Int J Adv Manuf Technol (2015) 76:1937–1945
DOI 10.1007/s00170-014-6423-1

ORIGINAL ARTICLE

Effect of uncut chip thickness on the ploughing force in orthogonal cutting

Alexey Popov · Andrey Dugin

Received: 2 June 2014 / Accepted: 19 September 2014 / Published online: 1 October 2014

Abstract Determination of the ploughing forces is necessary for monitoring the wear of the cutting tool in micro cutting. The aim of this research was to increase the accuracy of determining the ploughing force and the determination of the influence of the uncut chip thickness on the ploughing force. A new method for determining the ploughing forces is suggested in this article. It was found that the ploughing forces determined by the new method were greater than those determined by the method comparing total forces at different flank levels of wear. It was first established that the uncut chip thickness influences the ploughing force.

Keywords Machining · Cutting edge · Ploughing · Cutting forces

1 Introduction and motivation

Albrecht [1] has stated that the forces acting on the front face of a cutting element initiate the chip-forming process. Later, Zorev [2] experimentally proved that the ploughing forces are not part of this process; they are considered to be parasitic forces, and they arise as a result of the elastic reaction of the processed material on the rear surface of the tool (including a radius). Zorev [2] also assumed that the forces on the front face do not influence the ploughing forces.

In machining with small, uncut chip thicknesses, the ploughing forces may be higher than those on the front face. Chae et al. [3] and Jemielniak et al. [4] reported that in a production environment, cutting with small, uncut chip thicknesses occurs sufficiently often, for example, in finishing and micro cutting or in high-speed finish turning of AlMgSi alloy, such as what was presented by Samuel [5]. Dugin [6] experimentally proved that the ploughing forces grow substantially with increasing wear of the cutting tool. In this context, as presented by Hui et al. [7] and later Tasel et al. [8] and Afazov et al. [9], it is reasonable to perform wear monitoring of the cutting tool directly in the micro cutting process, depending on the increase in ploughing forces.

Different methods for determining the ploughing forces are known from literature, such as the extrapolation method on zero uncut chip thickness, based on which the forces on the front face do not influence the ploughing forces, as was first proposed by Albrecht [1] and Zorev [2] and later used by Guo et al. [10], Wyen et al. [11], and Dugin et al. [12]. Furthermore, the comparison method of total forces at different levels of wear of the rear surface of the tool was also proposed by Zorev [2] and used by Lipatov [13] and Popov et al. [14].

Popov [15] stated that the ploughing forces, determined by the extrapolation method on zero uncut chip thickness, prove to be substantially greater than those determined by the comparison method of total forces at different levels of wear of the rear surface. In this context, it is important to increase the accuracy of determining the ploughing force, to compare the accuracy of different experimental measurement methods of the ploughing forces and to explore the influence of the uncut chip thickness on the ploughing forces.

2 A new method for determining the ploughing forces

2.1 A comparison method of the total forces for different contact areas

To determine the ploughing forces, a special method of comparison is often used for the total forces at different levels of wear of the rear surface. This method, which was first

---

A. Popov · A. Dugin (✉)
Department of Machining and Assembly Faculty of Mechanical Engineering, Technical University of Liberec, Studentská 1402/2, 461 17 Liberec 1, Czech Republic
e-mail: andr.dugin@gmail.com

A. Popov
e-mail: alespopov@yandex.ru

proposed by Zorev [2] and then by Colwell [16], is based on the following idea.

If all cutting conditions are constant and only the wear of the rear surface (flank wear) is increased (Fig. 1a), the chip formation is usually not changed. Therefore, the force acting on the front surface is also not changed. However, due to the increase of the contact area between the rear surface of the tool and the processed material, the ploughing force is augmented, resulting in the total cutting force being increased as well. Hence, this observed increase of total cutting force should be considered as a result of the ploughing force increase.

The disadvantage of the comparison method of total forces at different levels of wear of the rear surface of the tool is that the wear of the rear surface is not the same as the real contact area between the rear surface of the tool and the processed material (Fig. 1). The reason for this phenomenon lies in the elastic reaction of the processed material.

A new method for determining the ploughing forces was suggested for increasing the accuracy of determining the ploughing force. This new method was named «the comparison method of the total forces for different contact areas». Increasing the accuracy of determining the ploughing force is based on measuring the real contact area between the rear surface of the tool and the processed material.

2.2 Cutting test and materials

The measurement process was carried out during the orthogonal chipping. In the chipping process, the experiments were performed on a milling machine. The cutter was fixed on a vertical milling hand. The PRAMET TOOLS cutter CTCPN 2514 M16 with a cutting plate TPUN 160308 of hard alloy ISO P30 was used. In cutting, the front and flank angles were 5° and 6°, respectively (Fig. 2). The cutting edge radius of the cutting plates was 0.03 mm. For processing, the work pieces with dimensions of 100 × 6 mm, aluminum alloys (AlCu4PbMgMn (122 HB), AlCu4MgSi (113 HB)), structural steels (16MnCr5 (138 HB), 50CrV4 (193 HB)), and stainless steels (X20Cr13 (230 HB), X5CrNiTi18-10 (259 HB)) were used (Fig. 2).

