DETERMINATION OF CUTTING FORCES IN DRILLING WITH HELICAL DRILLS USING DATA OBTAINED THROUGH TURNING OF CIRCULAR SEGMENTS

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Abstract. *The analysis of cutting forces in machining processes is very important for optimization of cutting parameters, power, costs and the cutting tool geometry. However, because of the high geometrical complexity of helical drills and the drilling process characteristics, analysis of cutting forces and their distribution along the cutting edges and other geometrical elements, are very difficult. Considering that these problems are significantly reduced in the turning process, and also the possibility to correlate data for cutting forces obtained in turning and drilling is given, this study presents a method for the prediction of cutting forces in drilling using results obtained in turning operations. The results for cutting forces in the turning of circular segments, with application of correction factors for variations in the tool geometry, are compared to results obtained during the full drilling of low carbon steels. Aspects of the influence of the cutting tool geometry and cutting parameters on the cutting and thrust forces are also discussed. With the drill model it is possible to indentify the regions with higher mechanical stresses and then geometrical changes on the drill point can be proposed.*

Keywords*: Drilling, Cutting Forces, Twist Drills, Simulation of Drilling*

1. INTRODUCTION

Drilling, along with turning, is one of the processes most used in the metal industry, and was one of the first machining operations to be carried out historically. Considering machining processes as a whole, drilling occupies a prominent place, both due to its widespread use as also the difficulties it presents. Since drilling is commonly used in the last stages of manufacturing, problems associated with it make the production process expensive due to wastage (Boeira *et al.*, 2009a; Castillo, 2005; Strenkowski *et al.*, 2004).

In drilling the most used tools are twist drills, mainly due to their universal application. Because it is a complex cutting process with many difficulties involved in gaining an understanding of the geometrical and cutting speed variations along the cutting edge, generation of chips inside a closed volume, and other characteristics, drilling with twist drills is still considered relatively little understood (Boeira *et al.*, 2009a; Hsieh and Lin, 2002; Bork, 1995).

One of the many options to improve the efficiency of drilling is to change the tool geometry. Many variations in this type of tool geometry have been proposed in order to reduce machining forces, to increase tool life, to decrease the machining time and to improve the hole quality, among others. However, while the characteristics of other machining processes are relatively easy to analyze in real time, monitoring the phenomena occurring during drilling is very complex. The reason for this is that viewing the region where the chips are produced is almost impossible, the plastic deformations produced by the end cutting edge in the center of the hole is significant and the cutting speed over the cutting lip shows large variations, being highest at the periphery and zero in the center of the drill. Also, difficulties arise in measuring the machining force components, since only the axial force and torque can be measured through the axis of the tool (Boeira *et al.*, 2009a; Boeira *et al.*, 2009b; Castillo, 2005; König, 2002; Bork, 1995).

To improve our knowledge of the machining technology, the use of computational tools that allow the reliable and accurate simulation of the process is becoming increasingly common, and thus replaces empirical data used on the shop floor with scientifically proven data. Specifically in the case of drilling, it is important to know the behavior of the forces in drilling with a twist drill, for different tool geometries, substrate materials, coatings and other tool characteristics (Boeira *et al.*, 2009a).

In the optimization of drilling, the techniques of modeling and simulation are important, since there is a complex relationship between the input variables and the results, making it difficult to evaluate certain process phenomena. To relate the influence of these experimental variables many tests would be needed, given the variations in the multiple cutting parameters (Boeira *et al.*, 2009a).

Information on the magnitude and direction of forces during machining is the basis for determining the parameter conditions, and also for evaluating the precision of a machine tool under certain work conditions (deformation of the piece and machine), to determine what occurs in the regions of chips formation and to explain the mechanisms of tool wear. Thus, the modeling and simulation of machining forces provides a simplified alternative, allowing the collection of data with a high degree of approximation, for the prediction of cutting forces (Kim and Ahn, 2005; König, 2002).

In this paper a model for drilling forces, developed by Boeira *et al.* (2009a), is applied and validated, which allows the use of the coefficients of the Kienzle equations obtained through turning tests, a process where the difficulties encountered in obtaining data are significantly lower.

With this model drilling forces for different tool geometries can be simulated, since the relations between forces at the drill cutting edge and their geometrical quantities are parameterized. The model validation is performed with the use of drills with three different diameters - 7, 10 and 13 mm - and drills with two types of relief on the chisel edge - Standard and Type A.

2. DRILLING FORCE MODEL

The drilling model here proposed simulates the cutting force and thrust force based on the specific force of the turning process determined with the Kienzle model. On applying the Kienzle model to drilling, the process is divided into three different regions of the drill point, the cutting lip, chisel edge and end cutting edge.

For the cutting lip, drilling and turning of segments in the form of cylindrical shells are carried out as proposed by Boeira *et al.* (2009a). For the turning, the values of the specific force $k_{c1.1}$ and Kienzle coefficient $(1\text{-}m_c)$ are determined from tests carried out on only one of the segments (usually that with the largest diameter). These values are taken as a reference for other segments covering the cutting lip. For the drilling, due to the variations in the geometry and cutting force as a function of the radius, tests are performed on each segment with the respective cutting speeds.

