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# Simulating Drilling Using a CAD System

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***Abstract*****—**Nowadays, the rapid development of CAD systems' programming environments results in the creation of multiple downstream applications, which are developed and becoming increasingly available. CAD based manufacturing simulations is gradually following the same trend. Drilling is the most popular hole-making process used in a variety of industries. A specially built piece of software that deals with the drilling kinematics is presented. The cutting forces are calculated based on the tool geometry, the cutting conditions and the tool/work-piece materials. The results are verified by experimental work. Finally, the response surface methodology (RSM) is applied and mathematical models of the total thrust force and the thrust force developed because of the main cutting edges are proposed.

***Keywords*****—**Application programming interface, CAD, drilling, response surface methodology, RSM.

## I. Introduction

THE process of drilling holes constitutes one third of machining work and is generally applied as the finish operation. The conventional drilling, being economical and easily applicable, is one of the preferred machining methods in the manufacture of various industrial products [1].

Although it appears to be a relatively simple process, it is actually a very complex one. One has to consider that, there are two basic tool areas where thrust force is generated; the main cutting lips and the chisel edge. The drilling point's chisel edge is dominant at the generation of the tool thrust force, while the torque is heavily depended on the action of the cutting lips [2].

A series of methodologies for the drilling process simulation have been developed from a variety of researchers. While some of them are using experimental work in order to derive equations calculating the thrust force developed during drilling, others deal with the creation of finite element (FE) models coupled with experimental verification results [3].

## II. Use of CAD Systems in Simulations

Nowadays, the use of programming languages and interfaces in order to interact with CAD/CAM systems and integrate a series of missions is becoming more popular.

Antoniadis simulates the kinematics of the gear skiving with the aid of commercial CAD software and allows the precise determination of the non-deformed chips and the developing cutting forces. The simulation model is verified based on the theoretical shape of the produced gear gap and the comparison between measured and calculated cutting forces [4]. Tapoglou and Antoniadis perform additional simulations in face milling using a general purposes CAD system's Application Programming Interface [5].

Haba and Oancea developed activities such as designing of various digital technologies in order to achieve virtual prototype, obtaining a prototype using additive manufacturing technologies and manufacturing of an engine block. Most of these design activities are implemented by GENgine$^{TM}$, a piece of software developed using Open DCL and Visual Lisp programming environments [6].

Mansour et al. proposes an expert CNC system which optimizes the machining path process by deciding the optimum path. The features of the designed parts are identified and extracted directly from CAD drawings in order to control the parts for automatic machining [7].

Huertas-Talon et al. used CAD based methodologies in order to deal with the technical problems when milling a surface. A series of undesirable marks on the surface can be avoided by the use of spiral tool paths when manufacturing a component [8].

## III. Drilling Simulation Using CAD

Fig. 1 depicts the workflow of the CADRILL simulation. A series of input parameters are incorporated in order to create all the appropriate pieces of solid models needed. The tool is based on Galloway's mathematical model [9]. In the initial research work, Galloway used a series of 3D equations solving routines in order to describe the tool geometry. On the contrary, in the current project the same principles were used in order to create a routine that builds the tool geometry as CAD solid model and all the processing is implemented by the system itself.

Two sets of data are introduced. The tool design parameters (diameter, web thickness, half point angle, helix angle) and the manufacturing parameters (distances of the cone vertex along the X and Y axes, half cone angle). When the tool solid model is created, the appropriate solid models of the workpieces are also created based on the tool dimensions. Two separate workpieces are created in order to simulate both the actions of the main cutting edges and the chisel edge during drilling. Initial positioning of the tool geometry inside the workpieces solid models is crucial in order to reach the steady state condition of the simulation as quickly as possible.

The digital drilling process is separated in two parts. The first is based on the cutting action of the main cutting lips and the second on the cutting action of the chisel edge. Both, are treated in a similar way, although individually. The final result is the creation of 3D solid models simulating the undeformed chip and the shape of the remaining work piece geometries for

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each case. The tool is virtually moved transitionally towards the –Z axis (feed) while at the same time, it is rotated around its Z axis of symmetry using a constant step.