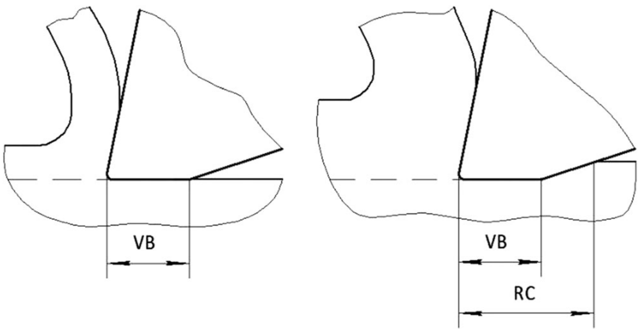


Fig. 1 Theoretical (*left*) and real (*right*) contact of the rear surface of the tool to the processed material; *VB* flank wear, *RC* real contact

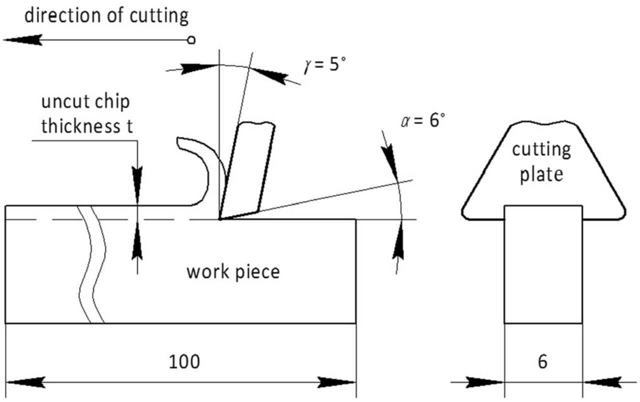


Fig. 2 Chipping scheme

The work piece was fixed in the clamp, which in turn was fixed on the three-component piezo-electric KISTLER dynamometer, model 9265B-9441B, connected with a computer with special MathLab software for the force measurements. The measurement error of forces amounted to ±2 %. Dynamometer and the software were previously calibrated, using standard mechanical precision dynamometers in the range of 10 to 6,000 N (Fig. 3).

Every measurement of the force (Fig. 4) was repeated five times, and then, the average force value was determined. The cutting rate, amounting to 0.45 m/min, was provided by longitudinal travel of the milling machine table (Fig. 3). Water was used as a coolant. The use of low cutting rates and water cooling is conditioned by the need to eliminate the influence of rate and temperature on the force values. The uncut chip thickness was set manually and controlled by an indicator at a scale of 0.002 mm.

2.3 Determination of the real contact between the rear surface of the tool and the processed material

The following procedure was carried out to determine the real contact between the rear surface of the tool and the processed material. The rear surface of the tool was painted before chipping. Figure 5 (left) shows a picture of the rear surface

