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Hard Cutting of AISI D2 Steel

Marton Takacs, Balazs Zsolt Farkas
Budapest University of Technology and Economics,
Department of Manufacturing Science and Engineering
H-1111 Budapest, Egry József str. 1, Hungary
tm@manuf.bme.hu; farkasb@manuf.bme.hu

Abstract **–** The importance of hard machining is steadily increasing as part of modern manufacturing technology. It can be applied as alternative machining process to grinding providing a more economical way to finish hard surfaces. During this process materials of hardness ranging from 45 to 68 HRC are cut mainly by CBN tools. This paper summarizes the latest results of the authors regarding experimental and theoretical investigations of cutting AISI D2 cold work tool steel, which is often used for blanking, punching, cropping or shearing. Cutting experiments were carried out to study and evaluate the effect of cutting parameters on surface roughness and cutting force components. Finite element model were prepared and used to simulate chip removal process at hard cutting. Results of FEM simulation and experiments are compared. Explored relations and validated FEM model can help to improve machining of AISI D2 steel and provide well controlled circumstances for hard machining.

Keywords**:** AISI D2 steel, Hard cutting, Effect of machining parameters, Cutting force components, FEM simulation.

1. Introduction

Machining of hard materials (45-68 HRC) is a significant research field in the modern manufacturing technology. Hard cutting provides economical way to finish hard surfaces as an alternative process to grinding. Main advantages of hard machining are the ability to produce complex shapes, good surface roughness, higher material removal rate, reducing of finishing time, cost reduction, and offsetting the environmental concerns by dry machining (Tang et al., 2011).

During the last decades intensive research activity dealt with the special circumstances of hard cutting (Bartarya, Choudhury, 2012). The investigations focused on the effect of different cutting parameters, tool geometry, tool wear, surface integrity, formation of white layer, cutting forces and temperatures, numerical analysis of chip removal process, etc. Even so there is a large demand to recognize the optimal and well controlled circumstances for hard machining of different materials.

Theoretical analysis of hard cutting can be supported in a very efficient and economical way by numerical simulation performed by finite element method. Valid and realistic result of finite element simulation can be ensured by an accurate geometric and material model, correctly set boundary conditions, adequate initial mesh, properly chosen remeshing strategy, well-defined friction circumstances, and reasonably applied material separation method (Takács, Farkas, 2013, Bartarya, Choudhury, 2012, Duan et al., 2009). Literature survey confirms that most often applied FEM software packages for theoretical analysis of chip removal process are Deform 2D/3D, Abaqus, AdvantEdge, and LS Dyna (Szabó, Kundrák, 2012, Attanasio et al., 2008, Woon et al., 2008, Maurel et al., 2008)

One of the characteristical phenomena of hard cutting is the formation of segmented chips. Two basic concepts were introduced as reason for that: surface shear cracking and catastrophic thermoplastic instability (Karpat, Özel, 2007, Chou, Song, 2004). The first theory was proposed by Nakayam et al. (1988), and Shaw and Vyas (1993), the second theory is originated from Recht (1964), and it was confirmed also by Poulachon és Moisan (2009), and Komanduri and Hou (2002), too. One of the main challenges of FEM simulation is the realistic visualization of segmented chips.

Two typical and often used hard tool materials are AISI H13 and AISI D2. AISI H13 hot work tool steel has already been investigated by the author previously (Takács, Farkas, 2013). This paper is focusing on the results of experimental and theoretical analysis of AISI D2 cold work tool steel.

Cutting experiments with varying feed rate and cutting speed were carried out on workpiece of AISI D2 steel (62 HRC) to determine their effect on components of resultant force. The investigated material is dimensionally stable, high-carbon and high-chromium steel with good toughness, and with wide application field. The steel can be used as cutting tools (dies and punches), blanking or punching tools, wood working tools, shear blades, thread rolling tools, tools for deep drawing and cold extrusion, pressing tools, and small moulds for plastic industry (Web-1).

Finite element simulation was performed by Deform 3D software to investigate the chip removal process under the same conditions used at cutting experiments. Theoretical and practical results were compared.