In every step, a boolean subtraction of the tool model, from the remaining work piece model is carried out. A specially shaped work piece is used, in order that the main cutting lips are directly engaged (steady state case), having a small hole in the middle (chisel edge area). Following that, another work piece of pure cylindrical shape with a diameter equal to each tool's chisel edge is used.

The 3D models of the un-deformed chip are segmented into smaller pieces. For each individual segmented solid model, a number of geometrical parameters are automatically recognized by the CADRILL, and all these data are introduced as input to the thrust calculation of the tool, based on the Kienzle-Victor method [10]. In more detail, both the un-deformed chip width and thickness are directly recognized from each segmented piece of the solid models, while the selection of the necessary coefficients Ki is made based on published data [11]. Finally, the outcome is the separate calculation of the thrust force i.e. $F_{ri}$, $F_{si}$ and $F_{vi}$ (Fig. 2).

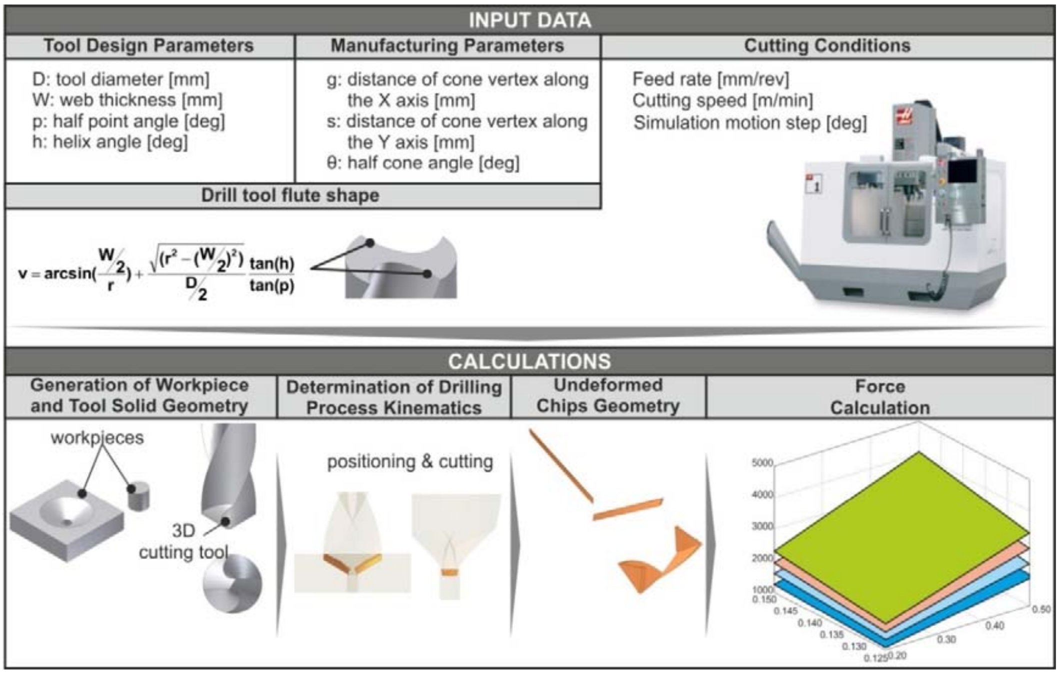


Fig. 1 Drilling simulation workflow

## IV. Verification of the Proposed Methodology

The results obtained from the CADRILL were verified by performing a series of experiments on a HAAS VF1 CNC machining center with continuous speed and feed control within their boundaries. The specimen used was a St52 plate. A Kistler type 9123 four components dynamometer was used and the signal was processed by a type 5223 multichannel signal conditioner and type 5697 data acquisition unit. The drill tools used were a D=8mm, D=10mm and D=12mm Bosch HSS-R (DIN 338) with 118 deg. point angle. Feed rates of 0.1, 0.15 and 0.2mm/rev were used together with cutting velocity values of 10, 30 and 50m/min.

In order to be able to separate the thrust force produced by the main cutting edges from the total thrust force, two series of experiments were conducted. The first series involved the direct drilling of the workpiece and resulted the total thrust force (both main edges and the chisel edge were engaged). In the second series, the workpiece was preshaped with an additional hole in the middle, with diameter equal to the chisel edge of the tool used. In this way the effect of only the main edges was measured and the direct comparison of the simulated and acquired results were possible.