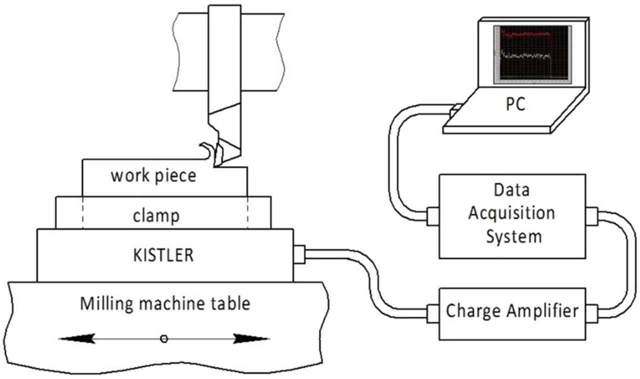


Fig. 3 Measurement scheme

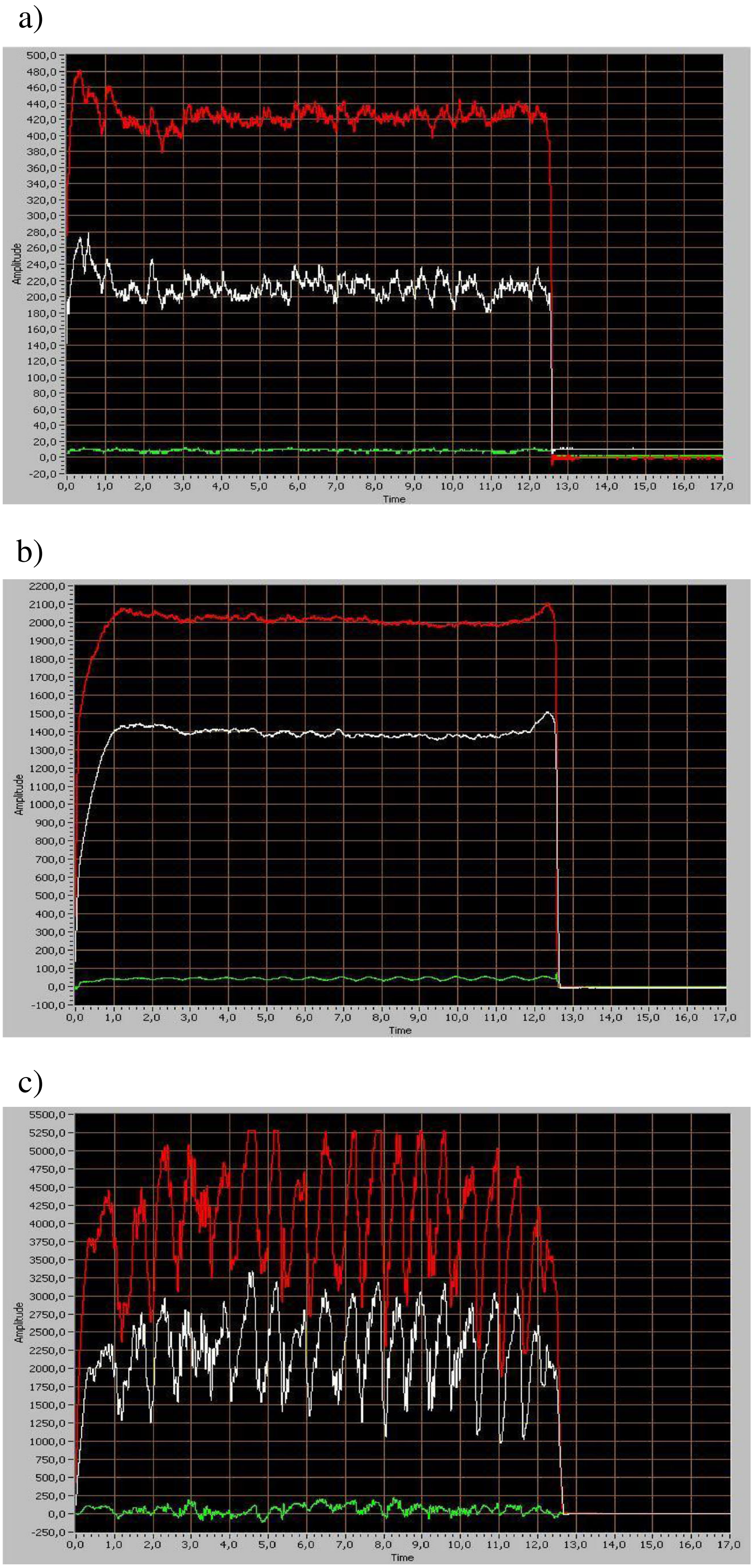


Fig. 4 Measurement results of two components of active force Fa cutting different materials with different flank levels of wear at different uncut chip thicknesses: **a** AlCU4PbMgMn with the uncut chip thickness t=0.05 mm, the flank level of wear VB=0.03 mm. **b** 16MnCr5 with the uncut chip thickness t=0.125 mm, the flank level of wear VB=0.3 mm. **c** X5CrNiTi18-10 with the uncut chip thickness t=0.125 mm, the flank level of wear VB=0.3 mm. *White line*—feed force Ff; *red line*—cutting force Fc

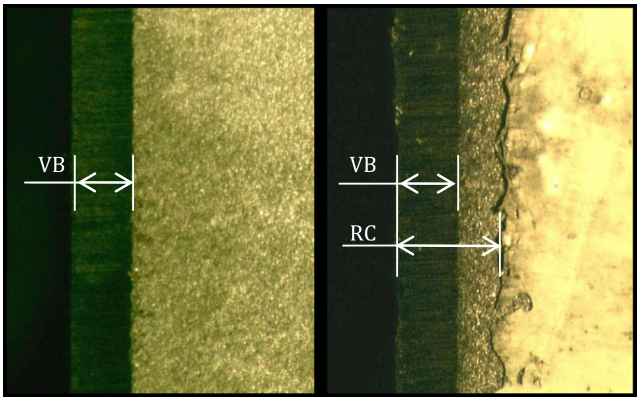


Fig. 5 Picture of the rear surface of the tool before painting (*left*) and picture of the rear surface of the tool after chipping (*right*)

of the tool before painting, and Fig. 5 (right) shows a picture of the rear surface of the tool after chipping. The length of the real contact between the rear surface of the tool and the processed material was measured by a microscope with an accuracy of 0.01 mm. Every measurement of the real contact was repeated ten times, and then, the average force value was determined.

Table 1 shows the differences between the flank wear VB and the real contact RC in chipping of different materials. The experiments were conducted at flank levels of wear VB of 0.03, 0.3, and 0.5 mm for six types of processed materials. The cutting edge radius of the new cutting plates was 0.03 mm. New cutting plates had a flank wear VB of 0.03 mm because they had a cutting edge radius. Flank levels of wear VB were ground by a diamond grinding wheel on the tool grinder at 0.3 and 0.5 mm. The choice of these flank levels of wear VB was explained by the fact that 0.3 and 0.5 mm are the maximum limited flank wear in turning, according to Axinte et al. [17], and milling, according to De Chiffre [18].

It should be noted that in the chipping of different materials with different flank levels of wear, the real contact areas were different at the same cutting conditions, which was a consequence of the different physical and mechanical properties each of the materials. It was proven that the real contact area between the rear surface of the tool and the processed material is substantially greater than the flank wear.

2.4 Determination of the ploughing force

To determine the ploughing forces, the expansion scheme of the total force on the flank surface Fa was used. The scheme is presented in Fig. 6.

Figure 7 shows the results of determining the ploughing forces in the chipping of the aluminum alloy AlCu4PbMgMn, obtained by the extrapolation method on zero uncut chip thickness, the comparison method of the total forces at different flank levels of wear and the comparison method of the total forces for different contact areas.