2. Cutting experiments on AISI D2 (62 HRC) steel

As part of our current research activity AISI D2 steel with a hardness of 62 HRC was hard machined. Common designations of this steel are as follows: DIN 1.2601, EN X165CrMoV12, BS BD2, Böhler K105. Chemical composition of the cut material can be found in Table 1.

Table 1. Chemical composition (average %) of machined AISI D2 steel

C	Si	Mn	Cr	Mo	V	W
1,60	0,35	0,30	11,50	0,60	0,30	0,50

Cutting experiments were carried out by an ultra precision machine of type of Hembrug Slentbed Mikroturn 50. The positioning accuracy and repeat accuracy are ±1 μm and ±0.1 μm, respectively, and the resolution of the programming system is as small as 10 nm. An 80° nose angle (C-insert type), rhombic shaped, uncoated CBN cutting insert with chamfered edge and nose radius of 0.4 mm was used (Fig. 1.).

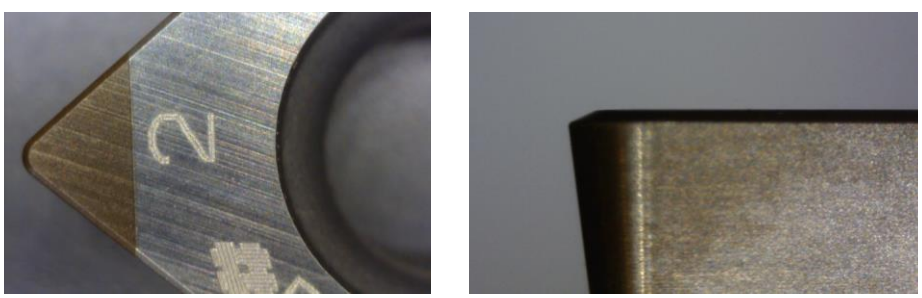

Fig. 1. Uncoated CBN cutting insert used for hard machining experiments

The standard designation of this insert is CCGW09T304NU2. The insert contains a chamfer, which aims a stronger edge geometry, but results in a local negative rake angle.

vc=130 (70-170) m/min and f=0.15 (0.03-0.3) mm/rev are the proposed parameters of the tool manufacturer. This was considered during the experiments, too.

Straight turning process was carried out on cylindrical shaped workpieces of initial diameter of 20 mm. Cutting length was 10 mm. For each parameter combination different workpiece sample was applied to ensure the same cutting conditions at same workpiece diameter.

The hardness of 62 HRC of the testing samples was achieved by hardening at 980°C followed by 2 hours tempering at 200°C.

Fixing of workpiece samples was realised by collet chucking system.

The tool holder was fixed on the plate of a Kistler 3-component piezoelectric dynamometer of type 9295B connected to a Kistler multi channel charge amplifier of type 5070. The dynamometer is mounted on the tool revolver of the UP turning machine tool. The experimental setup is shown in Fig. 2.

