TOOL-CHIP CONTACT LENGTH AND FEED INFLUENCE ON CUTTING FORCE

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ABSTRACT
This paper investigates the influence of cutting process parameters such as feed, cutting speed, depth of cut and tool-chip contact length on resultant force during machining of mild steel and aluminium alloys. Forty experiments were carried out on aluminium and mild steel alloys based on cutting parameters (feed rate, cutting speed and depth of cut). Experimental procedure invovoles measuring the lengths of chips that slide on the tool face (tool-chip contact length) at various combinations of cutting parameters. Results indicate that as the resultant force increased from 583N to 2037N at constant depth of cut (0.10mm) and cutting speed (47m/min), the contact length increased from 0.08mm to 0.58mm for Aluminium alloys. At higher cutting speed of 71m/min and 0.20mm depth of cut, lower force of 594N to 1483N was recorded giving rise to increased contact length of 0.62mm to 0.86mm. Higher values of contact length (0.08mm to 0.74mm) are obtained for mild steel as the resultant force increased from 1079N to 3111N at the same cutting conditions for aluminium. At higher cutting speed of 71m/min and 0.20mm depth of cut, lower force of 854N to 2193N were obtained for mild steel with contact length increasing from 0.78mm to 0.95mm. Therefore, tool-chip contact length decreases as feed rate increases and mild steel gives higher cutting force in machining process than aluminium alloys under the same cutting conditions.

Keywords: feed rate; depth of cut; cutting speed; machining; contact length

INTRODUCTION

Vast majority of manufactured products require machining at some stage in their production, ranging from relatively rough operations to high-precision processing (tolerances of 0.001 mm or less) associated with high quality surface finish. Machining is undoubtedly the most important of the basic manufacturing processes; especially as industries around the world spend billions of dollars per year to perform metal removal (DeGarmo *et al.*, 1997). Machining can be referred to as the removal of excess metal from a work-piece in order to obtain a finished product with the attributes like size, shape, and surface roughness (Hayes *et al.*, 2006). A recent estimate in industrialized countries showed that the cost of machining accounts for more than 15% of the total value of all products by their entire manufacturing industry. Whether or not these products are machined, an estimated 15% of the value of all mechanical components manufactured worldwide is derived from machining operations (Merchant, 1998; Astakhov, 2004). Despite its obvious economic and technical importance, machining remains one of the least understood manufacturing operations due to low predictive ability of the machining models (Coelho *et al.*, 2003).

It is important to maintain consistent tolerances and surface finish in machining because the demand for high quality and fully automated production focuses attention on the surface condition of the product. In particular, the roughness of the machined surface affects product appearance, function and reliability. The quality of the machined surface is useful in diagnosing the stability of the machining process, because a deteriorating surface finish may indicate work-piece material non-homogeneity, progressive tool wear, cutting tool chatter, etc (Mohammed *et al.*, 2007). The quality of the surface also plays a very important role in the performance of turning as a good-quality turned surface significantly improves fatigue strength, corrosion resistance, and creep life while surface roughness affects several functional attributes of parts, such as wearing, heat transmission, ability to hold lubricant, coating or resisting fatigue. On the other hand, several factors influence the final surface roughness in end-turning operation (Astakhov, 2004). Spindle speed, feed rate and depth of cut responsible for cutting operations can be set-up in advance. Tool geometry, tool wear and chip formation, or the material properties of both tool and work-piece are uncontrollable (Boothroyd and Knight, 1989).

According to some studies on metal cutting, speed has the greatest influence on tool wear and consequently tool life, while other parameters and characteristics of the cutting process have not attracted as much attention in this respect (Ashok and Tanmaya, 2008; Ivana, 1998). It was also found by (Astakhov and Shvets, 2004) that depth of cut does not have a significant influence on the tool wear rate.