Figure 7a shows the results of determining the ploughing forces by the extrapolation method on zero uncut chip thickness. The experiments were carried out at uncut chip thicknesses of 0.05, 0.075, 0.1, and 0.125 mm. Therefore, by using the plate with a flank wear of VB=0.3 mm, it was found that the ploughing force component $F_{Pl,c}$ amounts to 225 N in the direction of cutting and to 293 N in the feed direction $F_{Pl,p}$. It is important to notice that using the extrapolation method on zero uncut chip thickness, ploughing force components ($F_{Pl,c}$, $F_{Pl,p}$) are not dependent on the uncut chip thicknesses, and they are equal (225 and 293 N) for uncut chip thicknesses from 0.05 to 0.125 mm (Fig. 7a).

Figure 7b shows the results of determining the ploughing forces using the comparison method of the total forces for different flank levels of wear. It was found that at a flank wear of VB=0.3 mm, the ploughing force component $F_{Pl,c}$ equaled 126 N in the direction of cutting and 203 N in the feed direction $F_{Pl,p}$.

Figure 7c shows the results of determining the ploughing forces by applying the comparison method of total forces with different contact areas. Therefore, when using the plate at a flank wear of VB=0.3 mm, it was found that the real contact RC was 0.48 mm and that the ploughing force component $F_{Pl,c}$ amounted to 153 N in the direction of cutting and to 259 N in the feed direction $F_{Pl,p}$.

2.5 Experimental results and analysis

It should be noted that the comparison of the ploughing forces (Fig. 8) was carried out with the same flank level of wear VB=0.3 mm, during the chipping of different materials with the same cutting conditions.

Table 1 Flank wear VB and real contact RC in the chipping of different materials

Flank wear VB, mm	Real contact RC, mm					
	AlCu4PbMgMn	AlCu4MgSi	16MnCr5	50CrV4	X20Cr13	X5CrNiTi18-10
0.03	0.12	0.12	0.22	0.18	0.28	0.38
0.3	0.48	0.39	0.96	0.59	0.78	1.1
0.5	0.72	0.59	1.41	1	1.12	1.71

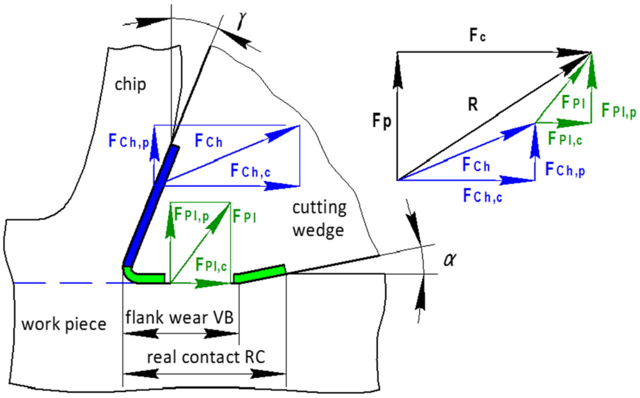


Fig. 6 Expansion of the active force Fa into the chip-forming force F_{Ch} and ploughing force F_{Pl} and into the components in the feed and cutting directions, according to Albrecht [1] and Wyen et al. [11]

Based on measurement results of the ploughing force in the direction of cutting $F_{Pl,c}$ and in the feed direction $F_{Pl,p}$ (Fig. 7), the ploughing forces F_{Pl} were determined for six types of processed materials. Figure 8 shows the differences between the ploughing forces F_{Pl}, obtained by the extrapolation method on zero uncut thickness, the comparison method of the total forces at different flank levels of wear, and the comparison method of the total forces for different contact areas between the rear surface of the tool and the processed material in the cutting of different materials. Ploughing forces, compared in Fig. 8, were determined for each of the six materials by three different methods at the same cutting conditions (the flank level of wear VB=0.3 mm).

It was found that in processing AlCu4MgSi, the ploughing force F_{Pl} determined by the comparison method of total forces at different contact areas between the rear surface of the tool and the processed material was 38 % greater than the one determined by the method comparing total forces at different flank levels of wear (Fig. 8). In the processing of AlCu4PbMgMn, the ploughing force F_{Pl} determined by the new method was 26 % greater than the one determined by the method comparing total forces at different flank levels of wear (Fig. 8). In the processing of 50CrV4, this difference amounted to a factor of 35 %; in processing of X20Cr13, this difference amounted to a factor of 41 %; in the processing of 16MnCr5, this difference showed a factor of 32 %; and in the processing of X5CrNiTi18-10, this difference amounted to a factor of 34 % (Fig. 8).