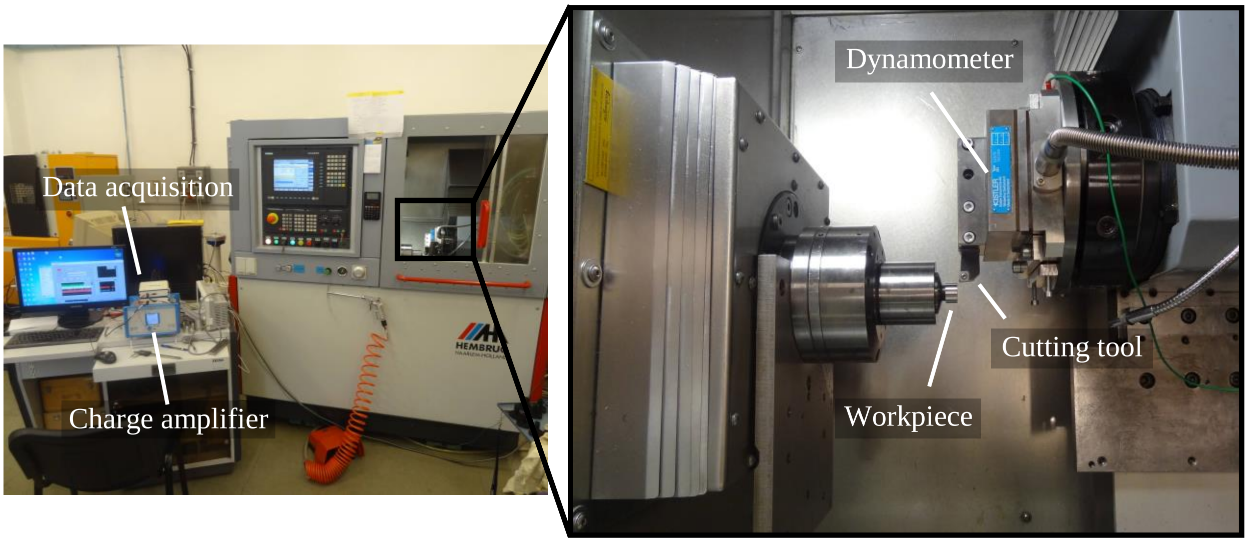

Fig. 2. Set up of cutting experiment of AISI D2 steel.

The variable parameters of the experiment are summarized in Table 1. The parameters are chosen in accordance with the usual applied values at hard cutting displayed previously.

Table 1. Cutting experimental parameters.

Cutting parameter	**Applied values**
Feed rate [mm/rev]	0.03, 0.05, 0.1, 0.15, 0.2
Cutting speed [m/min]	100, 130, 150, 200, 250
Nose radius [mm]	0.4
Depth of cut [mm]	0.1

The results of force measurement can be observed in Fig. 3. as a function of feed rate and cutting speed. Three force components, such as cutting force, thrust force and passive force are shown in different diagrams. The scales of the diagrams are chosen conform, which helps in compare. It can be stated that the larger the feed rate the higher the cutting force and the passive force. Passive force component is the most dominant in this case.