According to Coelho *et al.* (1986), cutting at a constant speed and width of cut can sometimes lead to the transition from an unstable to a stable condition by increasing the feed. The shape of the stable boundary obtained showed that the greatest benefit from increasing feed occurs at a relatively low feeds. At higher feeds the curve becomes flat making stabilization by this method, impractical. In addition, it should be noted that a large feed may not give stable machining and that a small feed (reduced metal removal rate) results in promoting chatter (Sadik and Lindström, 1993).

When cutting feed increases, the effect is more pronounced on cutting force depending on the combination of other parameters and the characteristics of a particular cutting system. This is more pronounced when cutting difficult-to-machine materials having a great number of alloying elements (Astakhov, 2006). The determination of too-chip contact length is very important in machining processes. Knowing the contact characteristic together with contact stress distribution makes it possible to determine cutting forces and temperature patterns, accurately calculate tool strength, choose the optimal tool geometry and the machining process as a whole. The aim of this work is to investigate the influence of cutting parameters (feed, depth of cut, speed and tool-chip contact length) on cutting force during machining operations.

MATERIALS AND METHODS

Materials Used for the Experiment

The following materials were used for the research work: Colcherster Mastiff 1400 lathe machine, Kistler force dynamometer (force transducer), high speed steel cutting tool, calliper/micrometer, mild steel and aluminium alloy workpiece, each with dimensions 32mm diameter by 290mm length. Fig. 1 shows the experimental set-up.

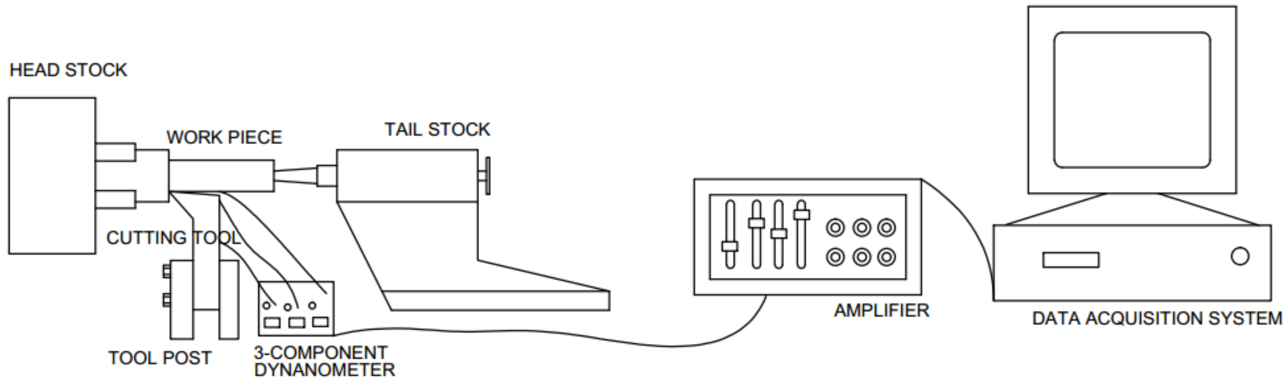

Fig. 1: Schematic diagram of the experimental setup

Concept of Cutting Forces and Tool-Chip Contact Length

Fig. 2 shows machining of work material and the region of tool-chip contact length. Based on the experimental studies by Ojolo and Awe (2011), contact length was determined by length AG using, force dynamometer-Type 9263 (force transducer). Aluminium and mild steel used were assumed to experience deformation along a thin shear plane. β =12^0 is the friction angle, where α is the rake angle $i.e.$ 5^0 and ϕ=45^0 is the shear angle