Fig. 3 presents the thrust force results for three tools with different diameters of 8, 10 and 12mm. A series of feed rates were used and both the thrust forces were simulated and experimentally verified. As expected, when either the tool diameter or the feed increases, both forces increase as well. The forces obtained due to the main cutting edges are approximately the 30-40% of the total thrust force in every case. This was expected because the tool's chisel edge is mainly responsible for the total force sustained in a drilling tool while the main cutting edges contribute towards the torque needed for the operation. Similar results are obtained for the cutting forces, when the tools of 10mm and 12mm are used and they are depicted in Figs. 4 and 5 respectively.

When comparing Figs. 3-5, there is a small increase in the force developed because of the tools' main cutting edges when the cutting speed increases. The opposite is true in the case of the total thrust force in all cases because for the same feed rate the size of the un-deformed chip is considerable smaller.

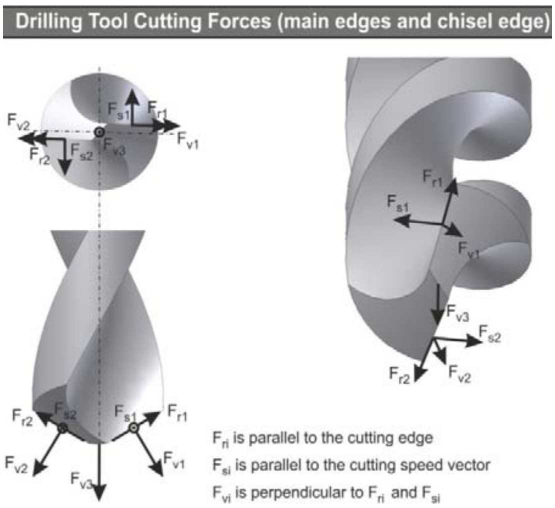


Fig. 2 Drilling forces developed on the tool

All the forces in all cutting speeds are substantially increased, when the diameter is increased. In all cases the results derived from CADRILL and experiments are very close, and prove the validity of the proposed methodology.

## V. Application of Response Surface Methodology

A polynomial mathematical model was used in order the total thrust force as well as the thrust force due to the action of the tool's main cutting edges, to be calculated. These models follow the form of:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{44}X_4^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{14}X_1X_4 + b_{23}X_2X_3 + b_{24}X_2X_4 + b_{34}X_3X_4 \quad (1)$$

where Y is the response i.e. thrust force, Xi stands for the coded values for i= D, V, f, and $b_0,\ldots,b_{34}$ represent the regression coefficients.

Using the data illustrated in Figs. 3-5 as well as the aforementioned mathematical model, the following equations form the final mathematical model proposed for the calculation of the thrust forces (in N) for both cases, total thrust force and thrust force due to the tool's main edges area respectively:

$$Fz\_total = 1759 - 295D + 19.7V - 2103f + 12.1D2 - 0.046V2 - 10667f2 - 1.31DV + 1608Df - 80.8Vf \quad (2)$$

$$Fz\_main = 267 - 71.9D + 1.9V - 728f + 3.33D2 - 0.0583V2 - 4000f2 + 0.688DV + 542Df - 13.3Vf \quad (3)$$

where D is the tool diameter in mm, f is the feed rate in mm/rev, V is the cutting speed used in m/min and the tool/work piece materials are HSS/St52.

The adequacy of the models is provided at 95% confidence level. The analysis of variance (ANOVA) has been performed to justify the validity of the models developed. The ANOVA table consists of sum of squares (SS) and degrees of freedom (DF). The sum of squares is usually contributed from the regression model and residual error. Mean square (MS) is the ratio of sum square to the degree of freedom and the F-ratio is the ratio of mean square of regression model to the mean square of residual error.