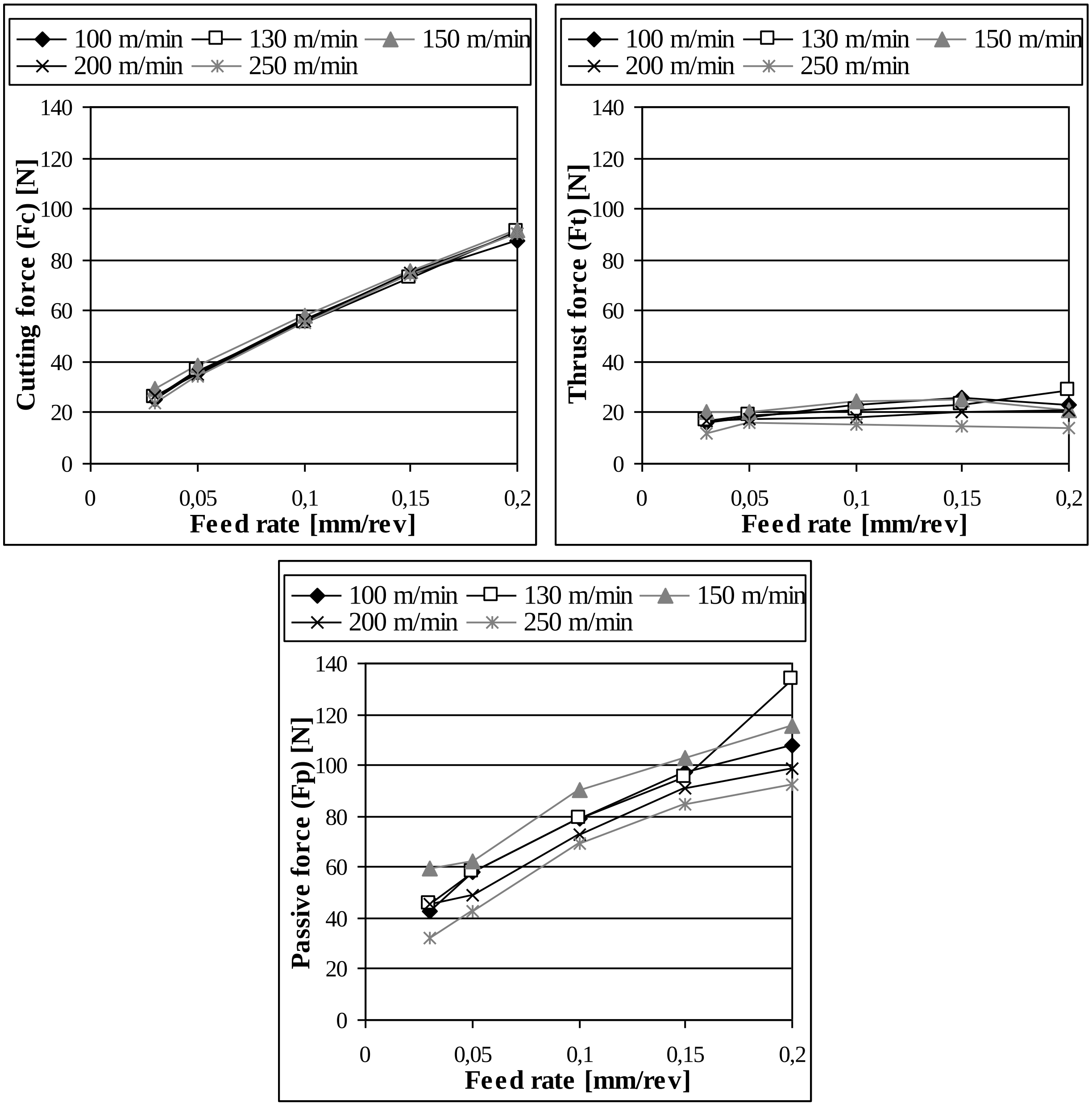

Fig. 3. Measured force components based on cutting experiments.

It can be observed that there is almost no change in thrust force and cutting force, and just a slight change in passive force as function of the cutting speed in the investigated parameter range. The main reason for the limited change is the almost independency of chip root area from cutting speed. The larger fluctuation of passive force component can be explained by the special circumstances of hard cutting.

The orientation of the thrust force component is parallel to the feed of the tool. The passive force component is oriented in radial direction to the workpiece. The applied cutting insert was chamfered to strengthen the cutting edge, which affects a negative value for the effective rake angle. Small depth of cut and feed rate are set during a hard cutting process to decrease tool wear and ensure good surface quality. This effects that chip removal takes place mainly along the tool nose radius. Further special characteristic of hard machining is the spring-back effect, which influences the chip removal, too (Astakhov, 2011). These can be the most important reasons for one of the specific phenomena of hard cutting, namely that the passive force component is the largest one among all components (Tönshoff et al., 2000, Bartarya, Choudhury, 2011). In the case of hard cutting mainly segmented chip is formed. This chip morphology can have a regenerative effect on the dynamic behavior of the cutting process (Taylor et al., 2012). Cutting speed has influence on the value of cutting temperature, which affects the cutting force, too. Considering the orientation of the passive force component all of the above mentioned elements can result in a larger fluctuation of this component, when cutting speed is changing.

On the base of the experiments carried out in the frame of this research work – especially in the investigated cutting speed range – no obvious correlation between cutting speed and passive force component can be observed. Further investigation is required on this field in the future.

3. FEM simulation

Exact CAD model of previously introduced cutting insert were prepared and imported to the FEM software Deform 3D (Takács, Farkas, 2013). The arrangement was the same used at cutting experiments (Fig. 4.). The data for workpiece material behavior are based on the Oxley's equation (Oxley, 1989), and given in tabular form in Deform 3D. The value of Young's modulus was 206754 MPa. The type of friction was Coulomb with a constant value of 0.7. The number of elements of the tool was set to 80000 to ensure the accurate geometry of chamfered cutting edge. Adaptive remeshing method and two local mesh windows were applied in the case of workpiece to maintain a locally higher mesh density in the case of large deformations, e.g. in the neighborhood of the chip root. The initial element size of the workpiece was chosen as high as 45000.