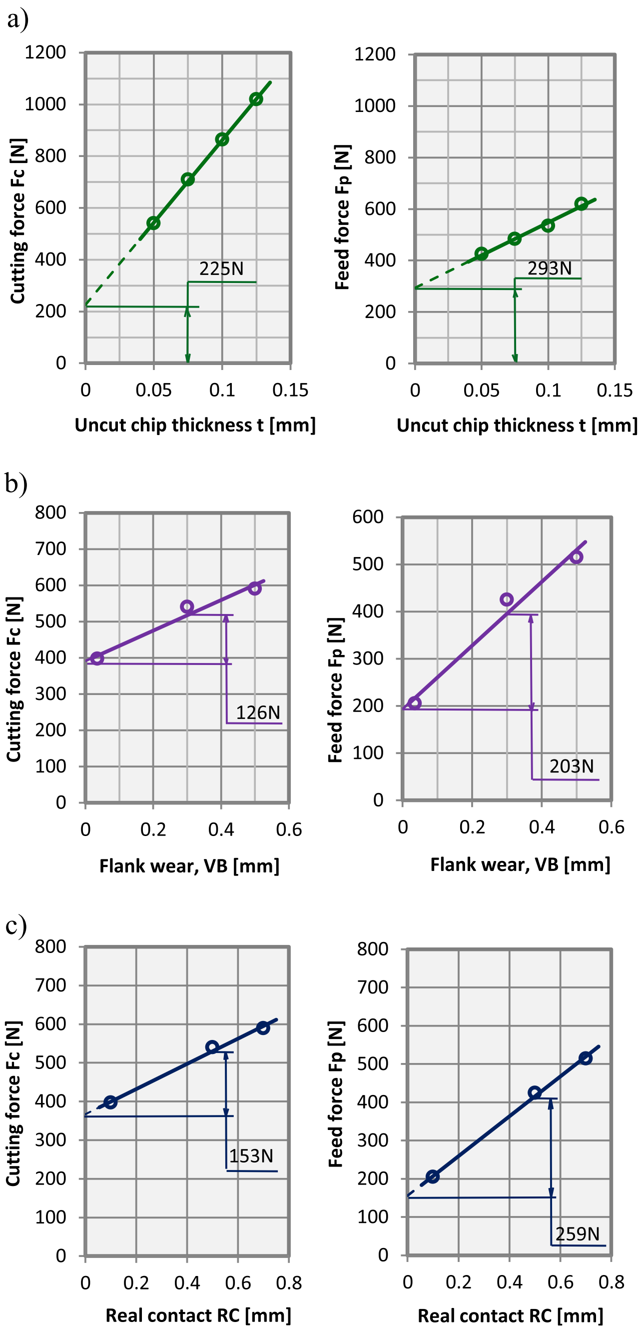


Fig. 7 Determination of the ploughing force in chipping of an aluminum alloy AlCU4PbMgMn by **a** the extrapolation method on zero uncut chip thickness, **b** the comparison method of the total forces at different flank levels of wear, and **c** the comparison method of the total forces for different contact areas

It was established that in the processing of AlCu4MgSi, the ploughing force F_{Pl} determined by the comparison method of the total forces for different contact areas between the rear surface of the tool and the processed material was 17 % lower than the one determined by the extrapolation method on zero uncut chip thickness (Fig. 8). In the processing of AlCu4PbMgMn, the ploughing force F_{Pl} determined by the new method was 23 % lower than the one determined by the extrapolation method on zero uncut chip thickness (Fig. 8). In the processing of 50CrV4, this difference amounted to a factor of 59 %; in the

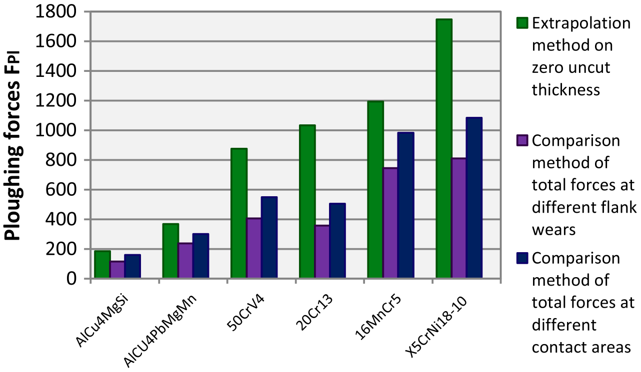


Fig. 8 Comparison of the ploughing forces F_{Pl} obtained by different methods

processing of X20Cr13, this difference amounted to a factor of 104 %; in the processing of 16MnCr5, this difference amounted to a factor of 21 %; and in the processing of X5CrNiTi18-10, this difference amounted to a factor of 61 % (Fig. 8).

3 Effect of the uncut chip thickness on the ploughing force

3.1 Experimental procedures

The comparison method of the total forces for different contact areas was used for determining the ploughing forces in chipping for six types of processed materials. The ploughing forces were compared for uncut chip thicknesses of 0.05 mm and of 0.125 mm. The experimental setup was described in Sections 2.2–2.4 of this paper.

Table 2 shows the differences between the flank wear VB and the real contact RC in the chipping of different materials. The experiments were conducted at flank levels of wear VB of 0.03, 0.3, and 0.5 mm for six types of processed materials. It was found that the real contact RC depends on the uncut chip thickness. For example, it was found that in processing AlCu4MgSi, the real contact RC=0.62 mm determined for the uncut chip thickness t=0.125 mm was 59 % greater than the real contact RC=0.39 mm determined for the uncut chip thickness t=0.05 mm (Table 2) at the same flank wear VB=0.3 mm. In this way, it was proven that the real contact area between the rear surface of the tool and the processed material determined for the uncut chip thickness t=0.125 mm was substantially greater than the real contact determined for the uncut chip thickness t=0.05 mm (Table 2) at the same flank wear.

Figure 9 shows the results of determining the ploughing forces ($F_{Pl,c}$, $F_{Pl,p}$) by applying the comparison method of total forces with different contact areas for six types of processed materials using the flank wear VB=0.3 mm for different contact areas at uncut chip thickness t=0.05 mm and t=0.125 mm. The determination of the ploughing forces was carried out by the comparison method of the total forces for different contact areas, the same method applied in Fig. 7c.

