, negative volume and distortion of mesh. These problems require a special technique to solve. Many studies employed the Arbitrary Lagrangian-Eulerian (ALE) method to treat the excessive element distortion by using the Johnson-Cook (J-C) material model take into account the equation of state (EOS). Liu et al. [17] used 3D FEM simulation to investigate the performance of newly designed curvilinear micro-grooved tool with non-textured and linear micro-grooved tools. Sampsa et al. [18] presented the effect of the tertiary shear zone on damage model performance in FEM-modelled chip formation. Parida et al. [19] proposed the effect ofnose radius on forces, and process parameters in hot machining of Inconel 718 using FEM analysis. Bollig et al. [20] performed a comparison of three different methods of simulation of heat sources in 3D-FEM-simulations with various levels of abstraction for drilling [20]. Laakso [21] used FEM to investigate the effect of temperature-dependent material properties on metal cutting. A 3D FE model of hard milling AISI H13 steel was developed by Zhang et al. [22] to predict cutting effects and cutting temperature depending on cutting parameters. Kong et al.

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[23] developed FEM based model of pure iron to determine the precision of cutting. González et al. [24] developed several models to predict dynamic recrystallization during orthogonal cutting of AISI 4140 using FEM-models. In ALE, the issues of element distortion, entanglement, and material separation were taken into account through re-meshing the unexpected mesh domain. However, this method was not only cost time but also difficult, sometime the researcher need a powerful tool for meshing. Thus, there were many tasks to investigate metal cutting with the ALE approach.

SPH (Smoothed Particle Hydrodynamics) is a meshless Lagrange method developed initially to model the fluid equations of motion problems. SPH is useful method in certain class of problems where ALE mesh distortions occur. Therefore SPH is a very interesting tool to solve the complex physic phenomenon.

There were a lot of studies used the SPH methods to model machining processing. For instance, Afrasiabi et al. [25] presented an implementation of a meshfree method to simulate an orthogonal metal cutting operation. The workpiece material is made of TiAl6V4. Islam et al. [26] presented numerical simulations of metal machining processes with Eulerian and Total Varangian SPH. Peng et al. [27] used SPH simulation to investigate the diamond fly-cutting milling of zirconia ceramics. Xi et al. [28] used SPH method in their research to develop machining models to study the thermally assisted machining of Ti6Al4V alloy. Madaj and Piska [29] presented some results of the SPH orthogonal cutting simulations of A2024-T351 aluminum alloy compared to the experimental and FEM simulation results. Shchurov et al. [30] used SPH method to simulate the fiber-reinforced composite workpiececutting for the quality product. Takabi et al. [31] conducted a numerical study of SPH, a mesh-free method, for orthogonal cutting simulations of both ductile and brittle materials. In their study, Stenberg et al. [32] used SPH method to predict wear in the machining. Zhang and Zong [33] built a FE-SPH model to simulate the effect of tool inclination angle in oblique diamond cutting of crystal. A FEM with a smoothed particle hydrodynamics approach were coupled to simulate guillotine cutting of multi-layered aluminum sheets by Gasiorek et al. [34]. The main focus of the paper by Spreng and Eberhard [35] was on the capability of the extended SPH solid model to describe real machining processes in simulations.

The meshless and Lagrangian nature of SPH makes it a good choice for metal cutting modelling. Hence, SPH simulation technique is an effective method to study the material cutting process. However, the researchers often use SPH for turning with the block workpiece.This method was rarely applied in the milling and drilling until now. In this study, series of numerical simulation based on SPH method were conducted on threepopular machining: turning, milling and drilling. This research performed FEM analysis of cutting process on the basis of the existing full-scale crash tests by using LS-DYNA software. The objective of this study is to develop and validatethe cutting process and thus to prove that SPH method is a reasonable approach to cutting research problems.