On the chisel edge, this being the region where the material cutting occurs with extremely negative rake angles and the cutting force tends to zero in the center of drill, understanding the phenomena occurring during the process becomes more complex. According to Risse (2006) and Witte (1980), among others, the contribution of the chisel edge to the total cutting force in drilling is small, but for the thrust force its contribution may be greater. It is estimated that these values are between 65 to 75% of the total thrust force in drilling, while the cutting lip is responsible for 17 to 25% and the other parts of the drill for less than 10%, including the end cutting edge.

Due to the small contribution of the end cutting edge to the components of cutting force and thrust force, it is modeled by a factor that corresponds to the percentage of total force and can be experimentally defined. This correction factor includes the force necessary to remove the chip through the drill channels, the friction of the drill guides on the wall of the hole and the elastic deformation of the hole, among other factors.

2.1. Force Simulation in Drilling

The simulation of cutting force and thrust force is obtained from the sum of different constituent parts of the twist drill. For the cutting lip (GP) the cutting and thrust forces are simulated using the integral applied to the Kienzle model, with values of specific cutting and thrust forces adjusted from data obtained in turning. For the chisel edge (GT) the Kienzle equation has direct application, while the part relating to the end cutting edge (GS) is obtained using a factor of adjustment associated with the sum of the components of cutting lip and chisel edge forces, according to Eq. (1) in the case of the cutting direction. To determine the part of the force at the end cutting edge according to the feed direction, the same procedure is used.

$$F_{cGS} = \left(F_{cGT} + F_{cGP}\right) \cdot C_{c,GS} \tag{1}$$

In the feed direction, because all components are aligned with the drill axis, the sum of all components is obtained directly, as shown in Eq. (2).

$$F_{fFC} = F_{fGP} + F_{fGT} + F_{fGS} \tag{2}$$

The cutting force F_{cFC}, is determined from the sum of the different moments generated by each component as a function of its point of application (Eq. (3)), that is, using the lever arms r_{AGP} for the cutting lip, r_{AGT} for the chisel edge, r_{AGS} for the end cutting edge and r_{AFC} for full drilling. Thus, the cutting force can be calculated through Eq. (4). The values of r_{aGS}, r_{aGP} and r_{aGT} are obtained as proposed by Wegener *et al.* (2008) and Boeira *et al.* (2009a).

$$M_{zFC} = M_{zGP} + M_{zGT} + M_{zGS} \tag{3}$$

$$F_{cFC} = \frac{r_{AGP} \cdot F_{cGP} + r_{AGT} \cdot F_{cGT} + r_{AGS} \cdot F_{cGS}}{r_{AFC}} \tag{4}$$

Through turning tests producing cylindrical shells the specific cutting $k_{c1.1}$ and thrust $k_{f1.1}$ forces, respectively, are determined, and also the coefficients ($1\text{-}m_c$) and ($1\text{-}m_f$) of the Kienzle equation (Boeira *et al.*, 2009a). For both forces, cutting and thrust force, a model is developed which, using adjustment factors related to geometric differences between the processes of turning and drilling, allows the calculation of forces predicted for a specific cutting condition in the drilling process.

2.2. Modeling of forces on the cutting lip

For the cutting lip, the applicability of the Kienzle equation for turning to drilling is assessed from the application of adjustment factors that take into account the differences between the cutting tool geometries of the two processes. Depending of the drill geometry region (cutting lip or chisel edge), this corrects the specific cutting force $k_{c1.1}$ and thrust $k_{f1.1}$ according to variations in the normal rake angle γ_n and back rake angle λ_s.

The adjustment of the γ_n and λ_s angles to give the specific cutting force of the drilling from the turning data is shown in Fig. 1. The equation of the line obtained for the drilling (orange line) is then used to calculate the forces along the cutting lip of the drill.

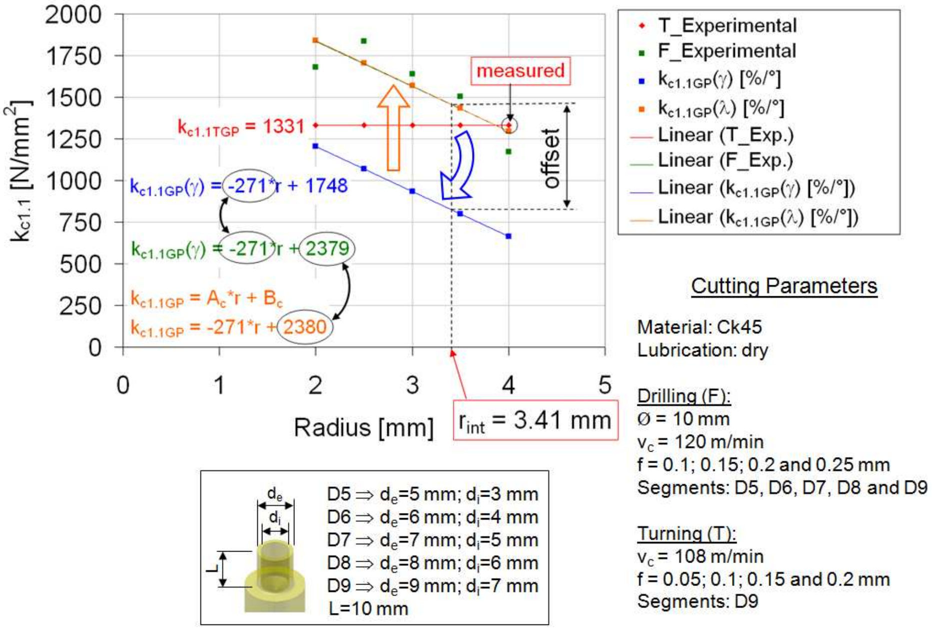


Figure 1. Determination of specific cutting force in drilling (F) from turning (T) data