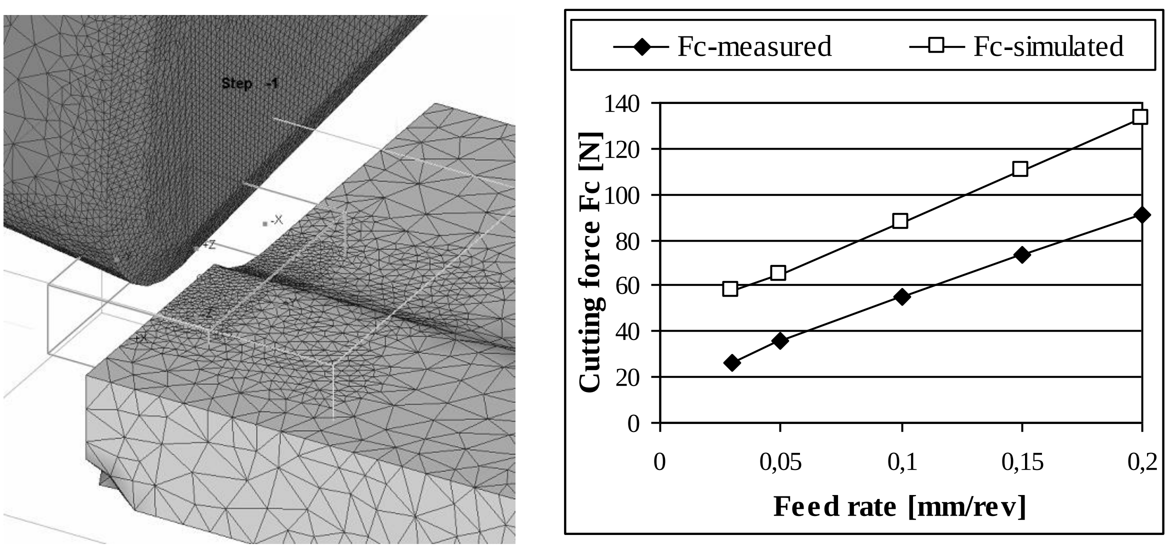

Fig. 4. FEM model and comparison of simulated and measured values of cutting force (F_c).

FEM simulation was performed under the following machining parameters: v_c=130 m/min, a_p=0.1 mm, f=0.03, 0.05, 0.1, 0.15, and 0.2 mm/rev. Comparison of theoretical and experimental results can be made on the base of the diagram of Fig. 4. The diagram shows average values of simulated cutting force components in the steady state section. The differences of the measured and calculated values are in the range of 45-120% depending on the feed rate. The most possible reason for this deviation can be the improper data of material behaviour of FEM software. Better results could be achieved in the future by applying different constitutive material models, such as Johnson and Cook model, by setting different initial mesh, by using other kind of remeshing strategy, or by applying other type of material separation method (e.g. fracture criteria).

Considering the small area of chip root a finer mesh can assure more accurate and realistic simulation of chip removal and formation, but the required computational capacity is much higher in that case.

Especially the material flow in the shear zone depends on the mesh size. According to the preliminary FEM simulation of the author it was experienced that not only the absolute value of the force components can be changed, but the fluctuation of them, too.

4. Conclusion

Hard cutting of AISI D2 (62 HRC) steel by CBN cutting insert was investigated by experimental and theoretical analysis. Cutting experiments were carried out with variable feed rate and cutting velocity in the ranges of 0.03 – 0.2 mm and 100 – 250 m/min, respectively. Effect of cutting parameters on force components was determined. It can be stated that the passive force is the most dominant force component, which corresponds to the general estimation at hard machining. No characteristic correlation was found between the cutting speed and the cutting force in the given parameter range.

3D finite element simulation of chip removal process was performed. It was found that in the case of the applied model the theoretical cutting force values are 45-120% higher, than the measured ones.

Further theoretical research has to aim the detailed analysis of chip removal process, focusing on the segmented chip formation and temperature distribution during the process. Different material constitutive model has to be applied to achieve better results.

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