2. METAL CUTTING AND SMOOTHED PARTICLE HYDRODYNAMICS METHOD

2.1. Metal cutting

Metal cutting processes are manufacturing processes in which metal parts are shaped by the removal of unwanted material from the workpiece so that what remains is the desired final geometry. Metal cutting processes can also be applied to nonmetallic materials such as polymers, wood, and ceramics. When these applications are considered, the subject is more commonly called machining. Therefore, machining is a manufacturing process in which a cutting tool is used to cut away material to achieve the desired part shape. The predominant cutting action in machining involves shear deformation of the work material to form a chip; as the chip is removed,a new surface is shown. There were many kinds of machining operations from the past but for now there were the most common types: turning, drilling, and milling, illustrated in Fig. 1.

In turning, a cutting tool is used to remove material from a rotating workpiece to generate a cylindrical part. The speed motion in turning is provided by the rotating workpiece, and the translating motion - from the cutting tool. Drilling is used to create a round hole. Drilling is the manufacturing process, where a hole is created within a work piece or enlarged by rotating cutting tool. Milling is a process in which the cutters rotate to remove the material from the work piece in the perpendicular direction to the tool's axis of rotation.

The cutting tool or cutter is any tool that is used to remove some material from the work piece and is made of a material that is harder than the workpiece material, as shown in the Fig. 1.

Moreover, the Fig.1 also shows the relative motion required between the cutting tool and workpiece to perform a machining operation as known the cutting condition. The primary motion is accomplished at a certain cutting speed v. In addition, the tool must be moved laterally across the workpiece. This is a much slower motion, called the feed rate f. The remaining dimension of the cutting is the penetration of the cutting tool below the original workpiece surface, called the depth of cut t. Collectively, speed, feed, and cutting depth are called the cutting conditions. They form the three dimensional nature of the machining process, as known cutting parameters.

2.2. Smoothed Particle Hydrodynamics method

Smooth particle hydrodynamics (SPH) is a meshfree, Lagrangian particle method for modeling fluid flows and solid bodies. The method was developed to avoid the limitations of mesh tangling encountered in extreme deformation problems with the finite element method and to model the complex free surface and material interface behaviors, including the break-up of solids into fragments. A main difference between classical methods and SPH is the absence of a grid. Therefore, the particles are the computational framework on which the governing equations are resolved. SPH has been applied extensively to problems involving incompressible flows, heat conduction, high explosives, and high velocity impacts. The SPH method in LS-DYNA software is coupled with the finite and discrete element methods to extend its application to a variety of complex problems involving multi-physics.