Based on the variation of the normal rake angle γ_n, as shown in Fig. 2, there is a rotation of the adjusted line that includes the values of specific cutting force for turning, making it parallel to the adjusted line for the points relating to drilling, according to the drill radius. After this rotation, the translation is made, using the value of the back rake angle λ_s, making the adjusted line of the turning coincide with the adjusted line of the drilling. To make this shift, the value of the back rake angle λ_s at the point of intersection r_{int}, which corresponds to the radius where the angles γ_n and λ_s have the same value, was determined.

Equation (5) shows the parameterized mathematical model that allows, through the application of adjusting coefficients $C_{c,GP(\gamma)}$ for the angle γ_n and $C_{c,GP(\lambda)}$ for the angle λ_s, the obtainment of the specific cutting force of drilling $k_{c1.1GP}$ from that of turning $k_{c1.1TGP}$ as a function of the drill radius r_i.

$$k_{c1.1GP}(r) = k_{c1.1TGP} \cdot \left\{ \left[1 + \left(\left(\gamma_{nT} - \gamma_n(r) \right) \cdot \frac{C_{c,GP(\gamma)}}{100} \right) \right] + \left(\frac{\lambda_{rint} \cdot C_{c,GP(\lambda)}}{100} \right) \right\} = A_c \cdot r + B_c \tag{5}$$

where:

$k_{c1.1GP}(r)$ - Specific cutting force adjusted according to the drilling radius;
$k_{c1.1TGP}$ - Specific cutting force from tests of orthogonal turning;
γ_{nT} - Normal rake angle used in the orthogonal turning;
$\gamma_n(r)$ - Normal rake angle determined as a function of drill radius;
$C_{c,GP(\gamma)}$ - Adjusting factor of the rake angle for the specific cutting force;

λ_{rint} - Back rake angle for the point of intersection of $\gamma_{n\,(r)}$ and $\lambda_{s\,(r)}$;
$C_{c,GP(\lambda)}$ - Adjusting factor of the lateral lead angle for the specific cutting force.

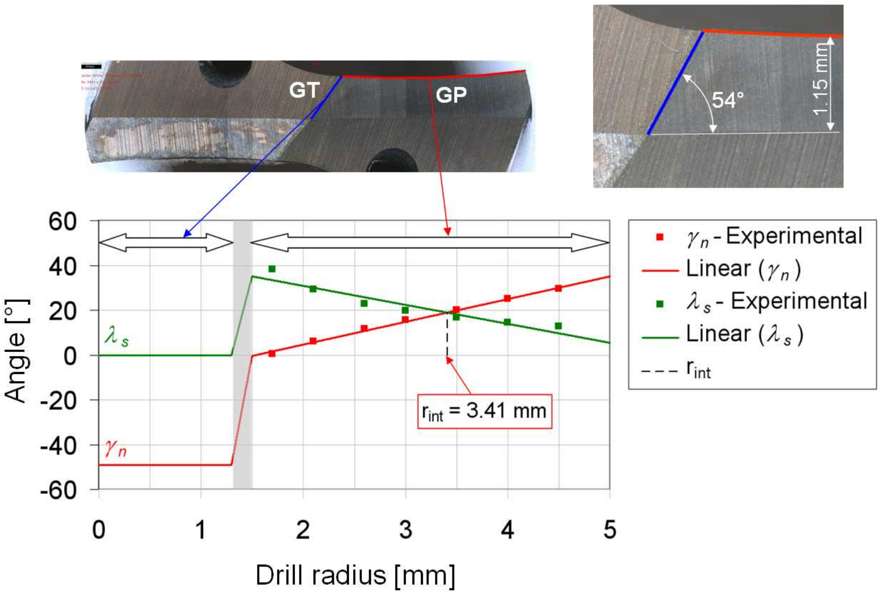
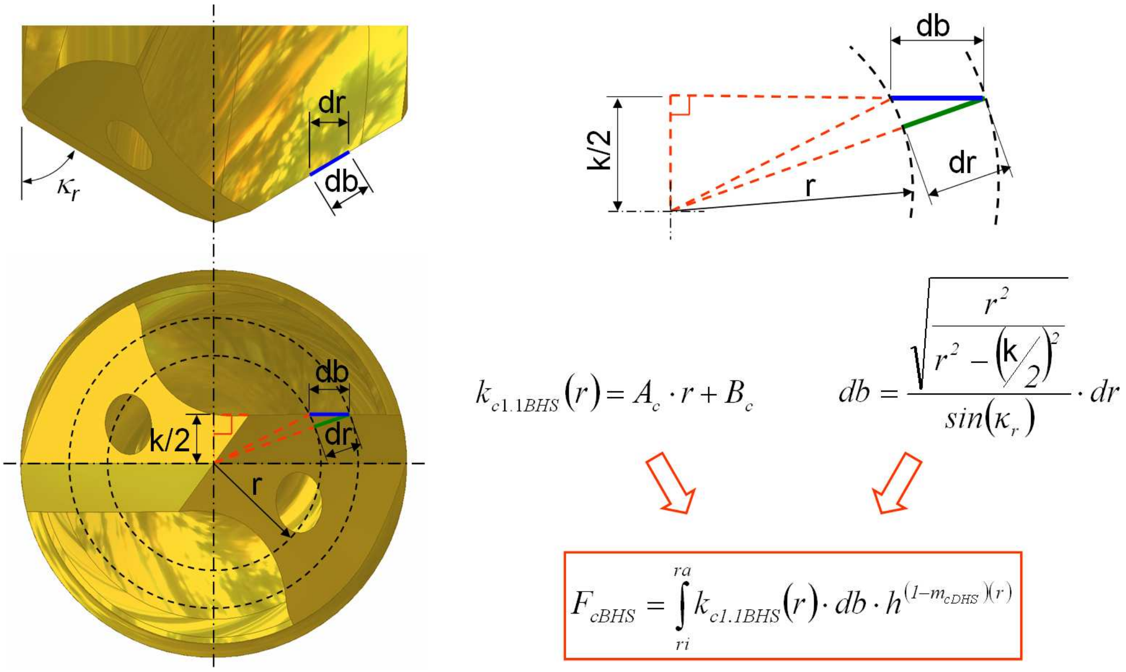


