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Experimental Examination of Main Cutting Force and Surface Roughness Depending on Cutting Parameters

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Main cutting forces acting on cutting tool depending on cutting parameters when machining AISI 1117 steel were examined experimentally. Experimental results obtained were compared with the empirical results. For the experimental studies, a Kistler 9257A three component (Fc, Ff and Fp) piezoelectric dynamometer was used to measure cutting forces. This dynamometer was associated with a 5019 B130 charge amplifier connected to a PC running Kistler Dynoware force measurement software. The empirical results were obtained through Kienzle approach. Five different cutting speeds, five different feed rates and two different depth of cuts were used in the experiments. It was observed that cutting forces decreased as the cutting speed increased and increased by the feed rate. Experimental results also showed similar trends with the empirical results. At the end of experiments, it was observed that surface quality increased by with increasing cutting speed and decreased with increasing feed rate.
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0 INTRODUCTION

Cutting forces developed during machining influence cutting performance and unit part cost directly. Although cutting edges of tools used in machining metals and their alloys are sharp enough, they hardly bear high stresses developed during machining. So, many researches have been performed to determine ideal tool geometry and optimum cutting tool cross section which facilitates machining metals. Making use of the contemporary computer technology in machining, many problems encountered in conventional machining have been eliminated. Significant improvements in mechanics of machining have been achieved by using computers software to estimate cutting forces and stress values before machining [1] and [2].

It can be seen from various studies that cutting forces have a direct influence on various cutting parameters such as; cutting speed, feed rate, depth of cut, rake angle and cutting tool life. Therefore various force measurement methods have been developed to this relationship. It is known that piezoelectric, thermo-electric, photoelectric, load-cell etc. transducer type dynamometers developed for cutting force measurements are known to convert the mechanic energy to electric signals by measuring the strain [2] and [3].

There are also various experimental studies for direct cutting force measurements along with estimating cutting forces depending on the cutting parameters. Simple analytic models are also used to show effects of cutting parameters such as cutting speed and feed rate [4] and [5].

In this work, the cutting parameters which effect main cutting forces acting on the cutting tool when orthogonal machining was examined.

1 MATERIALS AND METHOD

The machining tests were performed by single point continuous turning of AISI 1117 steel specimens in cylindrical form on a Johnford TC35 CNC turning centre, with a variable spindle speed of up to 4000 rpm and a power rating of 10 kW. The workpiece specimens were 400 mm long and 60 mm in diameter. Prior to the tests, the surfaces of the specimens were turned at 1 mm depth of cut to remove any possible hardened layers, scale, defects or other impurities. The chemical composition of the workpiece materials is given in Table 1. Coolant was not used during the tests. The cutting tools used were commercial grade cemented carbide inserts produced by Stellram with the geometry of SCMW 12 M508-S2F in accordance with ISO 1832. These inserts did not have chip breaker and are recommended

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for machining steels at high cutting speeds due to their high wear resistance. The grades of these inserts were between P10 and P20.

These inserts were clamped mechanically on a rigid tool holder with an ISO designation of SBCR 25 25 M12. The cutting parameters are given in Table 2. The cutting parameters were chosen by taking into consideration the recommendations in ISO 3685 [6].

Surface roughness measurements were carried out on the machined surfaces using a Mitutoyo Surftest 211 instrument. Three measurements were made on the each surface. Cutting force was measured with a Kistler 9257A three component piezoelectric dynamometer and an associated 5019 B130 charge amplifier connected to a PC employing Kistler Dynoware force measurement software. Fig. 1 shows the dynamometer and the tool holder.

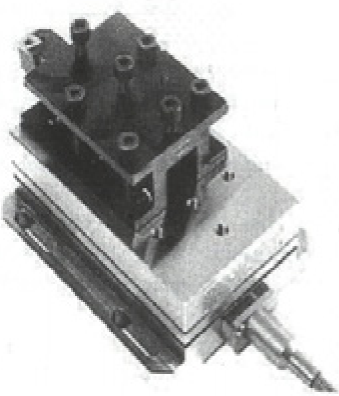

Fig. 1. *Kistler 9257A dynamometer and the tool holder*

According to Kienzle, main cutting force (FC); is equal to product of cross-section of chip and specific cutting resistance of workpiece material.

$$F_C = A_0 \,.\, k_s \tag{1}$$

where, A_0: is cross-section area of chip (mm^2) and k_s specific cutting resistance (N/mm^2). To calculate the cutting force for many machining operations, F_C is determined by this approach. In this calculation, chip geometry is important. The most important factor which determines the chip cross-section is cutting edge angle (Fig. 2).