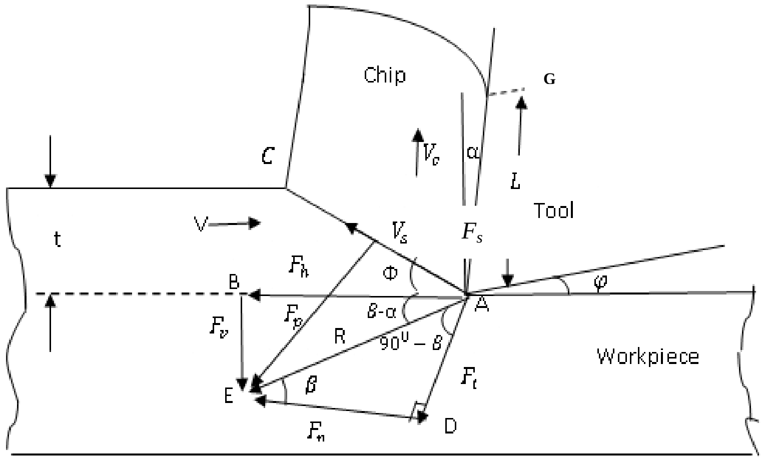

Fig. 2: Cutting forces components in orthogonal cutting (Juneja *et al*., 2003)

According to Hahu's analysis as presented by Karpat and Ozel (2006), taking uniform distribution of normal force on the tool face and on the shear, the equilibrium of their moments about the tool edge can be written as in Eq. 1

$$\frac{1}{2}F_nL_n = \frac{1}{2}F_p\frac{t}{Sin\phi} \qquad (1)$$

Where ϕ is the shear angle, F_n is the normal on the tool face, F_p is the normal force to shear plane, L_n is tool-chip contact length, t is the undeformed chip thickness.
The resultant force (R) is determined using Eq. 2:

$$R = \sqrt{F_h^2 + F_v^2} = \sqrt{F_s^2 + F_p^2} = \sqrt{F_t^2 + F_n^2} \qquad (2)$$

Where, F_h is the cutting force, F_v is the thrust force, F_t is friction force, F_s is the shear force
The resultant force, R was determined using dynamometer to measure force components. According to Ojolo and Awe (2011), it decreased as cutting speed increased to 71m/min on both metals; mild steel and aluminium having approximate reductions of 4.44% and 14.39% respectively
From mechanics of cutting,

$$F_s = K \times Area \qquad (3)$$

Where $area = AG \times width$
F_s is the force component parallel to shear plane.

$$AG = \frac{t}{Sin\phi} \qquad (4)$$

So,

$$F_s = \frac{t\,b\,k}{Sin\phi}$$

The tool-chip contact length can be expressed as

$$L_n = \frac{\xi t\left[tan\beta Cos\left[\frac{\pi}{4}-\frac{1}{2}\left(\beta + cot\theta\, tan^{-1}\left(\frac{t}{f + t\, tan\gamma_s}\right)\right) + Sin\left[\frac{\pi}{4}-\frac{1}{2}\left(\beta + cot\theta tan^{-1}\left(\frac{t}{f + t\, tan\gamma_s}\right)\right)\right]\right]\right]}{Sin\left[\frac{\pi}{4}-\frac{1}{2}\left[\beta - cot\theta tan^{-1}\left(\frac{t}{f + t\, tan\gamma_s}\right)\right]\right]}$$

ξ = is a constant determined from experiment which is a function of material properties, cutting speed, depth of cut; γ = shear angle, *f* = feed (mm).

Experimental Procedure

A total number of forty experiments were conducted in the Production Engineering laboratory of University of Benin; the first experiment entails keeping cutting speed and depth of cut at given values constant while feed is varied; the second involves keeping cutting speed constant while depth of cut and feed are varied across the range of values. The length of the chip that slides on the tool face, i.e., tool-chip contact length is measured. The tool surface was carefully polished and cleaned before each test is carried out while each successive test were performed on a new section of the cutting edge to eliminate wear effects. Graphs were plotted using Micosoft Excel.