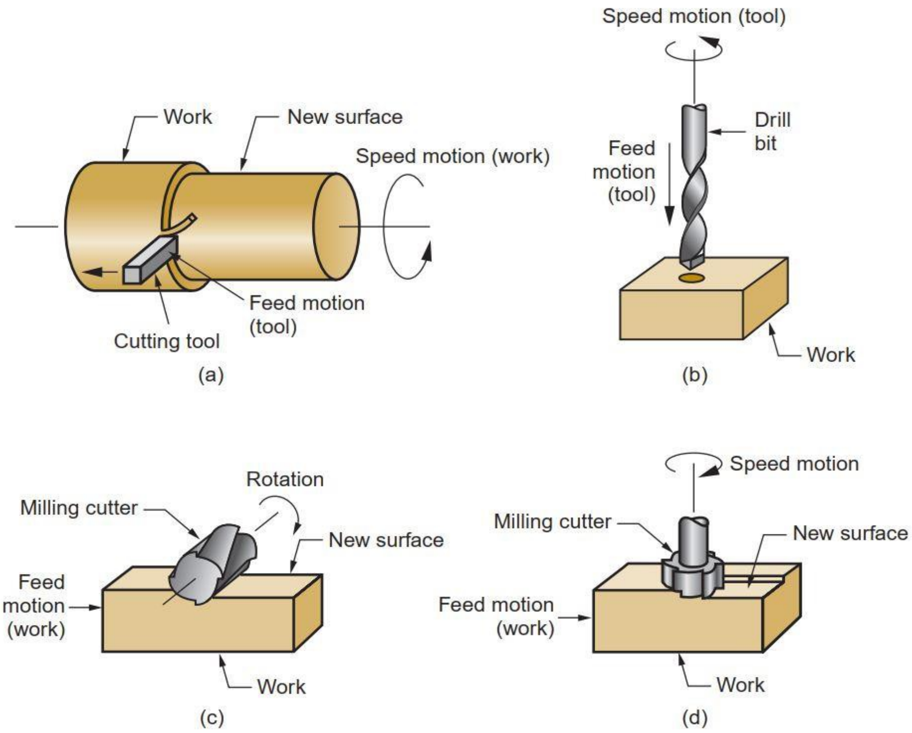


Fig. 1. Three most common types of machining processes: (a) turning, (b) drilling, and (c), (d): two forms of milling [36]

❖SPH Formulation [37,38]

The particle approximation of a function is:

$$\prod^h f(x)=\int f(y)W(x-y,h)dy\,, \tag{1}$$

where W is the kernel function is defined using the function θ by the relation:

$$W(x,h)=\frac{1}{h(x)^d}\theta(x)W(x,h), \tag{2}$$

where d is the number of space dimensions and h is the so-called smoothing length which varies in time and in space. The most common W function used by the SPH is defined by θ as:

for

$$\theta(u)=\begin{cases}1-\frac{3}{2}u^2+\frac{3}{4}u^3 & for\ |u|\le 1\\ \frac{1}{4}(2-u)^3 & for\ 1\le|u|\le 2\\ 0 & for\,|u|>2\end{cases} \tag{3}$$

where C is a constant of normalization that depends on the number of space dimensions. The SPH method is based on a quadrature formula for moving particles $x_i(t), i\in\{1...N\}$, where $x_i(t)$ is the location of particle i, which moves along the velocity filed v. The particle approximation of a function can be expressed by:

$$\prod^h f(x_i)=\sum_{j=1}^{N} w_i f(x_i)W(x_i-x_j,h), \tag{4}$$

where $W_j=\frac{m_j}{p_j}$ is the "weight" of the particle. The weight of a particle varies proportionally to the divergence of the flow. We define the gradient of a function as:

$$\nabla f(x)=\nabla f(x)-f(x)\nabla 1(x), \tag{5}$$

where 1 is the unit function. Then we can define the particle approximation to thegradient of a function:

$$\prod^h \nabla f(x_i)=\sum_{j=1}^{N}\left[f(x_j)A_{ij}-f(x_i)A_{ij}\right]\frac{m_j}{p_j}, \tag{6}$$

where

$$A_{ij}=\frac{1}{h^{d+1}}\theta'\left(\frac{//\,x_i-x_j\,//}{h}\right). \tag{7}$$

❖Time Integration

In the SPH method, the location of neighboring particles is important. SPH requires information of neighboring particles to compute the particle interactions. LS-DYNA software uses a simple and classical first-order scheme for integration. The time step is determined by the expression:

$$\delta_t=C_{CFL}Min\left(\frac{h_i}{c_i+v_i}\right), \tag{8}$$

where the factor is a numerical constant. The calculation cycle as shown in Fig. 2