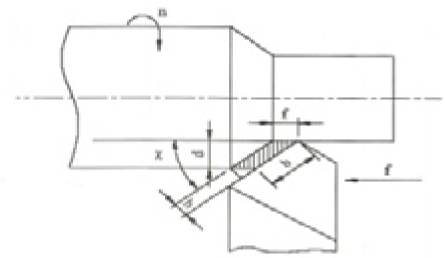

Fig. 2. *Relationship between chip cross-section and cutting edge*

In figure 2, (χ) stands for cutting edge angle, and can be written as as $A_0 = a.f$ or $A_0 = b.h$ chip cross-sectional area. Cutting edge angle can be found as

$$\sin\ (\chi) = \frac{h}{f} \tag{2}$$

so, we can write following equations for chip width and chip thickness, respectively:

$$b = \frac{a}{\sin(\chi)} \tag{3}$$

$$h = f \times \sin(\chi) \tag{4}$$

Specific cutting resistance used in calculation of main cutting force (FC) is found by following equation:

$$k_s = \frac{k_{11}}{h^m} \tag{5}$$

where: k_{11} specific cutting force of a section where h = 1 mm and b = 1 mm; m: a constant value depending on the type of material which is the characteristic slope of the curve showing logarithmic relation between k_s value and h value. Specific cutting resistance decreases by increasing chip thickness (h). m value is always different for each material.

As reported by many experimental researches, there are different factors effecting main cutting force during machining.

Cutting speed factor (k_v), rake angle factor (k_γ), tool wear factor (k_α) and cutting tool material factor (k_t) are the most significant factors. Similarly, use of the following equation to calculate k_γ is a common application.

$$k_\gamma = \frac{C - 1.5\gamma}{100} \tag{6}$$

Table 1. *Chemical composition of the workpiece material*

C	Si	S	P	Mn	Ni	Cr	Mo	Cu	Al	Nb	Ti	W	Pb	Sn
.114	.004	.382	.076	1.48	.345	.098	.027	.065	.011	.002	.001	.037	.002	.034

Table 2. *The cutting parameters used for the tests*

Group No.	Experiment no.	Cutting speed V m/min	Feed rate f mm/rev	Depth of cut a mm
1	1-5	50, 75, 100, 125, 150	0,10	1
2	1-5	50, 75, 100, 125, 150	0,15	1
3	1-5	50, 75, 100, 125, 150	0,20	1
4	1-5	50, 75, 100, 125, 150	0,25	1
5	1-5	50, 75, 100, 125, 150	0,30	1
6	1-5	50, 75, 100, 125, 150	0,10	2
7	1-5	50, 75, 100, 125, 150	0,15	2
8	1-5	50, 75, 100, 125, 150	0,20	2
9	1-5	50, 75, 100, 125, 150	0,25	2
10	1-5	50, 75, 100, 125, 150	0,30	2

where C is a constant and is determined depending on the type of material (for steel materials C = 109, for casting materials C = 103).

When these factors are taken into consideration, equation giving main cutting force can be derived as ;

$$F_C = A_0\, k_s\, k_v\, k_\gamma\, k_\alpha\, k_t \tag{7}$$

Many empirical models are used in calculation of main cutting force. Since k_s value is difference for each material, empirical results are obtained by using Equation 7 in this study and compared with experimental data [1] and [7].

2 RESULTS AND DISCUSSIONS

2.1. Evaluation of the Effect of Cutting Speed, Feed Rate and Depth of Cut on Cutting Forces

Table 3 shows average values of cutting forces developed for the uncoated cutting tool. By taking experimental results as reference, average of five different cutting speeds, and change of main cutting forces (F_c) depending on feed rate is shown in Fig. 3. It can be seen from Fig. 3 that for the five feed rates, cutting forces decrease by 14% to 27% as the cutting speed increases from 50 m/min to 150 m/min. This situation can be attributed to reaching enough level of energy needed for plastic deformation of material, a decrease in friction between cutting tool rake face and chips, and moving chips from flow zone fast [4] and [8] to [9].

When the cutting speed is increased from 50 to 100 m/min, cutting forces decrease by 16% to 24% (Fig. 3). It can be seen from Fig. 4 that for the five cutting speeds, cutting forces increased by 70% to 92% as the feed rate increased from 0.1 to 0.3 mm/rev.