Figure 2. Variation in angles for twist drills without relief on chisel edge

The specific thrust force in drilling $k_{f1.1GP}$ is also adjusted by Eq. (5) using the adjusting coefficients $C_{f,GP(\gamma)}$ for the angle γ_n and $C_{f,GP(\lambda)}$ for the angle λ, as well the Kienzle exponents ($1\text{-}m_{cGP}$), and for cut direction and ($1\text{-}m_{fGP}$) for thrust direction using, respectively, the correction coefficients $C_{mc,GP(\gamma)}$ and $C_{mc,GP(\lambda)}$ in the cut direction, and $C_{mf,GP(\gamma)}$ and $C_{mf,GP(\lambda)}$ in the thrust direction.

Because the specific force is a function of the drill radius and changes continuously, the calculation of the cutting and thrust forces is performed using the integration of the Kienzle equation along the cutting lip, as shown schematically in Fig. 3. With the variation in the specific cutting force $k_{c1.1GP}(r)$ with drill radius and using an infinitesimal cutting depth of the cutting lip db, the Kienzle equation for the cutting force in drilling $F_{cGP}(r)$, as a function of radius, can be applied.



$$k_{c1.1BHS}(r) = A_c \cdot r + B_c$$

$$db = \frac{\sqrt{\dfrac{r^2}{r^2 - \left(k/2\right)^2}}}{sin(\kappa_r)} \cdot dr$$

$$\boxed{F_{cBHS} = \int_{ri}^{ra} k_{c1.1BHS}(r) \cdot db \cdot h^{(1-m_{cDHS})(r)}}$$

Figure 3. Integration of forces in cutting lip of drill

where:

db - Infinitesimal cutting depth;
dr - Infinitesimal cutting depth adjusted in the radial direction;
κ_r - Side cutting edge angle;
F_{cGP} - Cutting force related to cutting lip;
r_{GT} - Radius of chisel edge.

2.3. Modeling of forces on the chisel edge

The Kienzle model is also used to estimate the forces in the region of the chisel edge, where it is assumed that the material must be effectively machined and that chip formation occurs, even with a rake angle of the order of -50°, as reported by Koch (1996) and Fang (2005). This assumption is based on the observations reported by Koehler (2004), Ohbuchi *et al.* (2003) and Dolinšek (2003), among others. Thus, the procedure adopted in this proposal to obtain the specific cutting and thrust forces in the region of chisel edge is similar to that used for the cutting lip. However, since not more than one segment can be machined in this region, the values obtained for the specific cutting and thrust force, respectively, as well as that obtained for the exponents ($1-m_{cGT}$) and ($1-m_{fGT}$), for turning and drilling, were directly correlated using only the correction of rake angle $\gamma_{n,}$ using Eq. (7) which adjusts the specific cutting force in drilling $k_{c1.1GT}$ as a function of the specific cutting force in turning $k_{c1.1TGT}$.

$$k_{c1.1GT}(r) = k_{c1.1TGT} \cdot \left[1 + \left(\left(\gamma_{nT} - \gamma_n(r) \right) \cdot \frac{C_{c,GT(\gamma)}}{100} \right) \right] \tag{6}$$

The same procedure is applied to the specific thrust force $k_{f1.1GT}$ and the cut exponents of Kienzle ($1-m_{cGT}$) and thrust ($1-m_{fGT}$).