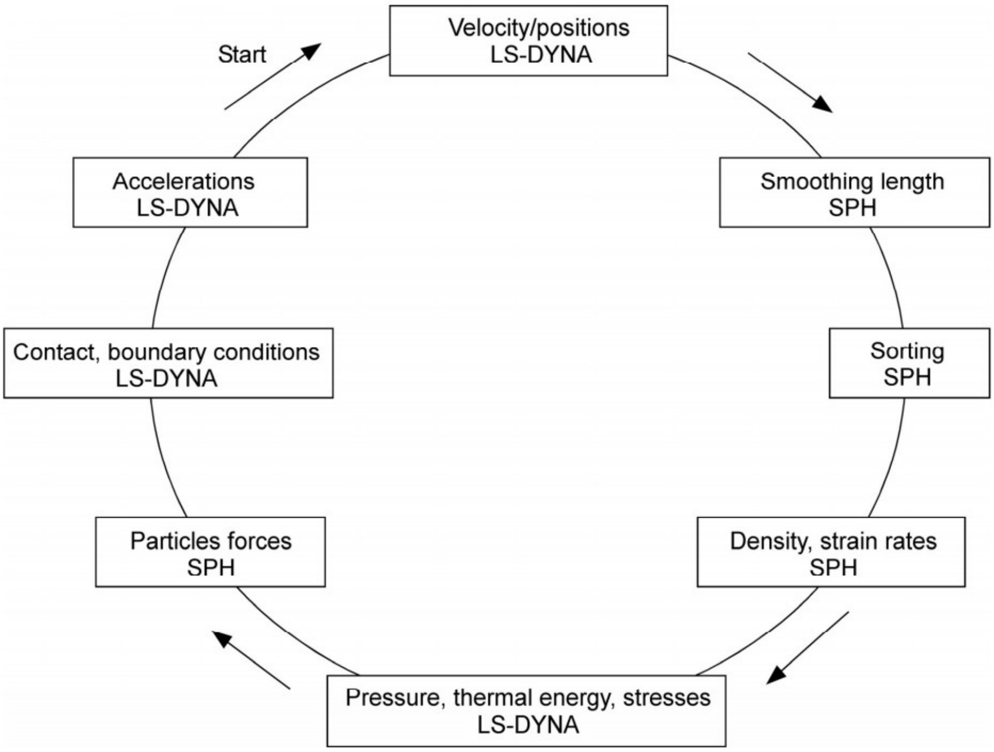


Fig. 2. The time integration loop in LS-DYNA

3. FINITE ELEMENT MODEL FOR THE METAL CUTTING TEST SYSTEM

❖ The drilling experiments were performed by Aamir et al. [39]

Fig. 3 illustrates the experimental setup of the drilling tests.

The experiments were carried out on a vertical turret milling machine with a maximum spindle speed of 3500 rpm and a feed of 0.04, 0.08 and 0.14 mm/rev. An Al5083 plate with a thickness of 10 mm and a size of 150×200 mm^2 was used in this work. The material properties are given in Table 1. The parameters of the drill were used in the experiment as shown in Table 2.

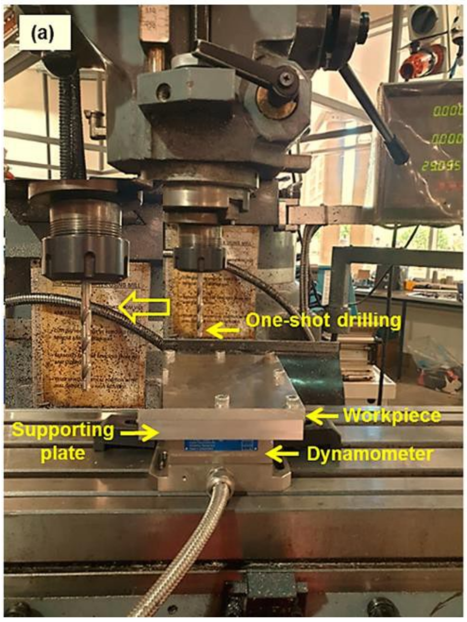


Fig. 3. Experimental setup [39]

Table 1 *Engineering material properties for work piece [40]*

Material Properties	
Density	*2650kg/m^3*
Young Modulus	*72 GPa*
Poisson's Ratio	*0.3*
Tensile strength	*317 MPa*
Shear strength	*185 MPa*

Table 2 *Parameter for the drill tool*

The Specifications of drill tool	
Overall Length	*93 mm*
Diameter	*6 mm*
Helix Angle	*30^0*
Flute Length	*57 mm*
Material	*High speed steel*
Group code	*D104*

The cutting parameters used in the experiments were chosen as follow: cutting speed at 19 (m/min), feed rate at 0.04 mm/ rev.

❖ The milling experimental were chosen as follow [41]: the material selected is Aluminum Alloy (Al2024-T4) with the size of 80×80×16 mm blocks. The experimentation performed on CNC FLEXMILL machine with end mill tool are shown in Fig. 4.