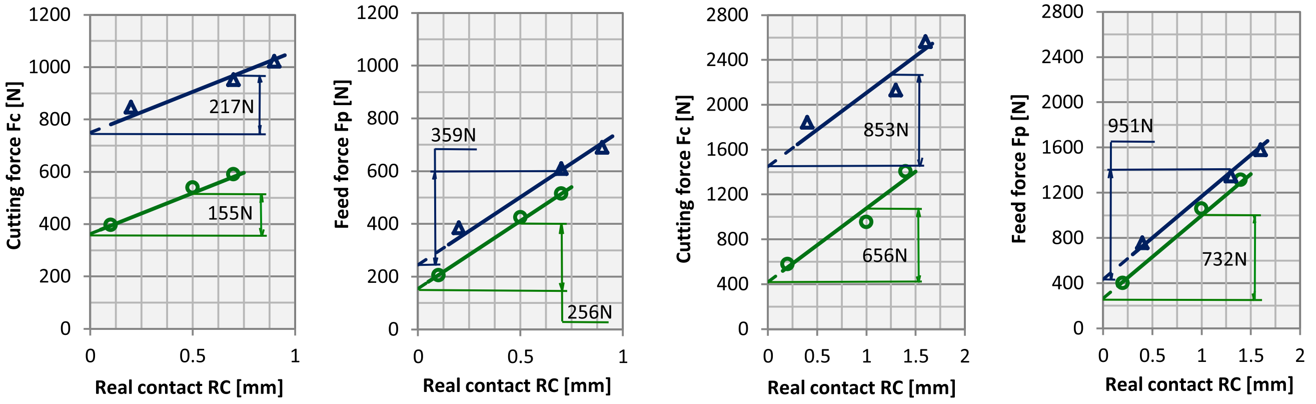
It should be noted that for different materials at different uncut chip thicknesses, the real contact areas were different at the same cutting conditions, which was a consequence of the different physical and mechanical properties of each material.

3.2 Experimental results and analysis

Figure 10 shows the results of determining the ploughing forces in the chipping of different materials, obtained by the comparison method of the total forces for different contact areas. It was found that in processing AlCu4MgSi, the ploughing force F_{Pl} determined for the uncut chip thickness t=0.125 mm was 52 % greater than the one determined for the uncut chip thickness t=0.05 mm (Fig. 10). In the processing of AlCu4PbMgMn, the ploughing force F_{Pl} determined for the uncut chip thickness t=0.125 mm was 39 % greater than the one determined for the uncut chip thickness t=0.05 mm (Fig. 10). In processing of 16MnCr5, this difference amounted to a factor of 29 %; in processing of 50CrV4, this difference showed a factor of 48 %; in processing of X20Cr13, this difference amounted to a factor of 38 %; and in processing

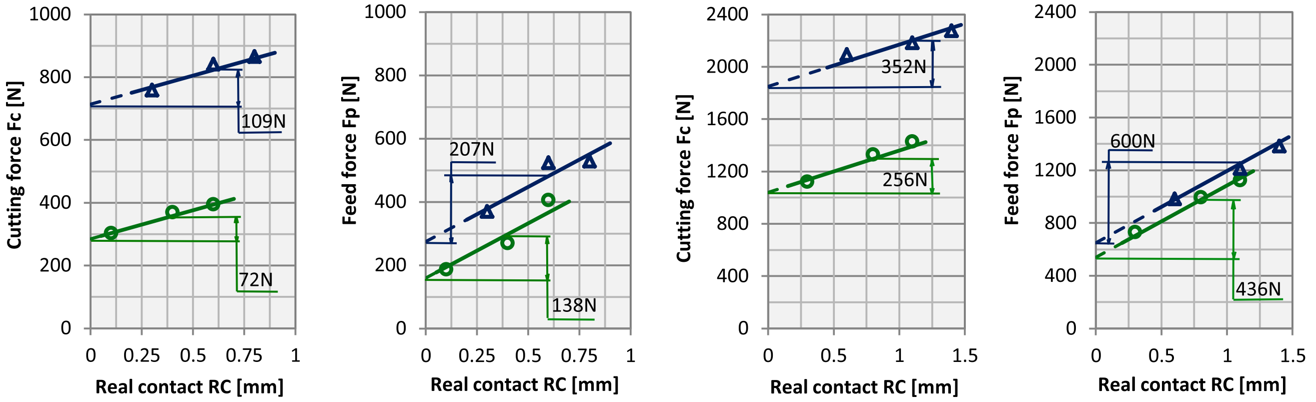
Table 2 Flank wear VB and real contact RC on the uncut chip thickness t=0.05 mm and t=0.125 mm for six types of processed materials

Uncut chip thickness t, mm		Real contact RC, mm											
		AlCu4MgSi		AlCU4PbMgMn		50CrV4		16MnCr5		X20Cr13		X5CrNiTi18-10	
		0.05	0.125	0.05	0.125	0.05	0.125	0.05	0.125	0.05	0.125	0.05	0.125
Flank wear VB, mm	0.03	0.12	0.28	0.12	0.23	0.18	0.38	0.22	0.39	0.28	0.61	0.38	0.58
	0.3	0.39	0.62	0.48	0.67	0.59	0.86	0.96	1.34	0.78	1.14	1.1	1.52
	0.5	0.59	0.83	0.72	0.9	1	1.28	1.41	1.63	1.12	1.37	1.71	1.93