The procedure used was in two stages. The first stage involved a procedure where a Kistler turning dynamometer (Type 9263) was used to measure the thrust, and cutting forces at a given depth of cut, feed rate and cutting speed. Outputs from the dynamometer were fed into the Kistler charge amplifiers; these generated direct current (DC) signals that were transmitted to the data-acquisition card installed on a personal computer. The amplifier was set to match the settings on the computer. Custom built software installed on the computer received the force data in analog form and thereafter converted same to a digital format, which is later transferred to spreadsheets for analysis. Fig. 1 shows the set up for the experimental procedure.

The second stage involved repeating the first procedure while adjusting each of the three critical parameters namely: depth of cut between 0.10 and 0.20mm, feed rate from 0.05 to 0.50mm/rev and cutting speed between 47 and 71m/min. This was used to measure the tool-chip contact length.

RESULTS AND DISCUSSION

The interaction of a cutting tool with the rotating work-piece produced cutting forces that combine with tangential, feed and radial forces. These forces were measured by a three-component turning dynamometer. The tangential force produced the greatest among the three cutting force components, generating torque on the work-piece being rotated by the spindle. The outputs are shown in Table 1.

Table 1: Tool-chip contact lengths, feeds and resultant forces

				Aluminum				
		47m/min				71m/min		
Feed, f (mm/rev.)	Chip-tool contact length (mm)	Cutting force, F (N)	Thrust F(N)	Resultant F(N)	Chip-tool contact length	Cutting force, F(N)	Thrust force, F(N)	Resultan force, F(N)
				d=0.10mm				
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.11	0.32	475.00	662.40	815.11	0.14	353.45	614.91	709.25
0.13	0.39	550.00	751.50	931.26	0.28	345.85	705.00	798.93
0.19	0.41	810.00	1042.60	1320.27	0.34	636.00	960.55	1152.02
0.26	0.53	1376.00	1502.00	2037.00	0.47	540.69	1270.91	1199.66
				d=0.20mm				
0.30	0.57	354.60	616.90	711.55	0.51	281.18	523.67	594.38
0.35	0.63	496.90	862.20	995.14	0.58	369.01	711.18	801.21
0.40	0.71	541.50	965.60	1107.07	0.61	424.63	803.45	908.76
0.45	0.77	640.30	1305.80	1454.34	0.73	431.65	900.11	998.26
0.50	0.81	716.40	1738.50	1880.32	0.78	632.16	1342.47	1483.86

				[illegible]				
		47m/min				71m/min		
				d=0.10mm				
0.05	0.08	525.30	942.30	1078.83	0.04	364.30	728.50	814.51
0.11	0.40	633.30	1197.10	1354.30	0.36	523.30	922.91	1060.95
0.13	0.47	804.20	1392.10	1607.69	0.43	546.20	1071.72	1202.88
0.19	0.59	1081.18	2042.10	2310.65	0.52	768.60	1567.70	1745.98
0.26	0.74	1207.27	2866.70	3110.54	0.61	1088.30	2710.50	2920.82
				d=0.20mm				
0.30	0.76	1233.29	743.80	1440.22	0.73	504.34	875.06	1009.99
0.35	0.81	1668.15	930.00	1909.88	0.78	632.56	1174.36	1333.89
0.40	0.86	2040.20	1252.20	2393.83	0.82	854.26	1430.43	1666.10
0.45	0.91	2518.06	1314.10	2804.33	0.85	896.86	1759.33	1974.74
0.50	0.94	3662.03	1933.90	4141.31	0.90	1125.07	2802.69	3020.08

The result of the experiments carried out on aluminum and mild steel to investigate the effect of feed and tool-chip contact length on metal cutting stability during orthogonal machining is shown in Figs. 3 to 6.

Figs. 3 and 4 show the relationship between contact length and feed rate at different cutting conditions. Fig. 3 shows the relationship obtained between the tool-chip contact length of aluminum and mild steel at varying feed rates (0.05-0.26 mm/rev), constant depth of cut of 0.10mm and constant speeds (47m/min and 71m/min).