Experimental results show that in contrast to cutting speed, increasing feed rate improves cutting force. Equation 1 defines this relationship between cutting force and feed rate. It can be seen from Table 3 that cutting force increase by 108% to 228% as the depth of cut is increased from 1 to 2 mm. It was observed that the cutting forces peak at 2 mm depth of cut and 50 m/min cutting speed. This situation can be attributed to excessive friction between cutting tool rake face and chip at low cutting speed.

Regular decrease is seen in main cutting force values (between 25% to 56%) when cutting speed is increased from 50 to 150 m/min with 2 mm depth (Fig.5). This situation can be attributed to reaching enough level of energy needed for plastic deformation of material, decreasing shear angle and decreasing friction between tool-chip interface. When theoretical approach is taken into consideration, cutting speed factor (k_v) decreases when cutting speed decreases, so main cutting force decreases in calculation of main cutting force.

Table 3. *Main cutting forces obtained for different cutting speeds, feed rates and depth of cuts*

Cutting Speed V m/min	Feed rate f m/rev	Depth of cut a mm	Exp. no.	Main cutting forces (N)			Depth of cut a mm	Exp. no.	Cutting Forces (N)		
				F_C Exp.	F_C Emp.	Deviation %			F_C Exp.	F_C Emp.	Deviation %
50	0.10	1	1	283	271	4.24	2	26	745	656	-13.56
	0.15		2	364	335	7.96		27	993	886	-12.07
	0.20		3	379	347	8.44		28	1260	1128	-11.7
	0.25		4	433	401	7.39		29	1373	1236	-11.08
	0.30		5	483	483	0		30	1586	1412	-12.32
75	0.10	1	6	267	251	5.99	2	31	691	638	-8.3
	0.15		7	339	311	8.25		32	832	822	-1.21
	0.20		8	363	322	11.29		33	983	1000	1.7
	0.25		9	409	373	8.8		34	1163	1185	1.85
	0.30		10	458	448	2.18		35	1348	1378	2.17
100	0.10	1	11	229	244	-6.55	2	36	574	591	2.87
	0.15		12	285	302	-5.96		37	772	794	2.77
	0.20		13	295	313	-6.1		38	937	971	3.5
	0.25		14	342	362	-5.84		39	1137	1154	1.47
	0.30		15	441	435	-3.4		40	1248	1251	0.23
125	0.10	1	16	238	239	-0.42	2	41	540	580	6.89
	0.15		17	290	296	-2.06		42	752	781	3.71
	0.20		18	290	307	-5.86		43	905	952	4.93
	0.25		19	339	354	-4.42		44	996	1075	7.34
	0.30		20	422	426	-0.94		45	1141	1226	6.93
150	0.10	1	21	228	236	-3.5	2	46	476	554	10.46
	0.15		22	267	293	-9.7		47	740	763	3.01
	0.20		23	274	304	-10.94		48	880	942	6.58
	0.25		24	326	351	-7.66		49	940	1064	11.65
	0.30		25	414	422	-1.89		50	1076	1213	11.29

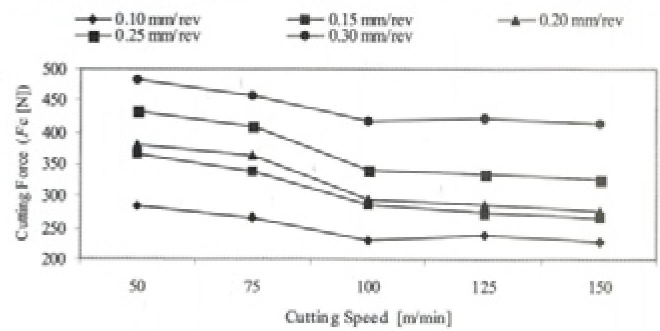

Fig. 3. *Main cutting force variations depending on the cutting speed at 1 mm depth of cut when machining with uncoated cutting tool*

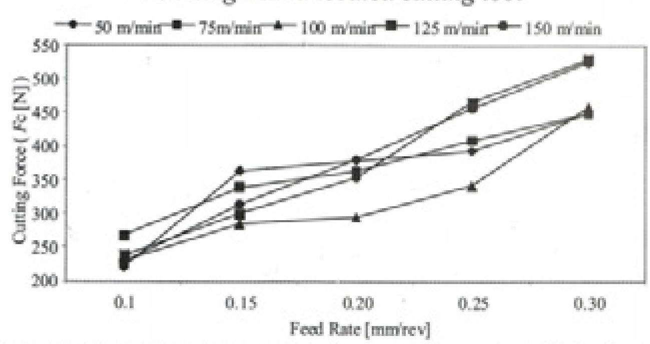

Fig. 4. *Cutting force variations depending on feed rate at 1 mm depth of cut when machining with uncoated cutting tool*