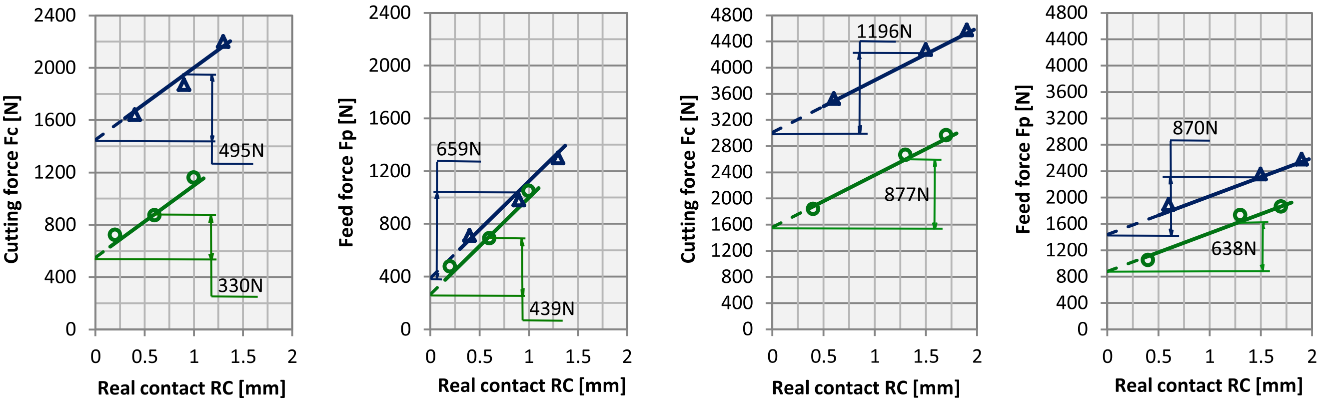
a) AlCU4PbMgMn

d) 16MnCr5



b) AlCu4MgSi

e) X20Cr13



c) 50CrV4

f) X5CrNiTi18-10

Fig. 9 Determination of the ploughing force in the chipping of different processing materials by the comparison method of the total forces for different contact areas at uncut chip thickness t=0.05 mm (*circles*) and t=0.125 mm (*triangles*) at flank wear VB=0.3 mm

of X5CrNiTi18-10, this difference amounted to a factor of 36 % (Fig. 10).

This way, it was found that the uncut chip thickness influences the ploughing force: The greater the uncut chip thickness, the greater the ploughing force. Based on this finding, determination of the ploughing force by the extrapolation method on zero uncut chip thickness cannot be used, because this method was based on the false idea that the uncut chip thickness does not influence the ploughing force (Fig. 7a). The results obtained confirm the conclusion of Stevenson [19, 20] that the extrapolation method on zero uncut thickness cannot be used to determine the ploughing forces.

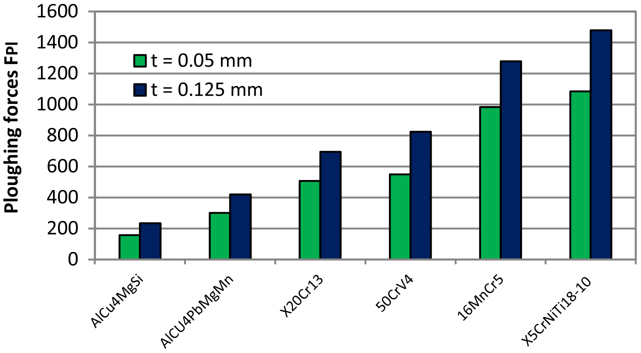


Fig. 10 Comparison of the ploughing forces F_{Pl} obtained at different uncut chip thicknesses (t=0.05 mm and t=0.125 mm) at flank level of wear VB=0.3 mm

It should be noted that in the comparison carried out with the same flank level of wear VB=0.3 mm, during the chipping of different materials at different uncut chip thicknesses, the real contact areas were different at the same cutting conditions, which was a consequence of the different physical and mechanical properties of each material.

The real contact area between the rear surface of the tool and the processed material is influenced by the uncut chip thickness. However, the flank level of wear is not influenced by the uncut chip thickness. According to this fact, the new comparison method of the total forces for different contact areas, based on measuring the real contact area, is more accurate than the method comparing total forces at different flank levels of wear, based on the flank level of wear.

The results obtained can be explained as follows: In chipping with the great uncut chip thickness (Fig. 11, right), the stress field in front of the cutting element is higher than that in cutting with the smaller uncut chip thickness (Fig. 11, left). The high stress field has a stronger influence on the machined surface, and plastic deformation (the LO line) starts at a larger depth of the material (Fig. 11). Therefore, the machined surface obtains a higher degree of deformation. Thus, chipping with great uncut chip thickness influences the rear surface of the tool and results in much more deformed material—this explains the increase of the ploughing forces and the increase of the real contact area between the rear surface of the tool and the processed material (Fig. 11).

4 Conclusion

A new method for determining the ploughing forces was suggested for increasing the accuracy when determining the ploughing force. This new method was called the «comparison method of the total forces for different contact areas». Increasing the accuracy of determination of the ploughing force is based on the measurement of the real contact area between the rear surface of the tool and the processed material, influenced by the uncut chip thickness. The real contact area between the rear surface of the tool and the processed material is influenced by the uncut chip thickness. However, the flank level of wear is not influenced by the uncut chip thickness. According to this fact, the new comparison method of the total forces for different contact areas, based on measuring the real contact area, is more accurate than the method comparing total forces at different flank levels of wear, based on the flank level of wear.

It was found that the ploughing forces determined by the new method were greater than those determined by the method comparing total forces at different flank levels of wear.