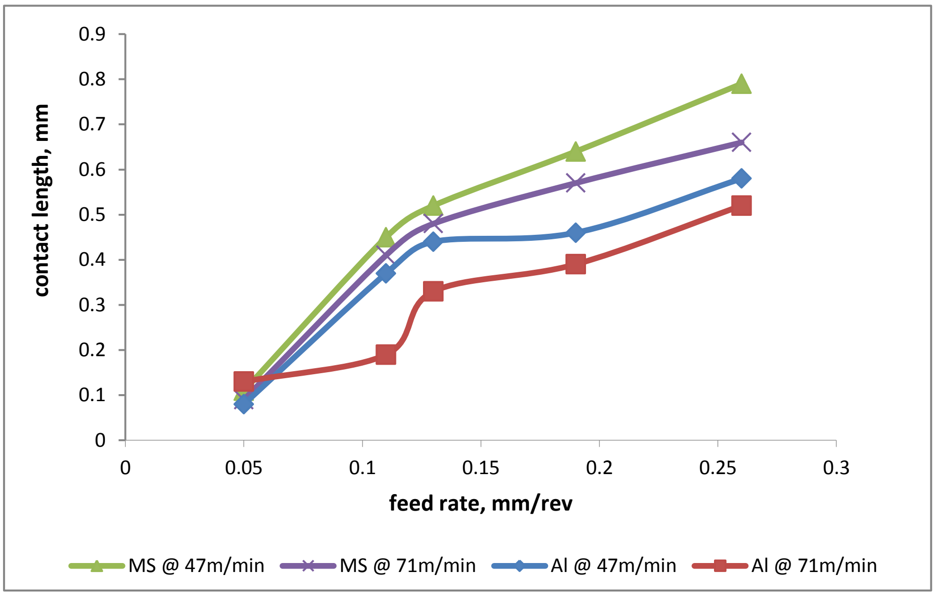

Fig. 3: Effect of tool-chip contact length and feed on aluminium and mild steel at a depth of cut, 0.10m and constant speeds V= 47m/min and 71m/min

The tool-chip contact lengths obtained for aluminium at constant speed of 47m/min and 0.10mm depth of cut increased from 0.08mm to 0.58mm as the feed rate increased from 0.05mm/rev to 0.26mm/rev. As the cutting speed increased to 71m/min under the total contact length l_n was obtained measuring chip same conditions, lower values of tool-chip contact traces on the rake face by a caliper. The tool rake face lengths 0.08mm to 0.52mm were obtained. This is similar to 0.38 mm and 0.32 mm obtained by Iqbal *et al.* (2008) at cutting speeds of 200m/min and 800m/min for high speed machining of AISI 1050 steel.

Though aluminum is more ductile than mild steel, results clearly showed that the tool-chip contact lengths values obtained at cutting speeds of 41m/min and 71m/min were less than 0.11mm to 0.79mm and 0.09mm to 0.66mm for mild steel at the same cutting conditions as compared to the results of Ojolo and Awe (2011). This gave an average value of 25.4% reduction in tool-chip contact lengths. This showed that less cutting force is required in aluminium aloy cutting than that of mild steel. The result obtained here was similar to that of low contact length at low speed obtained by Molinari *et al.* (2002) during high speed machining of Ti-6Al-4V alloy.

As the depth of cut increased from 0.10mm to 0.20mm, the tool-chip contact length of aluminium increased from 0.57mm to 0.86mm at constant speed of 47m/min (Fig. 4). The same trend was observed at cutting speed of 71m/min but with reduction in the tool-chip contact length (0.51mm to 0.83mm). At these conditions, more materials were removed from the work piece, leading to longer chips sliding on the tool face. This result agreed with 0.38mm and 1.08mm obtained by Abukhshim *et al.* (2006) during high speed machining of alloy steel at depth of cut of 0.1mm and 0.30mm respectively. This shows an average reduction of approximately 4.67 and 8.02% in mild steel and aluminum respectively. There was a considerable reduction in the cutting foce required in machining process with increased cutting speed.