According to the methodology, the calculated value of F-ratio of the developed model is significantly increased compared to the tabulated value of F-table for 95% confidence level (54.85 and 351.97 respectively). The P value is 0.000, which proves the highest correlation; hence, the developed response function is quite adequate at a 95% confidence level. The validity of the fit of the models can also be proved, by the adjusted correlation coefficient (R-sq (adj)), which provides a measure of variability in observed output and can be explained by the factors along with the two factor interactions. This coefficient in both cases is 94.9% and 99.2% respectively and as a result the models appear to have adequate predictive ability (Table I).

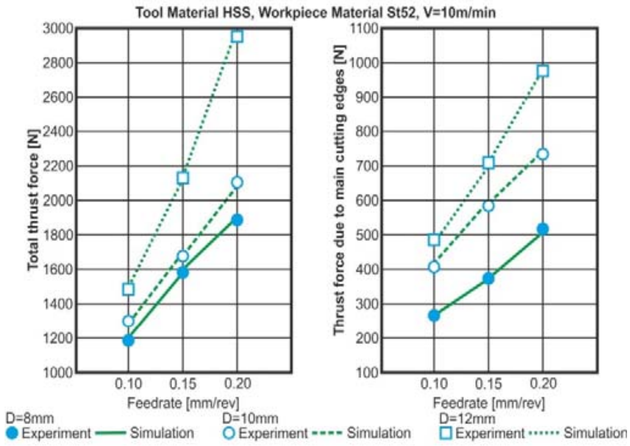


Fig. 3 Verification of CADRILL using HSS tools, St52 workpiece and V=10m/min

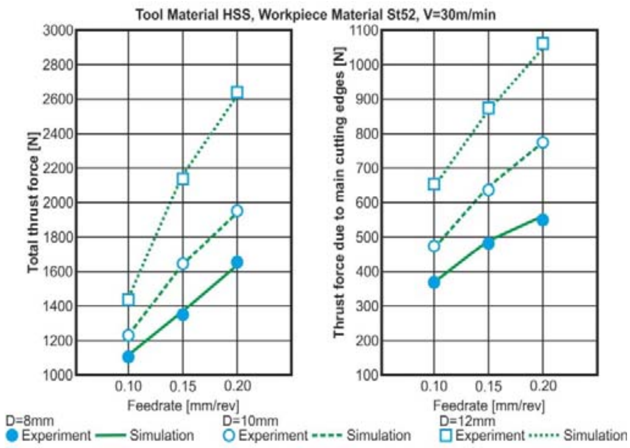


Fig. 4 Verification of CADRILL using HSS tools, St52 workpiece and V=30m/min

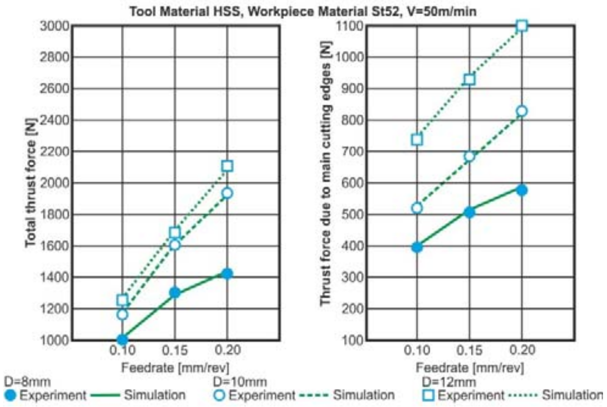


Fig. 5 Verification of CADRILL using HSS tools, St52 Work-piece and V=50m/min

TABLE I
ANOVA TABLE FOR THE RSM MODELS

| Source of variation for $F_{z\_total}$ | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 9 | 5652203 | 628023 | 54,85 | 0,000 |
| Residual error | 17 | 194664 | 11451 | | |
| Total | 26 | 5846867 | | | |
| R-sq(adj) | 94.9% | | | | |
| Source of variation for $F_{z\_main}$ | DF | SS | MS | F | P |
| Regression | 9 | 1230861 | 136762 | 351,97 | 0,000 |
| Residual error | 17 | 6606 | 389 | | |
| Total | 26 | 1237467 | | | |
| R-sq(adj) | 94.9% | | | | |

