Twist drilling SPH simulation for thrust force and torque prediction

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Abstract. Drilling is one of the most common processes in metalworking. The cutting forces that occur during the drilling process have a significant impact on the accuracy and quality of the holes. Uncompensated radial cutting forces lead to an increase in the diameter of the hole being machined, which reduces its accuracy. And when machining laminated materials, excessive axial cutting force leads to a stratification of the composite and reduces the quality of the hole. In this regard, the task of determining or predicting cutting forces is currently quite relevant. This article proposes a method for calculating cutting forces when drilling aluminum homogeneous and isotropic alloy 6061-T6 using smoothed particle hydrodynamics method (SPH). The calculation results are compared with calculations using empirical formulas and the results of experiments of other authors. The influence of the chip separation criterion type and material model on cutting forces during drilling were also investigated.

1. Introduction
In mechanical processing, the drilling process is one of the main operations in the production of machine parts and equipment. This process, the geometry of drills, the mechanics of the drilling process has been well studied in recent years. Cutting forces during drilling affect the quality and accuracy of the holes. Previously, Parsian et al. applied a mechanistic approach to predicting cutting forces during drilling [1]. Hamade et al applied the same approach to determining cutting forces when drilling aluminum. It consists in defining empirical power equations and corresponding coefficients [2]. Giasin et al. investigated the axial cutting force when drilling fiber-reinforced composites using the finite element method [3]. Matsumura et al. proposed a model of cutting forces for drilling multilayered materials [4]. Wang et al determined the coefficients in power equations for the calculation of cutting when drilling [5]. Watson proposed a model of drilling on the cutting edges and chisel of the drill and compared it with experimental data [6]. Marusich et al modeled the process of drilling with carbide drills using the finite element method [7]. Merino-Perez et al. investigated the effect of cutting speed and material properties on cutting forces when drilling CFRP composites [8]. Sreenivasulu et al simulated the formation of chips when drilling aluminum 6061-T6 alloy [9]. Patra et al used neural networks to predict the state of the tool based on the measurement of axial cutting force [10]. Uhlmann et al investigated deep drilling with spiral drills [11]. Mathew et al investigated the temperature distribution in the material being processed [12]. Sultan et al studied the formation of chips when drilling stainless steel with spiral carbide drills [13]. Beer et al. investigated the effect of tool geometry on cutting forces when drilling Inconel 719 alloy [14]. Sambhav et al have created...
geometric models of spiral drills with various forms of sharpening the back surface [15]. Abouridouane et al investigated the machinability of ferritic-pearlitic steels [16]. Abele et al has been optimizing the geometry and design of spiral drills based on numerical simulation [17]. Girinon et al used commercial packages (Abaqus) to simulate the drilling process and cutting forces [18]. Gaikhe et al. predicted the axial force and the moment of cutting when drilling fiberglass [19]. Diaz-Alvarez et al proposed numerical approach to thermo-mechanical modelling of drilling process. Previously, for the 6061-T6 alloy, the finite element method was used mainly for modeling free orthogonal cutting [21]. When drilling, chip formation conditions make it difficult to use FEM. In addition, usually in the process of calculating the elements forming the chips are usually removed from the calculation, as they reach the limit deformation. This article also proposes to use SPH to simulate the drilling process for 6061-T6 aluminum alloy and to predict the axial cutting force and torque.

2. Analysis of factors affecting the cutting forces during drilling

The working process of metal cutting consists in the dynamic and kinematic interaction of two solids - the workpiece and the cutting tool. The surface layer of metal, which is cut from the workpiece, is subjected to intense plastic deformation, as a result of which the material of the cut layer in a partially or completely destroyed state is removed from the workpiece in the form of cut chips. During the cutting process, new surfaces continuously appear on the workpiece and on the cutting chips.