3. EXPERIMENTAL PROCEDURE

The development of the force model for drilling is based on Ck45 steel as the cutting material and a Standard twist drill with a diameter of 10 mm as the tool, both widely applied in industry. The validation of the model in a first step, is carried out with the variation of the drill diameter and then with the implementation of relief on the chisel edge.

3.1. Materiais

The turning and drilling tests were performed on pieces of Ck45 steel obtained from wire rods with an external diameter of 15 mm. Table 1 shows the main characteristics of this material.

Table 1. Mechanical properties and chemical composition of Ck45 steel

	Composition (% mass)				
	C	Si	Mn	P	S
Ck45 DIN 1.1191	0.42 – 0.50	max. 0.40	0.50 – 0.80	max. 0.035	max. 0.035

3.2. Cutting tools

The drilling tests were carried out with carbide twist drills with three different diameters, one type of relief on the chisel edge and one type of coating.

The diameters for the drilling tests were chosen so as to facilitate the modeling process and to better adapt to the testing procedures, besides enabling comparison with results published in the literature. In this context, diameters of 7, 10 and 13 mm were chosen, the Standard drill (without relief on the chisel edge) of 10 mm diameter being used as a reference for the preparation of the drilling model. The 7 and 13 mm diameters were used to validate the model taking into account the effect of scale, especially of the chisel edge, which may lead to different results during machining.

Regarding the type of relief on the chisel edge, the drills were grouped as follows:

Standard – drill without relief on the chisel edge (Fig. 5);
Type A – drill with type A relief on the chisel edge (Fig. 4).

The twist drills used in the drilling tests were coated with TiAlN, recommended by the tool manufacturer Sphinx, and they are special manufactured for the experiments with a point angle of 118° and a helix angle of 30°.

The turning tests were carried out with rhombic carbide inserts type CNMM120408 from Sandvik with Standard geometry, without chip breaker, coated with TiN and with a rake angle of 6°, constant along the entire edge. The tool holder used resulted in a back rake angle (κ_r) of 93° and in a null rake angle (0°).

Figure 4. Type A relief sharpening of the chisel edge

3.3. Experimental set-up

The turning and drilling tests were performed on a Schaublin CNC machining center for turning and milling, model 42L, equipped with a test bench for turning and drilling, with a maximal power from 48 kW and a maximal rotation from 6000 rpm (Figure 5). Both benches were equipped with Kistler force dynamometers, type 9121A5 for turning and type 9271A for drilling.

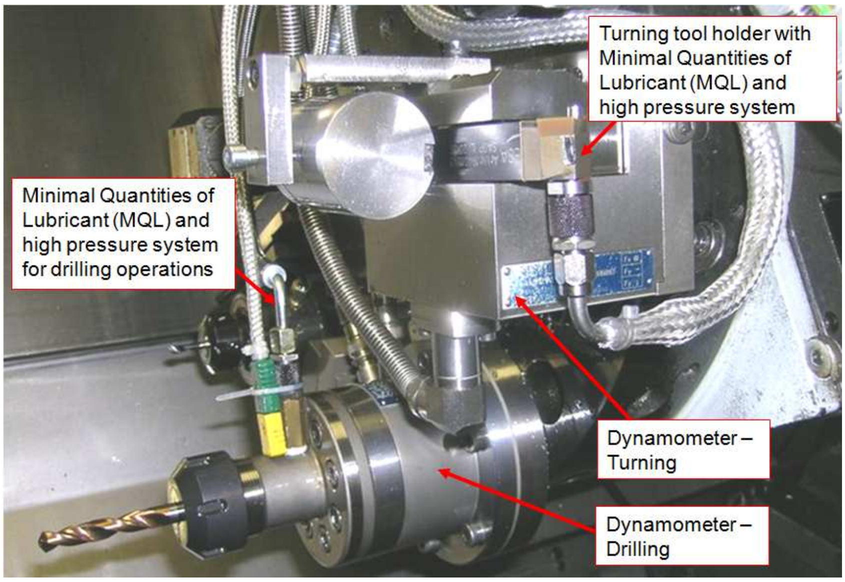


Figure 5. Test Bench for turning and drilling

3.4. Cutting parameters

The cutting parameters for the drilling were defined based on the conditions used in industry, and the cutting speed, for a coated carbide drill with TiAlN, was set at 120 m/min.

As mentioned above, the segment with the largest diameter obtainable with the cutting lip (in this case segment D9, shown in Figure 7) is used, which is taken as reference for the turning tests, with the cutting speed. Besides the piece shown in Fig. 1, pieces for full drilling (FC) and with a hole of 3 mm diameter (GP) were also used, corresponding to the diameter of a drill web, for modeling the chisel edge. Table 2 shows the cutting parameters used in the modeling of the drilling process and the validation tests.