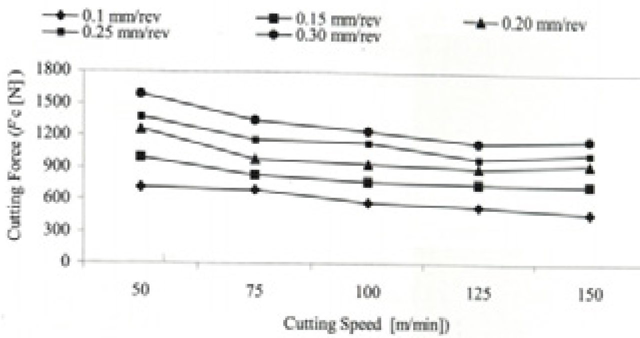

Fig. 5. *Cutting force variations depending on the cutting speed at 2 mm depth of cut when machining with uncoated cutting tool*

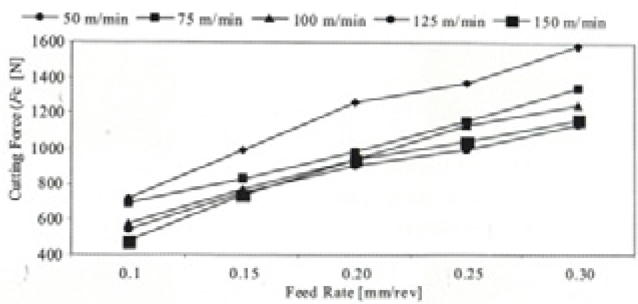

Fig. 6. *Cutting force variations depending on feed rate at 2 mm depth of cut when machining with uncoated cutting tool*

At 2 mm depth of cut, it can be seen from Fig. 6 that for the five cutting speeds, cutting forces increased by 95% to 126% as the feed rate increased from 0.1 to 0.3 mm/rev.

There is not enough and certain information in the literature for k_s value of AISI 1117. For determination of k_s value, various experimental studies were performed and main cutting force obtained through these experiments was used. Using Equation 7, k_s values were found from the results obtained from the experiments and arithmetical average of them was taken. Empirical results were taken by using ks values obtained from this.

Cutting speed factor (k_v) in the equation was taken as 1.11 for 50 m/min, 1.03 for 75m/min, 1 for 100 m/min, 0.98 for 125 m/min and 0.97 for 150 m/min. Main cutting forces obtained by experimental and empirical results at 1 mm depth of cut show similar trends at all the cutting speeds (Fig 7). It was observed that there were some deviations between experimental and empirical results. Chip cross-sectional area increases with increasing feed rate, so it causes increase in the amount of deviation. Maximum deviation was observed at cutting speeds of 50 and 75 m/min. Main cutting forces obtained from experimental results are higher than empirical ones. This can be due to low feed rate in ductile materials at 1 mm depth of cut and the built-up edge (BUE) problem created by cutting speed. This situation showed that experimental work is more reliable.

Main cutting forces obtained by experimental and empirical results at 2 mm depth of cut show similar trends at all the cutting speeds (Fig. 8). Maximum deviation occurred at cutting speed of 50 m/min. These deviations originate from parameters in Equation 7. Here, the most effective factors are depth of cut (a) and feed rate (f). Other causes are k_s and cutting speed factor. Values used in empirical model are data obtained at the end. There are different values related to these parameters of AISI 1117 steel.