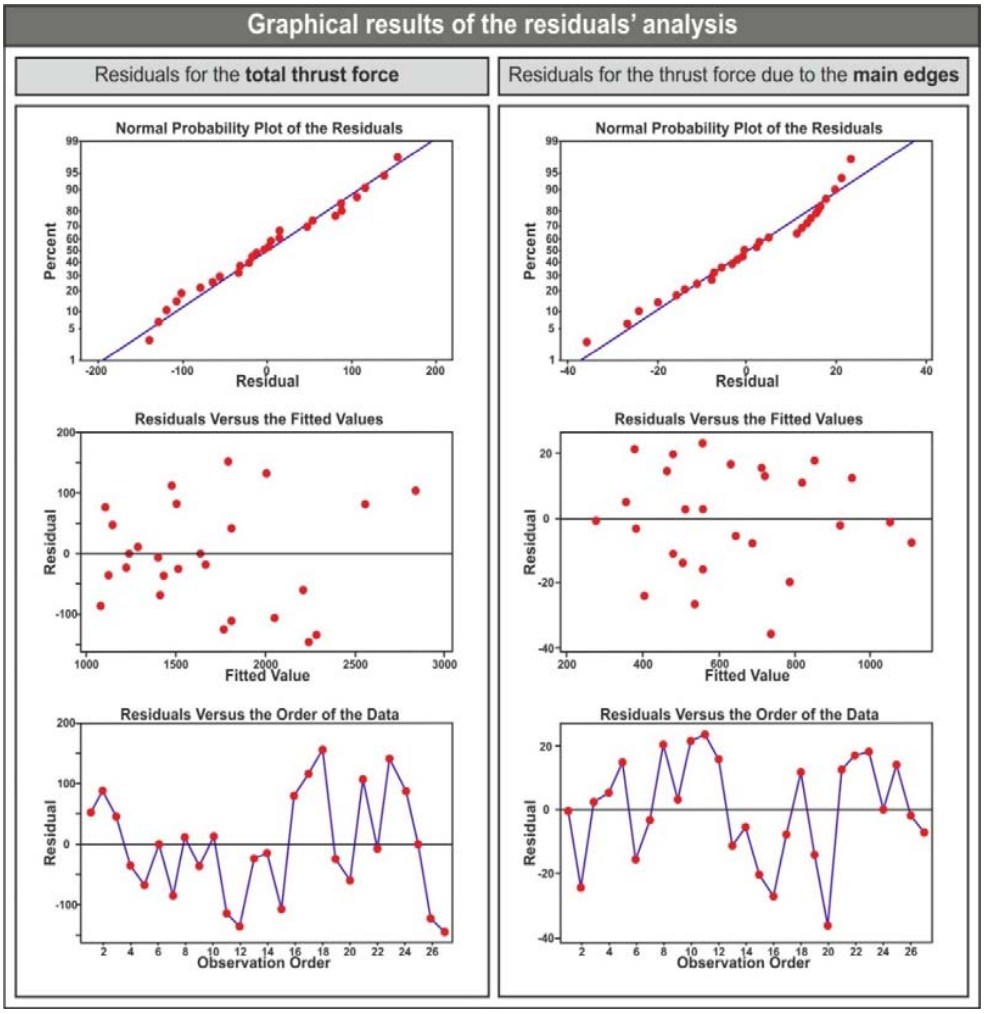


Fig. 6 Residuals analyses for the thrust forces

The accuracy of the models has been checked by the residual analysis, and it is essential that the residuals are normally distributed in order for the regression analysis to be valid. The normal probability plots of the residuals for both the thrust forces calculated are depicted in Fig. 6. The graphs show that the residuals closely follow straight lines (approximately linear pattern), denoting that the errors are normally distributed. In addition, both the scatter diagrams of the thrust forces residuals versus the fitted values and the residuals versus the order of the data presented in Fig. 6 depict that the residuals are almost evenly distributed on both sides of the reference line.

## VI. Conclusion

A novel simulation model which has been developed and embedded in a commercial CAD environment was presented in this paper. The model simulates precisely the tool kinematics and considers the effect of the cutting parameters on the cutting forces during drilling. The accuracy of the simulation model has been thoroughly verified, with the aid of a variety of cutting experiments. Finally, mathematical models of the forces developed were derived using RSM.

## Acknowledgment

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