In contrast to turning, it is not one main edge that takes part in the cutting of chip, but two and additionally a chisel edge. Each edge has a cutting force that can be decomposed into three mutually perpendicular components. The cutting force acting on the main edge is decomposed into a force $F_z$, tangent to the circle on which the edge point is located, a radial $F_y$ force passing through the axis of the drill, and $F_x$ force parallel to the axis of the drill. Pair of tangential forces creates torque $M$. On the other main edge operates a similar system of forces. The cutting force acting on the half of the chisel can also be decomposed into three forces. However, due to the relatively small influence exerted on the power characteristics when drilling two components, they are not taken into account. Auxiliary edges in cutting chips are not significant. However, due to the fact that the auxiliary clearance angle is zero on the chamfers of the drill, there is friction between them and the hole wall. Make the sum of the projections of the acting forces on the axis $X$, which coincides with the axis of the drill. The specified amount of projections is the axial force when drilling. Axial force counteracts feed motion. It is calculated on the strength of the details of the feed mechanism of the drilling machine. For large overhangs, the axial force causes a longitudinal bending of the drill. We make the sum of the moments of the acting forces relative to the $X$ axis. The specified sum of the moments is called the cutting resistance torque when drilling (the cutting torque). Under the effect of cutting torque, the drill twists. The radial forces of $F_y$, acting on both main blades of the drill and directed towards each other, should theoretically be balanced. However, due to the inaccuracy of sharpening the drill (different angles in terms of the length of the main edges), the forces of $F_y$ are not equal. Therefore, a resultant force directed towards a greater force appears. Under the action of the resultant, the diameter of the hole increases as compared with the diameter of the drill. This increase in a hole diameter causes another macro-geometric error — leading the drill away from the geometric axis of the hole, since the drill will no longer be centered in the hole with its chamfers. Hole diameter increase and withdrawal of a hole from a geometric axis are always inherent in drilling holes with double-blade screw drills. The influence of the structural elements of the drill on the power characteristics of the drilling process is different. Most of the torque falls on the main edge of the drill. The chisel accounts for most of the axial or thrust force. By changing the magnitude of the axial force and torque can be judged on the state of the drill during the cutting process. If there is a sharp increase in torque, then this corresponds to the predominant wear of the main edges of the drill. The sharp increase in axial force indicates the predominant wear of the chisel. With an increase in feed and drill diameter, the cross-sectional area of the chip cut by the main edges increases, as a result of which the axial force and torque increase. However, just as with turning, the feed and the diameter of the drill do not have the same effect on thrust force and torque. Since in any type of work, the thickness of the chip affects the components of
the cutting force less strongly than the width, then the feed to the axial force and torque also affects less than the diameter of the drill. The main influence on the axial force and torque is exerted by the angle of inclination of the helical groove $\omega$, the point angle of the drill $2\varphi$ and the angle of inclination of the chisel. Increasing the angle of inclination of the helical groove reduces both the axial force and the torque, but the axial force decreases more intensively. The effect of the angle $\omega$ on $F_x$ and torque is noticeable only at angles $\omega < 30-35^\circ$. A further increase in angle $\omega$ practically does not affect the change in $F_x$ and torque. The experimentally established influence of angle $\omega$ on axial force and torque is due to the fact that an increase in angle causes an increase in the rake angle of the drill, which reduces the cutting force on the main edge and its components. The effect of the point angle on $F_x$ and torque when drilling is similar to the effect of side cutting edge angle $F_x$ and $F_z$ forces when turning. As the angle $2\varphi$ increases, the ratio of the width of chip being cut to thickness decreases. This should reduce the force $F_z$ on the main edge and, as a consequence, the magnitude of the torque. Just as when turning, an increase in the angle $2\varphi$ when drilling results in an increase in the angle between the main edge and the direction of feed movement, which increases the axial component of the cutting force on the main edges and the axial force.

The angle of the chisel on the axial force and torque affects the most difficult. On the one hand, an increase in the angle causes a reduction in the length of the chisel, which should somewhat reduce the torque and more significantly axial force. On the other hand, as the angle increases, the length of the main edges and their sections with a small static rake angle increase. The latter should lead to an increase in both torque and $F_x$. Such a contradictory influence of the $\varphi$ angle leads to the fact that with its increase the axial force increases continuously, and torque decreases initially and then decreases.