4. RESULTS AND DISCUSSIONS

Figure 6 shows the simulation of the cutting and thrust forces corresponding to the cutting lip (GP), and the sum of cutting edge (GP), chisel edge (GT) and end cutting edge (GS), which correspond to full drilling (FC) for Ck45 steel. The values of the simulated cutting forces have a confidence interval (CI) of 95%. The simulated cutting force for the chisel edge (GT) is around 54% of the total force in full drilling. It can be verified that the simulated thrust force for the cutting lip reaches values of around 18% of the total value in full drilling. These values are similar to those reported by Risse (2006) and Witte (1980), thereby validating the extended Kienzle model. Differences between measured and simulated values for the cutting force on the cutting lip can be attributed to the method of segmentation used to create the model, in which the chips have degrees of deformation and different temperatures experienced in full drilling. These differences between measured and simulated values are higher in the feed direction, since the thrust forces are more influenced by the phenomena occurring on the chisel edge. According to Dolinšek (2003), on the chisel edge large deformations occur and the formation of a build up edge (BUE) is often observed, which brings additional disturbances to the process.

Table 2. Cutting parameters of drilling and turning tests

Parameter	**Turning**	**Drilling**
Segments of cutting lip GP	D9	D5, D6, D7, D8, D9,
Segments of chisel edge GT	D9	GP, FC
Cutting speed for GP [m/min]	108 (Segment D9)	120
Cutting speed for GT [m/min]	24 (Segment D9)	36
Feed rate [mm]	0.05; 0.1; 0.15 and 0.2	0.1; 0.15; 0.2 and 0.25

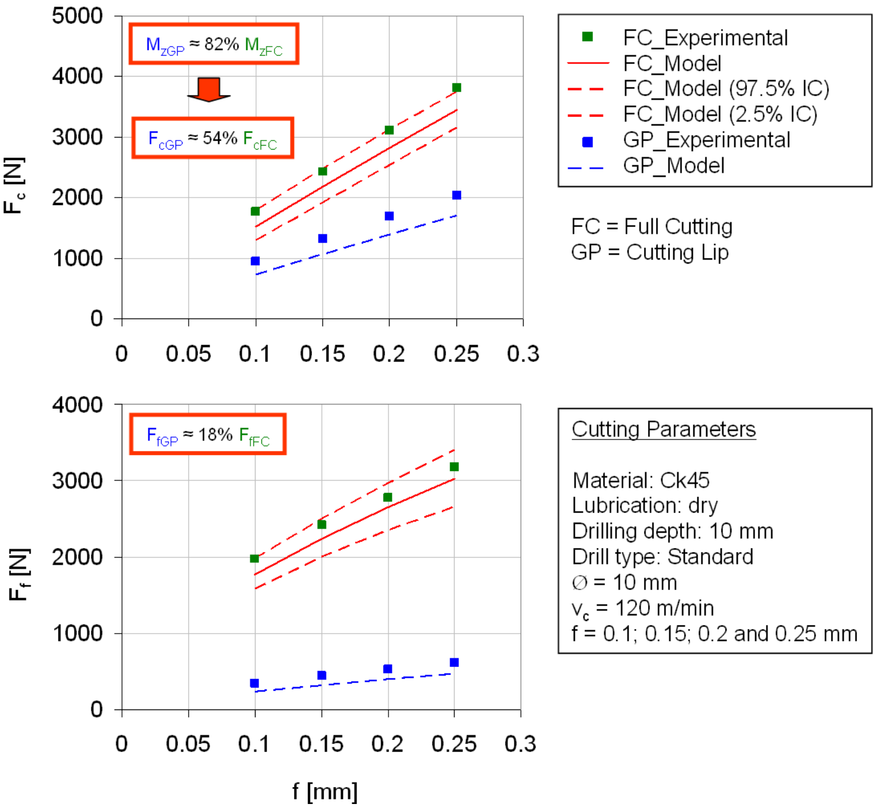


Figure 6. Cutting and thrust force for drilling Ck 45 steel with 10 mm Standard carbide drill

Figure 7 shows the results of the use of the drilling force model for different drill diameters, with the cutting forces and thrust forces for drills with 7, 10 and 13 mm diameters. Analysis of these results shows that the cutting forces for the drill diameters of 13 and 7 mm have great similarity with that simulated. These differences can again be attributed to the phenomena mentioned above for the drilling with a 10 mm diameter drill. In the feed direction, the considerable influence of the chisel edge on the forces is evident. The smaller the size of the chisel edge, the greater the similarity between the values of the forces obtained experimentally and by simulation.

Figure 8 shows the effect of the chisel edge relief on the cutting and thrust forces. A comparison is made between the results of the tests with a Standard drill of 10 mm in diameter without chisel edge relief (Fig. 2) and a drill with Type A relief (Fig. 4). For the cutting force the effect of chisel edge relief is practically nonexistent, since the influence of this drill region on the torsion moment is very small. In the case of feed direction, it can be verified that the reduction of the chisel edge due to the relief brings a substantial reduction in the forces.