There were 27 test, carried out by Kamble et al. [41], One of them was chosen in this study with cutting parameter as follow: cutting speed at 1910 rpm, feed rate at 1.5 mm/rev and depth of cut at 0.5 mm.

Fig. 4. Experimental milling setup [41]

3.1. Workpiece model

The workpiece, shown in Fig. 5, was modeled by SPH method. The mass, density constitutive laws are defined in the ELEMENT-SPH and the PART card. The geometrical properties are defined in the SECTION_SPH card with scale factor for the minimum smoothing length (HMIN) and scale factor for the maximum smoothing length (HMAX) equal to 0,2 and 2, respectively. The workpiece model consisted of 64,000 nodes for drilling model and 26,250 nodes for milling.

In this study, the work part's material model was represented by MAT015 (Johnson-Cook) in LS-DYNA. The following parameters was proposed as follow: A=0,305 B=1,161 N=0,61 C=0,01 and M= 0,517.

3.2. Tool model

The study used solid mesh to analyze cutting tool. The drilling tool consists of 8016 nodes and 35678 solid elements, the milling tool consists of 2014 nodes and 7246 solid elements as shown in Fig. 6 and Fig. 7, respectively.

3.3. Simulation of impact test

Fig. 7 presents initial condition of the metal cutting simulation tests on the basis of the experimental tests. The test model consists of the block workpiece and the cutting tool. The AUTOMATIC_NODES_TO_SURFACE card was used as a contact between the workpiece and the tool. Tool was defined as master part. Workpiece, a deformable body,was defined as slave part.

The time analysis was approximately 4 hrs. for drilling model and 25 minutes for milling model, as the configuration of one computer was 24 GB RAM, Intel Core i7-9750H 2.6GHZ (12 CPUs were used).

4. RESULTS AND DISCUSSION

Tables 3 and 4 present the FEM of metal cutting results on drilling and milling, respectively

Fig. 9 presents the formation of chips from the simulation and compared with experiment under different cutting condition as follow: cutting speed at 19m/min and feed at 0,08 rev/mm.The result shows that there is very good agreement in the comparison results of the behavior between the experimental and simulation tests. The chip formation is realistically captured, as well as the tool-workpiece contact zone. Fig. 9 and 10 shows that the model results confirm to basic physics laws. Moreover, material separations can be simulated naturally in numerical models. It is clear that the SPH method works well for simulation of drilling.

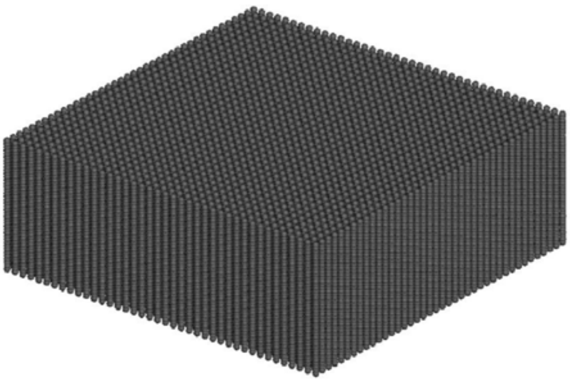
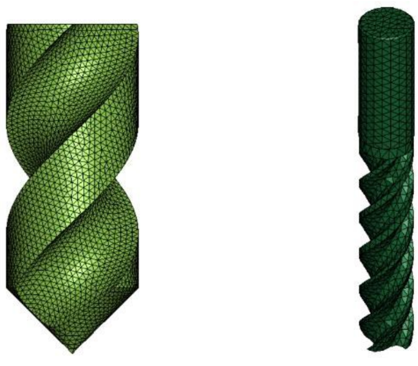


Fig. 5. SPH model of work piece



a *b*

Fig. 6. Finite element of drilling tool (a) and milling tool (b)