3. 3D SPH model description
The original combined 3D finite element-SPH drilling model is presented in Fig. 1. Modeling was done in the LS-Dyna package. The model consists of a square workpiece 50x50 mm, 10 mm thick and HSS twist drill. The material of the workpiece is aluminum alloy 6061-T6 (the Russian equivalent of the alloy AD33 according to GOST 4784-97). The mechanical properties of the material of the workpiece: density of 2700 kg / m$^3$, a tensile elasticity modulus of 68900 MPa, an elongation of 25%, a yield strength of 270.2 276 MPa. Material model (strain curve) - bilinear kinematic hardening (*MAT_PLASTIC_KINEMATIC). The first part of the curve is linear elastic, the second is linear hardening with a hardening modulus of 200 MPa [21]. A high speed steel (HSS) twist drill with a diameter of 7.5 mm was used as a tool. Geometrical parameters of the drill: helix angle 30°, point angle 118° clearance, clearance diameter 7.3 mm, flute length 50 mm, core thickness 2 mm. The simulation was carried out with the following cutting conditions: cutting speed 310 m/min, feed 0.64 mm/rev. The workpiece and drill were meshed by a finite element mesh. The element type is SPH at the workpiece and a 8-node solid elements at the drill. The deformations of the drill were not taken into account in the calculation, the material of the drill is of the RIGID type. For adequate modeling it is necessary to apply a chip separation criterion. In this case, and in order to exclude material failure in triaxial compression, the maximum principal strain of the workpiece deleted elements was 25%. To reduce calculation time part of model was made of usual finite elements, whereas drilling area of SPH.
4. Results of numerical simulation
The results of numerical simulation of drilling of the alloy 6061-T6 are presented in Fig. 2, 3. Fig. 2 represents distribution of equivalent stresses in workpiece at the final moment of simulation. Fig. 3 depicts thrust force and torque values during the simulation. The calculation time for a 6-core processor was 2.5 hours. As a result of the simulation, it was possible to obtain distribution curves for axial force and torque. For comparison, the results of the experiment are as follows: thrust force 700 N, torque 500 Nm [2]. As a result of the simulation, the following conclusions can be drawn. The results on thrust force differ by experiment no more than 15%, while for torque there is no convergence. Such a discrepancy in terms of the torque can be explained by the fact that in the process of simulation, elements that have reached the limit state are removed from the calculation. Since the torque is created mainly by the friction of the guides of the twist drill on the workpiece, when the corresponding elements are removed, it becomes close to zero.

To study the influence of the model of the processed material in the simulation, the Johnson-Cook model with the following parameters was also used: A=324.2 MPa, B=113.8 MPa, N=0.41, C=0.003, M=1.35, strain rate effect was not considered. The failure model parameters for Johnson-Cook model are as follows: D1=–0.76, D2=1.44, D3=–0.46, D4=0, D5=1.5 [21]. As the simulation results showed, the material model have little effect on the force characteristics of the cutting process. However, the experiment shows that such a relationship exists [2].

Figure 2. SPH model: Von Mises stress distribution in workpiece at the final moment of simulation.
5. Conclusions and further research
Modern methods of modeling the cutting process using the finite element method have now been significantly developed, making it possible to predict the shape and size of chips and the machined surface, the stress-strain state, the temperature field, the projections of the cutting force, residual stresses, if necessary, even with additional energy. However, the simulation results, especially 3D, coincide with the experiment more qualitatively than quantitatively. The most likely reasons for this situation are imperfect algorithms for modeling fracture and friction, as well as inaccuracies in the preparation of the initial data. The results of numerical simulation showed that SPH makes it possible to predict the axial cutting force when drilling an aluminum alloy with an accuracy of 20%. As for the torque, the result is more satisfactory. This is a advantage of the proposed approach.
This study can be useful in predicting the accuracy of drilling holes, as well as to assess the quality of the machined surface when machining composites.

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