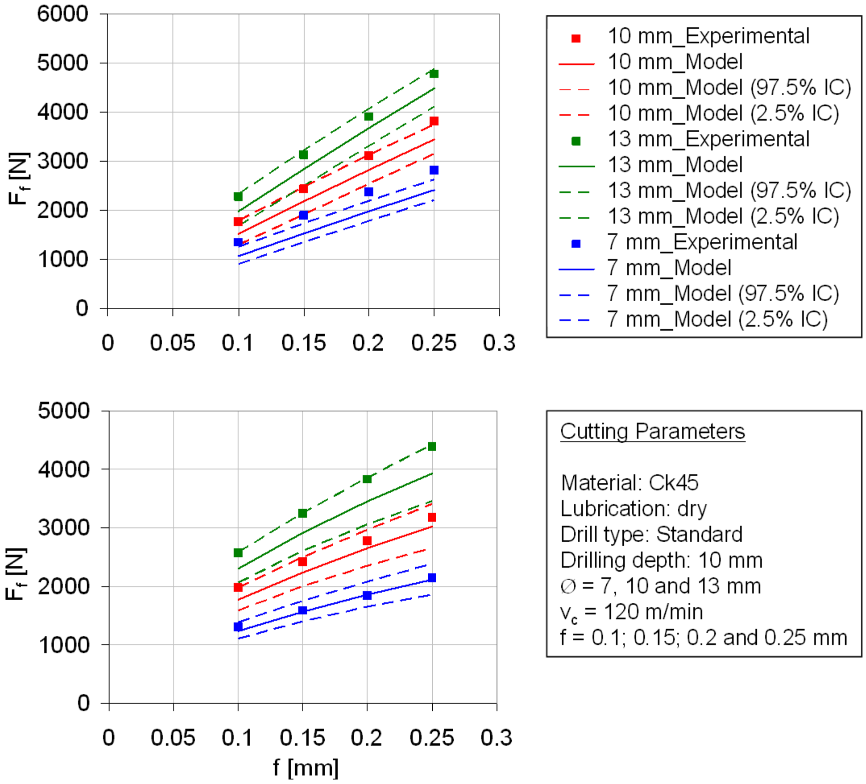


Figure 7. Cutting and thrust forces for drilling Ck45 steel with Standard carbide drill and different diameters

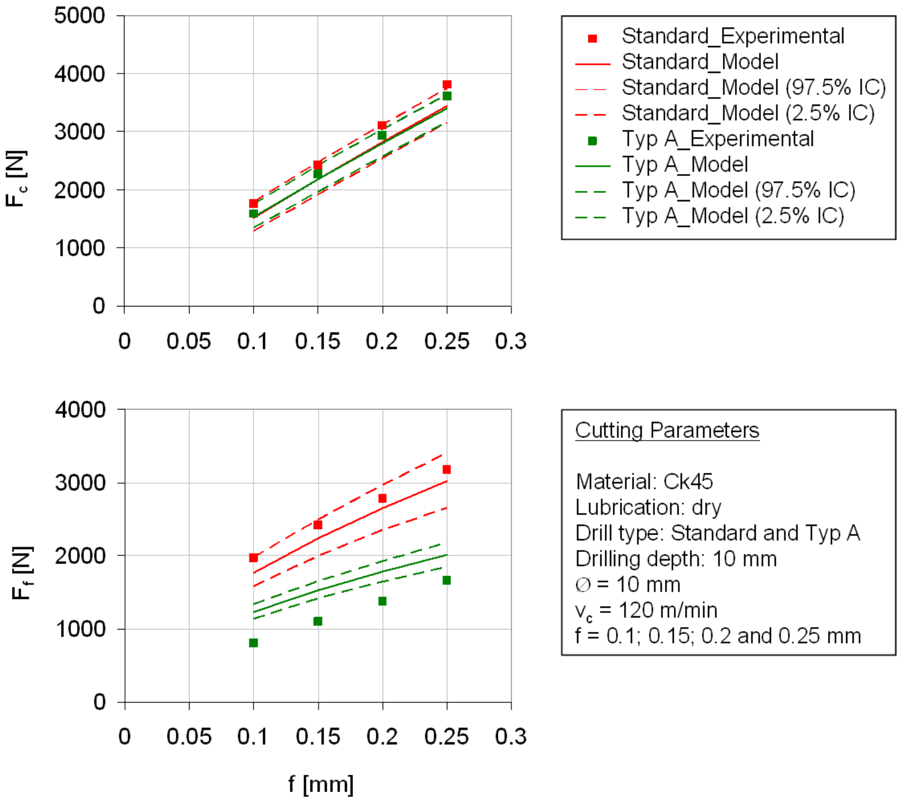
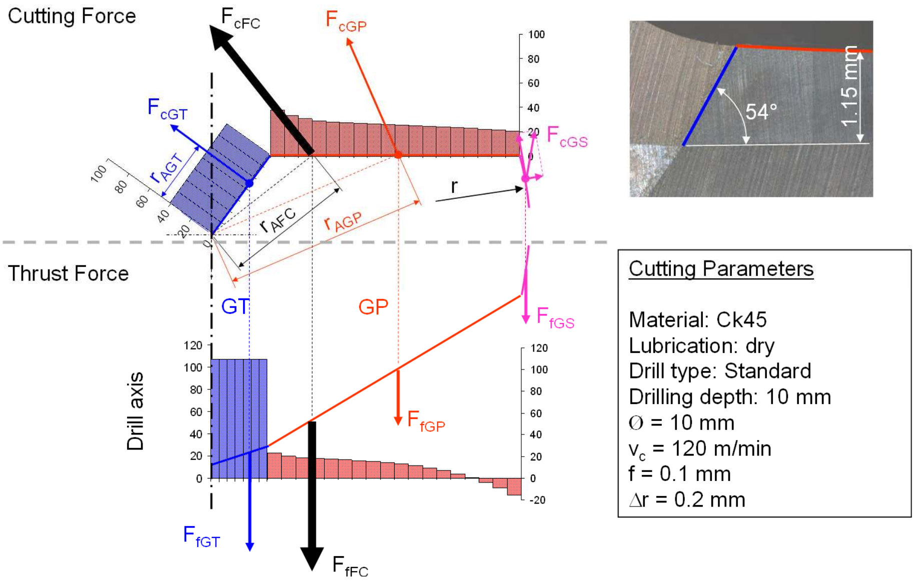