It was found for the first time that the uncut chip thickness influences the ploughing force—the greater the uncut chip thickness, the greater the ploughing force. The extrapolation method on zero uncut chip thickness for determining the ploughing forces cannot be used due to the fact that this method is based on the false idea that the uncut chip thickness does not influence the ploughing force.

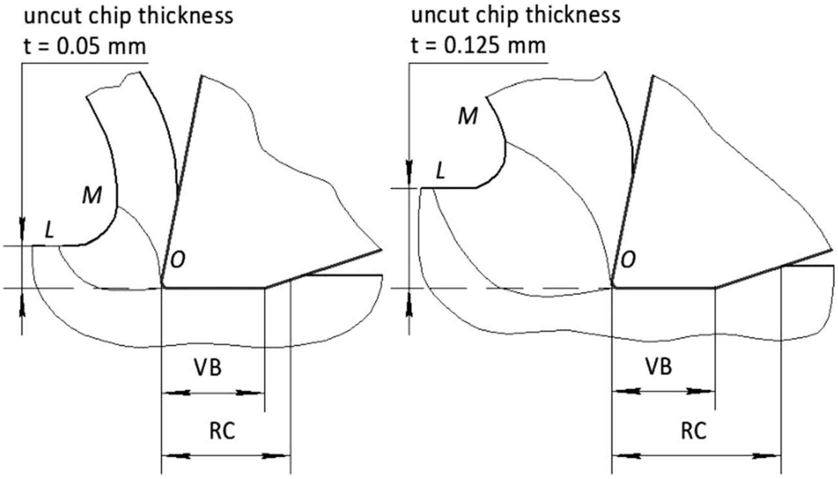


Fig. 11 The chip-forming process in chipping with different uncut chip thicknesses t=0.05 mm (*left*) and t=0.125 mm (*right*). *LO* beginning of plastic deformation, *MO* ending of plastic deformation, according to Zorev [2]; *VB* flank wear, *RC* real contact

Acknowledgments This paper is related to the investigation on the Specific University Research Projects, which are supported by the Ministry of Education (MSMT) of the Czech Republic.

References

1. Albrecht P (1960) New developments in the theory of the metal cutting processes, part 1. The ploughing process in metal cutting. ASME J Eng Ind 82:348–357
2. Zorev N (1966) Metal cutting mechanics. Pergamon Press, Oxford, pp 135–180
3. Chae J, Park S, Freiheit T (2006) Investigation of micro-cutting operations. Int J Mach Tools Manuf 46:313–332
4. Jemielniak K, Bombinski S, Aristimuno P (2008) Tool condition monitoring in micro-milling based jn hierarchical integration of signal measures. Ann CIRP 57(1):121–124
5. Dugin A, Popov A (2013) Increasing the accuracy of the effect of processing materials and cutting tool wear on the ploughing force values. Manuf Technol 13(2):169–173
6. Kalyan C, Samuel GL (2014) Cuttingmode analysis in high speed finish turning of AlMgSi alloy using edge chamfered PCD tools. J Mater Process Technol. doi:10.1016/j.jmatprotec.2014.09.003
7. Hui TY, Segon H, Min KL, Byung-Kwon M, Sang JL (2011) Ploughing detection in micromilling processes using the cutting force signal. Int J Mach Tools Manuf 51(5):377–382
8. Tasel I, Arkan T, Bao W, Mahendrakar N, Shisler B, Smith D, McCool M (2000) Tool wear estimation in micro-machining, part 1: tool usage—cutting force relationship. Int J Mach Tools Manuf 40:599–608
9. Afazov SM, Zdebski D, Ratchev SM, Segal J, Liu S (2013) Effects of micro-milling conditions on the cutting forces and process stability. J Mater Process Technol 213(5):671–684
10. Guo Y, Chou Y (2004) Determination of ploughing force and its influence on material properties in metal cutting. J Mater Process Technol 148(3):368–375
11. Wyen C, Wegener K, Zyust R (2010) Influence of cutting edge radius on cutting forces in machining titanium. Ann CIRP 59(1):89–92
12. Dugin A, Popov A (2012) Effect of the processing materials on the ploughing force values. Manuf Technol 12(13):169–173
13. Lipatov A, Chigirindkii Y, Kormilitsyn S (2010) Determining the cutting forces at the rear tool surface. Russ Eng Res 30(11):1158–1160
14. Popov A, Dugin A (2012) Experimental methods of determining the cutting forces at the tool's rear surface. Russ Eng Res 32(1):68–69
15. Popov A, Dugin A (2013) A comparison of experimental estimation methods of the ploughing force in orthogonal cutting. Int J Mach Tools Manuf 65:37–40
16. Colwell L (1970) Methods for sensing the rate of tool wear. Ann CIRP 4:647–651
17. Axinte DA, Belluco W, De Chiffre L (2000) Reliable tool life measurements in turning—an application to cutting fluid efficiency evaluation. 41(7):1003–1014
18. De Chiffre L, Belluco W (2002) Investigations of cutting fluid performance using different machining operations. Lubr Eng 58(10):22–29
19. Stevenson R, Stevenson D (1995) The mechanical behavior of Zink during machining. Trans ASME J Eng Mater Technol 117:172–178
20. Stevenson R (1998) Measurement of parasitic forces in orthogonal cutting. Int J Mach Tools Manuf 38:113–130