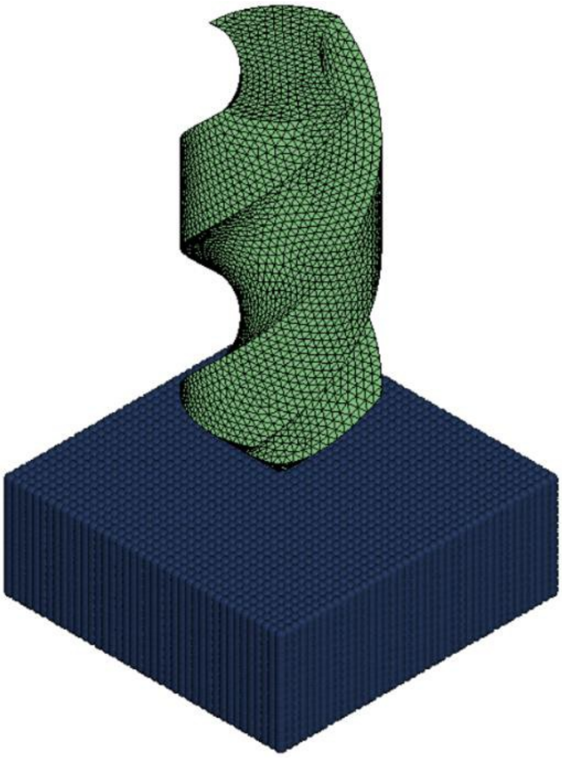


Fig. 7. Drilling test simulation on isometric view

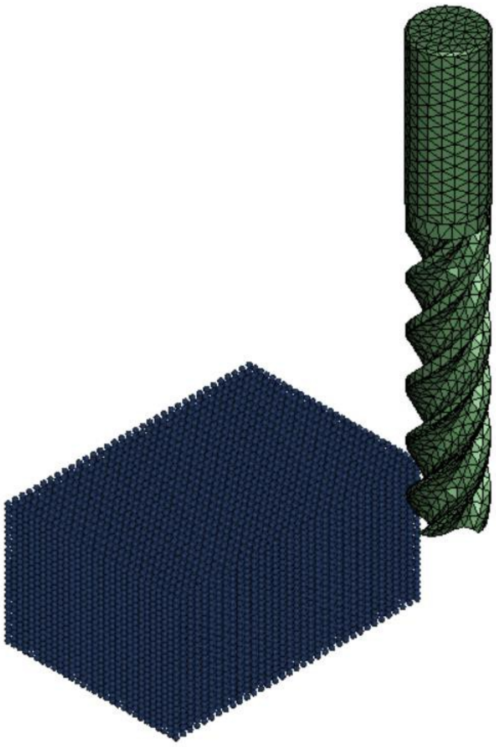
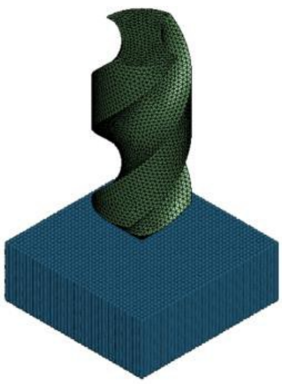
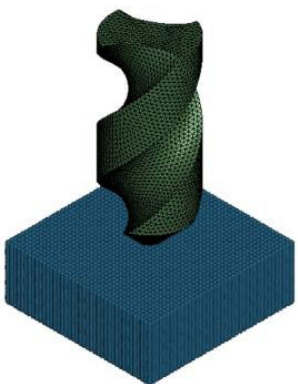
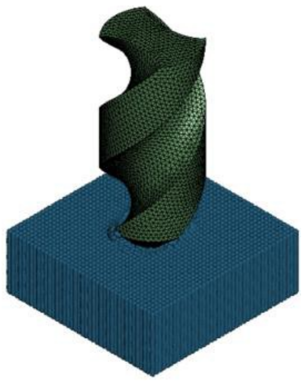
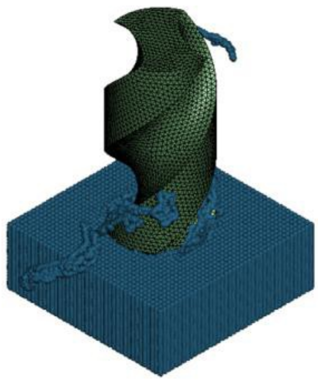
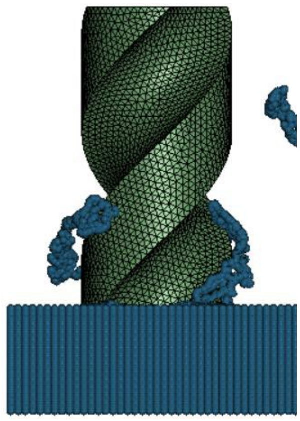