Figure 8. Cutting and thrust forces for drilling Ck45 steel with and without relief in GT using carbide drill

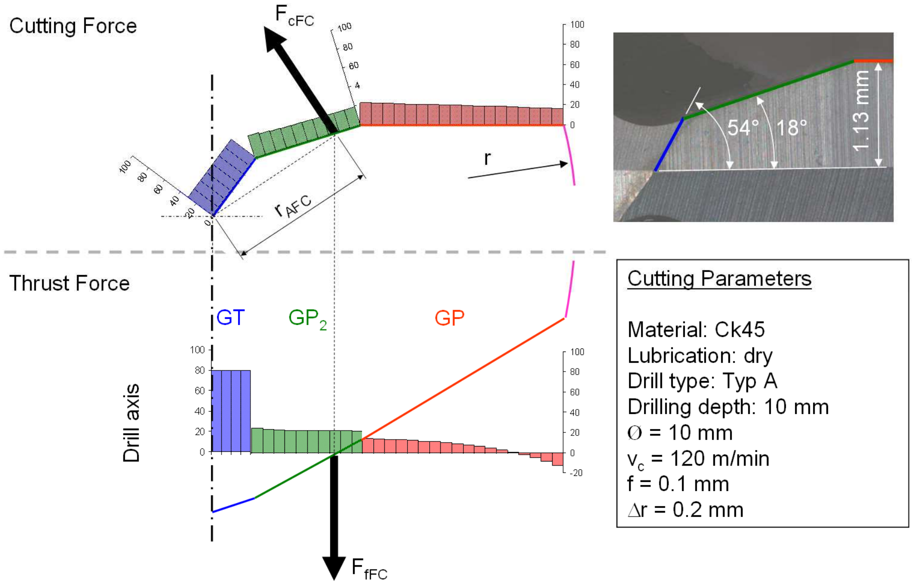
The distribution of forces on the drill edge, based on the model developed and presented in this paper, is shown in Figs. 9 and 10. Here, it is possible to verify that the thrust force is mainly influenced by the chisel edge component. Thus, one way to reduce this component is through chisel edge relief. This finding, previously observed by analyzing the results of Fig. 8, is shown in detail for the force distribution over the chisel edge and in Fig. 10, specifically for a drill of 10 mm in diameter and chisel edge relief of type A.



Cutting Parameters

Material: Ck45
Lubrication: dry
Drill type: Standard
Drilling depth: 10 mm
Ø = 10 mm
v_c = 120 m/min
f = 0.1 mm
Δr = 0.2 mm

Figure 9. Forces along the cutting lip and chisel edge - Standard drill



Cutting Parameters

Material: Ck45
Lubrication: dry
Drill type: Typ A
Drilling depth: 10 mm
Ø = 10 mm
v_c = 120 m/min
f = 0.1 mm
Δr = 0.2 mm

Figure 10. Forces along the cutting lip and chisel edge –Type A drill

5. CONCLUSIONS

The Kienzle model extended to the drilling process, which takes into account the geometric variations of the drill in terms of normal rake angle γ_n, and the back rake angle λ_s, showed results for the simulated forces similar to those obtained experimentally. In the region of the cutting lip the model developed for the simulation of forces showed good results, the values of the cutting and thrust forces being similar to those obtained in the literature for the drilling process. However, for the chisel edge region, it is still necessary to improve the model in order to obtain smaller differences between the results for the measured and simulated forces. Also, a better understanding of the chip formation mechanisms in this region is needed.

The reduction of the chisel edge effect on the thrust force component was evident when drilling with different diameters, where a reduction in the drill diameter and the consequent reduction of the chisel edge bring the values for the simulated forces closer to the measured values. This effect is also observed in the application of relief on the chisel edge.

Using a drill with type A relief on the chisel edge, the geometric change imposed on the chisel edge leads to a reduction in this region of extremely negative geometry, resulting in less force in the feed direction.

The model of drilling forces described in this paper allows, through the segmentation carried out along the main and chisel edge, the identification of regions with higher mechanical stresses during the drilling. With this information, it is possible to propose geometric changes to the tool and changes in the tip of the drill to minimize these forces, besides enabling the evaluation of the effect of the application of other materials to the cutting tool and new coatings. Another advantage is that the model allows the use of the coefficients of the Kienzle equation, taken directly from books and tables.

6. ACKNOWLEDGEMENTS

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