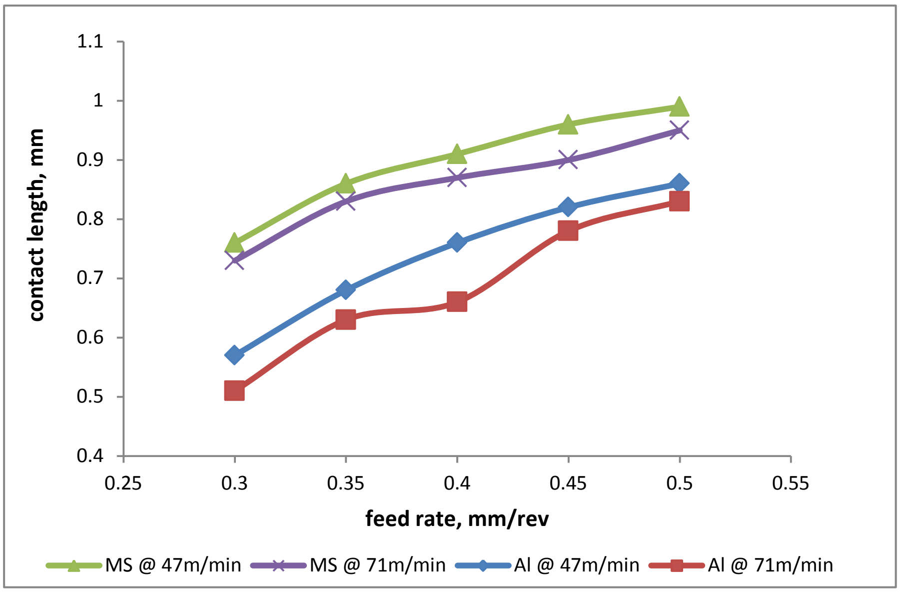

Fig. 4: Effect of tool-chip contact length and feed on aluminium and mild steel at a depth of cut, 0.20mm and constant speeds, V=47m/min and 71m/min

Fig. 5 shows the relationship obtained between the resultant force of aluminum and mild steel at varying feed rates 0.05 to 0.26 mm/rev, constant depth of cut and speed of 0.10mm and 47m/min respectively. As shown in the figure, resultant force rose (583N to 2037N) with increase in feed rate (0.05 mm/rev to 0.26mm/rev). It implies that as the feed rate increased, more material is removed from the work-piece, this will require more force to achieve this removal. It can be seen that instability of cutting in mild steel is similar in trend to that of aluminum, the only difference being that mild steel gives higher instability than aluminum, under the same cutting conditions. This could be due to the high percentage of carbon present in mild steel thereby making it harder than aluminum. As the cutting speed increased to 71m/min, there is decrease in the resultant force on mild steel (1078N to 815N) and aluminum (482N to 583N) having approximate reductions of 5.10% and 15.25% respectively.