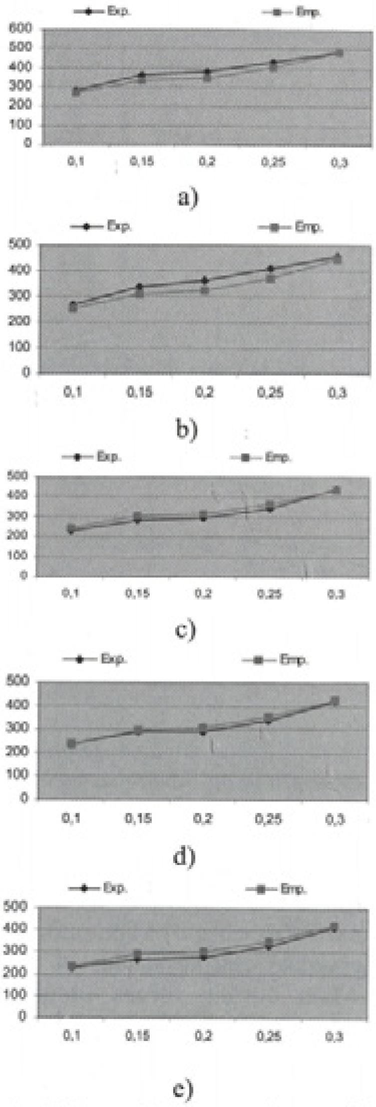

Fig. 7. *Main cutting forces obtained from empirical and experimental results at 1 mm depth of cut a) 50 m/min, b) 75 m/min, c) 100 m/min, d) 125 m/min and e) 150 m/min.*

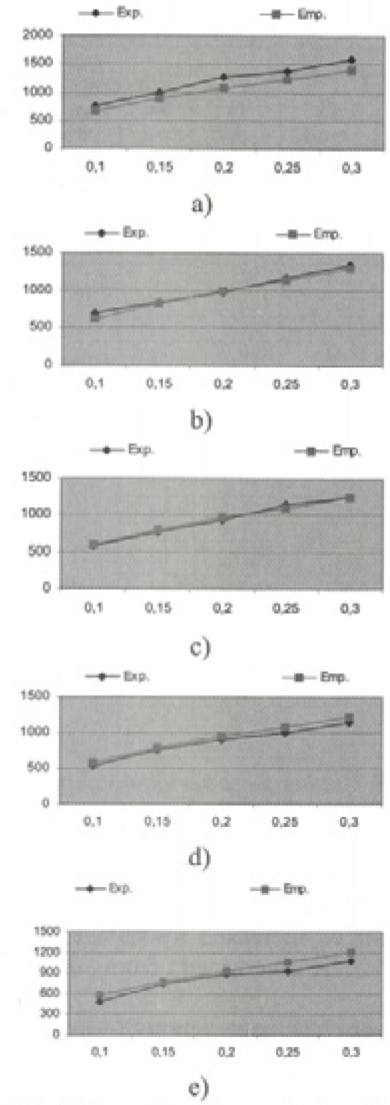

Fig. 8. *Main cutting forces obtained from empirical and experimental results at 2 mm depth of cut a) 50 m/min, b) 75 m/min, c) 100 m/min, d) 125 m/min and e) 150m/min*

2.2. Evaluation of the Effect of Cutting Speed, Feed Rate and Depth of Cut on Surface Roughness

Average surface roughness values (*Ra*) obtained for five different cutting speeds and feed rate and two different depth of cuts are listed in Table 4.

Fig. 9 shows the variation of surface roughness by cutting speed for 1 mm depth of cut and five different feed rates.

It is known that surface roughness has a decreasing trend with increasing cutting speed. The findings obtained also support the same trend. Especially, when speed increases from 50 m/min to 75 m/min, a serious improvement in surface roughness and an increased improvement in surface quality for feed rates with cutting speed are observed. When the results given in Table 4 are evaluated according to feed rate, a reverse trend of one stated for cutting speed appears (Fig. 10).

For all cutting speeds, surface quality decreases and *Ra* values increase by increasing feed rate. In theoretical approach, it is known that surface roughness increases in direct proportion of square feed rate.

According to results obtained from the experiments performed at 2 mm dept of cut, variation of surface roughness depending on cutting speed and feed rate are given in Figs. 11 and 12.

The most important result of increasing depth of cut to 2 mm is better surface quality than surface quality obtained from 1 mm depth. In normal conditions, the worsening in surface quality is expected by increase in cut depth, however a reverse trend was observed in experiment. This situation can be evaluated as negative reaction of 0.8 mm tool nose radius chosen for intermediate machining conditions. Normally, while 2.5 mm depth of cut is given as reference in ISO 3685 for 0.8 mm tool nose radius, 2 mm depth of cut also exist between boundaries given for tool nose radius of 0.8 mm (Figs. 11-12). By taking depth of cut as 1 mm, the boundaries given for tool nose radius of 0.8 mm are exceeded. Furthermore, 1 mm is a low depth of cut, so it can be said that there is a worsening in surface quality as negative effect of machine tool and tool vibrations.