Fig. 8. Milling test simulation on isometric view

Table 3 *Computational simulation of the drilling*

t=0 s	*t=0.1 s*	*t=0.3 s*	*t=0.5 s*
			
			

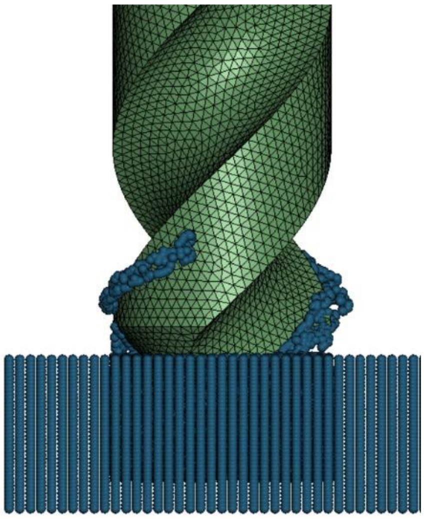
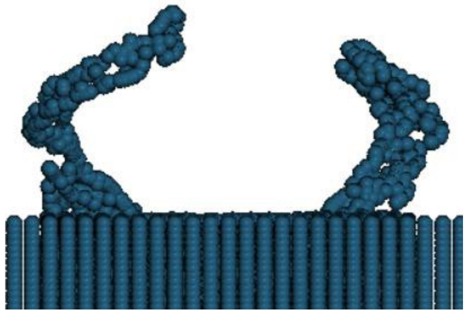
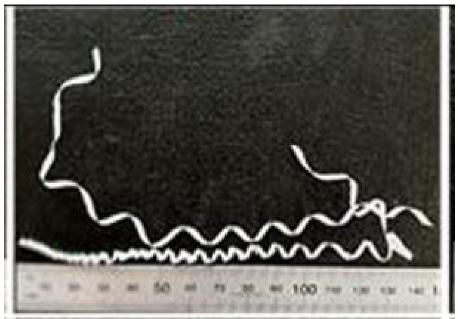
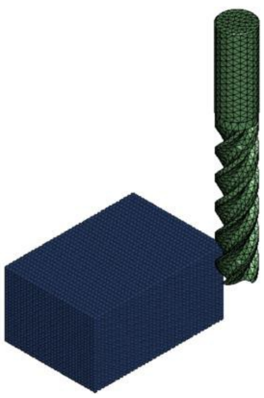
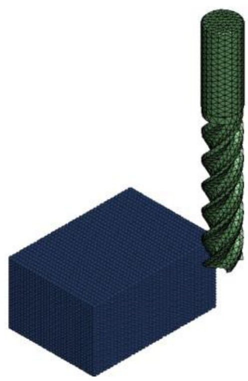
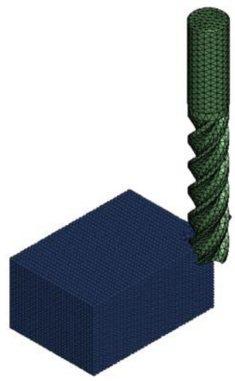
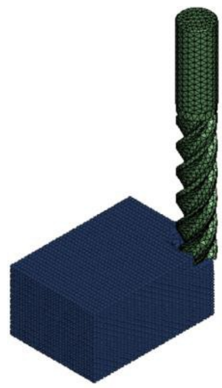
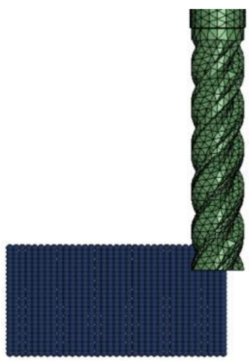
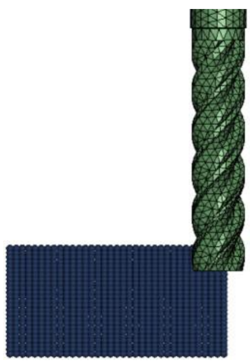
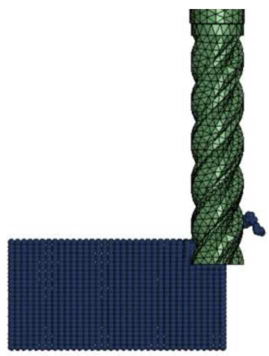
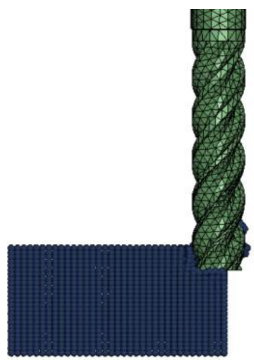
	*Simulation* 
Experiment [39]	