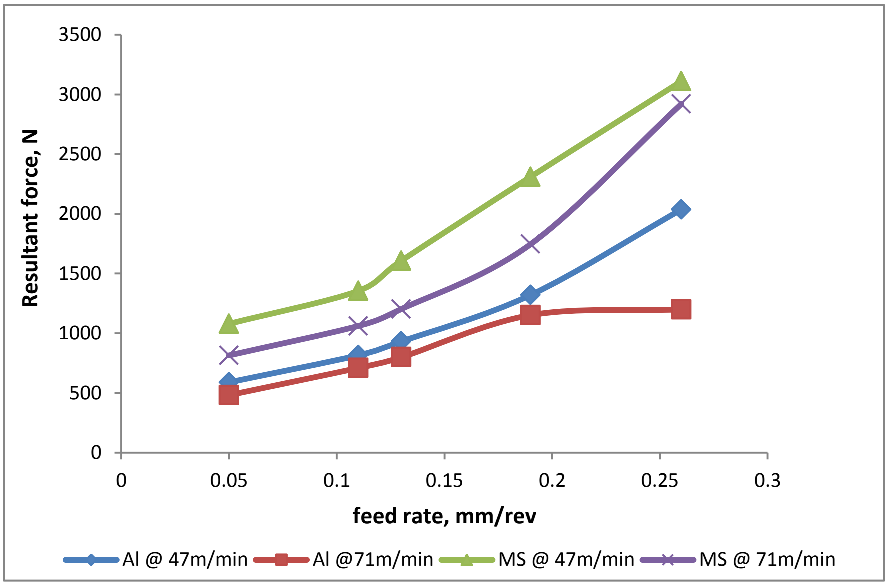

Fig. 5: Effect of feed on the resultant forces of aluminum and mild steel at a depth of cut, 0.10m and constant speeds, V= 47m/min and 71m/min

At the same speed of 47m/min but different depth of cut of 0.20mm and feed rate of 0.3mm/rev to 0.50 mm/rev, there is an increase in the resultant force as depicted in Figure 6. There is a slightly steady increase in the resultant force for mild steel up to 2840N before a sudden upswing to 4141N giving an approximate increase of 45%. There was a reduction in resultant force as the cutting speed increased to 71m/min, ranging from 2508.16N to 1429.1N and 1192 to 1141.9N approximating 75.5% and 4.4 % reductions for mild steel and aluminum respectively. It can be concluded that cutting force is higher when turning mild steel than when aluminium alloys are machined.

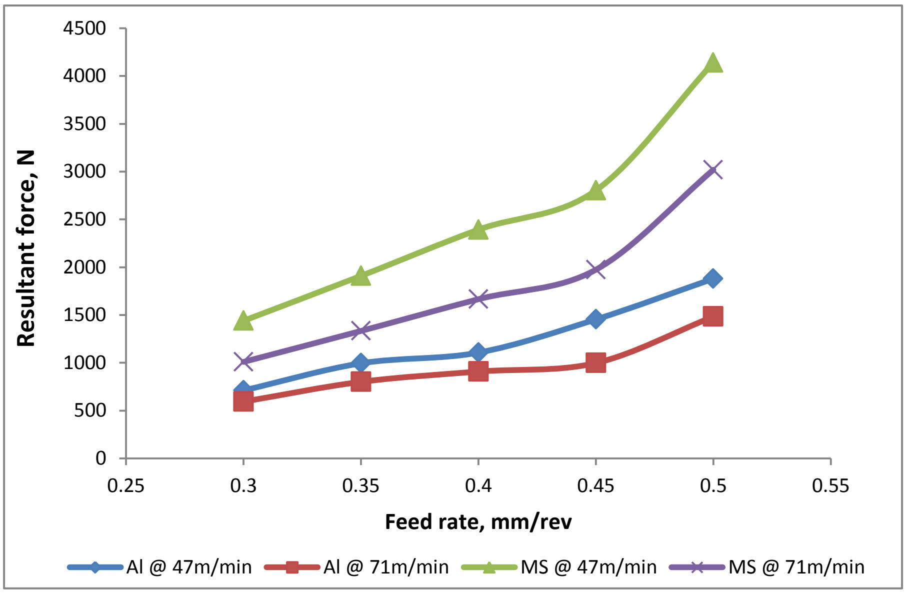

Fig. 6: Effect of feed on the resultant forces of aluminum and mild steel at a depth of cut, 0.10m and constant speeds, V= 47m/min and 71m/min

CONCLUSIONS

From this study, the following conclusions are made:

(i) Tool-chip contact length decreased with increased cutting speed under the same conditions of feed rates and depth of cut for the two metals considered.

(ii) When the feed rates increased, the tool-chip contact length increased at constant cutting speed for the two metals.

(iii) As cutting force increases, the tool-chip contact length increases leading to decrease in cutting stability.

(iv) Low feed rates lead to low tool-chip contact length which in turn increases metal cutting force.

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