3 CONCLUSIONS

The most suitable cutting speeds for 1 mm and 2 mm depth of cuts were found as 100 m/min 75 m/min respectively in terms of cutting forces. It was observed that the highest cutting forces were obtained at lower cutting speeds. Cutting forces decreased when cutting speed was increased. It was also observed that cutting forces increased with increasing feed rate.

Considering *Ra* and cutting parameters it was observed that increasing cutting speed improves the surface quality but increasing feed rate worsens it. These findings are in agreement with the literature. By increasing depth of cut from 1 to 2 mm, a trend of improvement in surface quality was observed. This situation shows that 1mm depth of cut is not suitable for 0.8 mm tip radius which is suitable for intermediate cutting conditions.

Table 4. *Average surface roughness obtained from different cutting parameters*

Cutting Speed V m/min	Feed rate f mm/rev	Exp. no.	Depth of cut a mm	Average surface roughness µm	Exp. no.	Depth of cut a mm	Average surface roughness µm
50	0.1	1	1	4.6	26	2	2.52
	0.15	2		5.23	27		3.3
	0.20	3		5.12	28		3.55
	0.25	4		5.35	29		4.31
	0.3	5		5.75	30		5.14
75	0.1	6	1	2.97	31	2	1.95
	0.15	7		3.72	32		2.39
	0.20	8		3.58	33		3.18
	0.25	9		3.59	34		3.52
	0.3	10		4.74	35		4.64
100	0.1	11	1	2.42	36	2	1.63
	0.15	12		2.92	37		1.82
	0.20	13		2.76	38		2.49
	0.25	14		3.11	39		3.18
	0.3	15		4.41	40		4.39
125	0.1	16	1	1.88	41	2	1.29
	0.15	17		1.98	42		1.56
	0.20	18		2.43	43		2.14
	0.25	19		2.8	44		2.75
	0.3	20		4.35	45		4.23
150	0.1	21	1	1.51	46	2	1.1
	0.15	22		1.73	47		1.52
	0.20	23		1.96	48		1.9
	0.25	24		2.69	49		2.37
	0.3	25		4.25	50		4.37

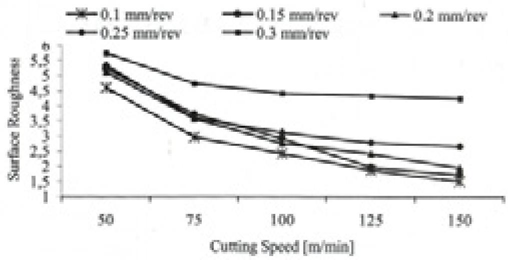

Fig. 9. *Average surface roughness variations depending on cutting speed at 1 mm depth of cut*

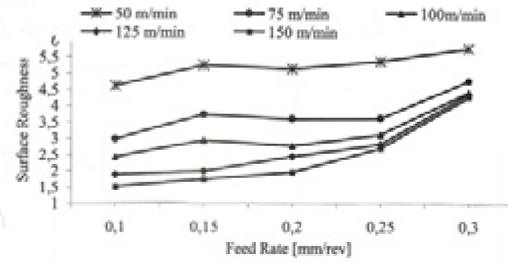

Fig. 10. *Average surface roughness variations depending on feed rate at 1 mm depth of cut*

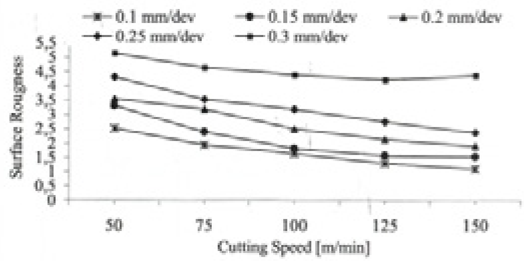

Fig. 11. *Average surface roughness variations depending on cutting speed at 2 mm depth of cut*

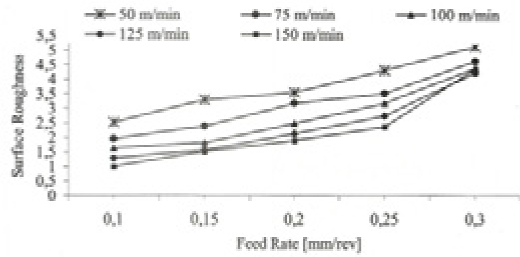

Fig. 12. *Average surface roughness variations depending on feed rates at 2 mm depth of cut*

3 ACKNOWLEDGEMENT

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