Fig. 9. Formation chip from simulation and experimental

Table 4 *Computational simulation of the milling*

t=0 s	*t=0.1 s*	*t=0.3 s*	*t=0.5 s*
			
			

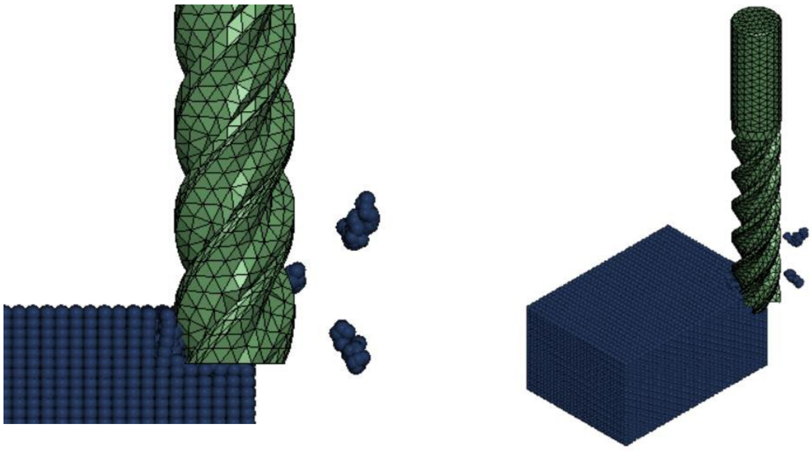


Fig. 10. Formation chip from milling simulation

Table 5 shows a close cutting force value between the experiment and simulation tests both of drilling and milling. In the SPH model, cutting forces were taken from the interface between the tool and the SPH particles. The best correlation with the experiment can be examined for the milling at t=0.4s, the drilling at t=0.5s. The differences in results are also related to the nature of the SPH method, in which the radius of particle and the shape of the smoothing function are decisive factors.Therefore, the difference value is still acceptable. The SPH model of the metal cutting corresponds to reality.

Table 5 *Compare cutting force between simulation and experimental*

Value	*Simulation*	*Experimental [39,41]*
Cutting force (N)-Drilling	*550*	*600*
Cutting force (N)-Milling	*330*	*312.4*

5. CONCLUSION

The metal cutting process is a complex problem with many physical phenomena.The mesh-based methods such as FEM are not a suitable choice due to mesh distortion, complex, time consume etc. This paper presents the method of constructing a FEM for metal cutting tests. Simulations were performed using SPH technique. Good agreement was observed in the comparison results of the chip formation and cutting force values between the experimental and simulation tests. Theproposed model could be used as a reliable tool to ensure the capability of SPH method.

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