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The Impact of Cutting Conditions on Cutting Forces and Chatter Length for Steel and Aluminum

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Abstract- ***In the present study, an attempt has been made to investigate the effect of primary cutting parameters (cutting speed, feed and depth of cut) and tool overhang length on cutting forces and chatter starting point lengths in finish turning of EN8 steel, EN24 steel, Mild steel and aluminum. Machining test cuts are conducted using sharp tool and the effect of cutting conditions and tool overhang length are also studied. Here experiments are conducted on four work piece materials at different cutting parameters and different overhang lengths. The chatter starting point is measured from the free edge of the work piece and graphs were plotted between overhang length verses cutting forces and chatter staring point lengths.***

Keywords: Cutting Parameters

I. INTRODUCTION

Many engineering components manufactured using casting, forming and other processes often require machining as their end operation. Machining or metal cutting is an important manufacturing process. With the modern trend of machine tool development, accuracy and reliability are becoming prominent features. To achieve higher accuracy and productivity, it requires consideration of dynamic instability of cutting process. When there is a relative motion present between the tool and work piece, the performance of the operations may not be satisfactory. The machine tool vibrations have detrimental effect on tool life which in turn lowers the productivity and increases cost of production.

The dynamic loads during machining operations have periodic or impact characteristics. These loads are associated with the cutting process and movements of the machine tool members. While analyzing dynamic behavior of machine tools, rigidity and stability are two important characteristics to be considered. Rigidity refers to the steady-state vibrations, where as stability corresponds to transient response characteristics. A dynamically stable system has masses oscillating with decreasing amplitudes towards original state of equilibrium, while an unstable system oscillates with increasing amplitude deviating more and more from the original position of equilibrium. The most common phenomenon of dynamic instability in machine tools is through an interaction between the structure and cutting process, which is known as self-excited vibrations or chatter. Feedback in this closed-loop system is due to cutting force variations caused by machine structure deflections, which in turn alter cutting forces by changing tool position and velocity. The machine structure and cutting process interaction is mainly due to two main principles: ‘wave regeneration’ and the ‘mode coupling’.

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In wave regeneration, unreformed chip thickness variations are caused by surface waviness left during previous revolutions, while in mode-coupling, it varies due to instantaneous tool vibrations, which take place at least in two directions. The instability caused by regeneration usually takes place earlier than by mode-coupling in most of the machining processes.

In order to obtain chatter-free machining conditions, conservative cutting parameters are to be selected based on the stability limits. Machine tool operators often select these process parameters from the stability-lobe diagrams, which are conveniently obtained from the analytical cutting models. In most of the works it is resumed that the machine tool structure is simplified to a single degree of freedom system and dynamic equations are appropriately developed. Nevertheless, these focused on state of cutting with a rigid work-piece model using a stability criterion. In practice, accurate cutting dynamic models are needed to get the realistic representation of stability states. There are several parameters such as work piece deflection, nonlinear force-feeding variations and many secondary features like tool-overhang have marked influence on cutting dynamics. To predict stability state of cutting, output features like surface roughness, nature of chip as well as tool wear can also be employed effectively along with the cutting force data.

II. INSTABILITY IN TURNING

The process of cutting in turning exhibits complicated and interesting dynamics. During the cutting operation, several types of vibrations influence the chip flow-rate and final work surface. Compared to free and forced vibrations, self-excited vibrations are more detrimental to the finished surfaces and cutting tools. Self-excited vibrations are developed at one of the natural modes of cutting system as a result of dynamic interaction between the structure and cutting process. This may result in large amplitudes of relative motion between the cutter and work-piece. Such a phenomenon also known as ‘chatter’ can in general result from one or more of the following: regenerative effects, mode coupling, loss-of-contact dynamics, and friction, structural and other sources of nonlinearities. Of all these, regenerative chatter has more influence on the stability of cutting. The regeneration is due to interaction of cutting force and work-piece surface undulations reduced by the preceding tool passes. It occurs when the cuts overlap and cut produced at a time t leaves small waves in the material that are regenerated during each subsequent pass of the tool. If regenerative vibrations become large enough so that the tool does not be in contact with work-piece, another type of chatter known as multiple regenerative chatter occurs.

Another chatter mechanism known as mode-coupling is produced by relative vibrations between the tool and work-piece that occur simultaneously in two different directions in the plane of cut. Usually mode-coupling occurs without any interaction between the vibration of the system and undulated surface of work-piece. Here the tool traces out an elliptical path that varies the depth of cut in such a way as to strengthen the coupled modes of vibration. The amplitude of self-excited vibration increases until some nonlinearity in the machining process minimizes this.

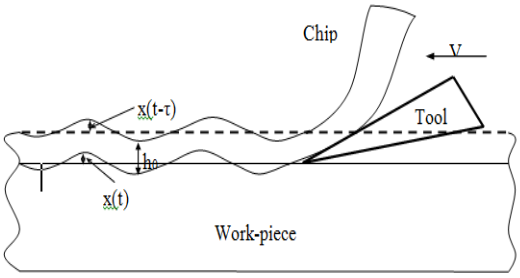

Fig: The turning operation in a chatter situation

The cutting edge of the tool is orthogonal to the cutting velocity v. When there is no chatter, the cutting tool will remove chips from the work piece with a nominal chip thickness h0. The resulting surface profile for such a situation is flat and the required cutting forces have constant values. On the other hand, when the turning operation is excited by abrupt changes in the cutting forces such as those generated by a hard spot in the work piece or the phase shift between the modulations of successive tool cuts, then the machined surface profile is no longer flat. As shown in Figure, such a wavy profile has a depth of cut x(t) for time t. A similar wavy profile has also been cut at a preceding time instant (t−τ) under a depth of cut of x (t−τ) as shown. These are called respectively as inner and outer modulations. Thus the instantaneous chip thickness (depth of cut) in the current pass can be written as h(t)=h0+x(t)-x(t- τ).

In machining operations, the parametric data consisting of cutting forces, tool wear and surface roughness gives vital information relating to the state of cutting. So it is required to measure and employ these parameters for the stability analysis.

III. EFFECTS OF SECONDARY PARAMETERS

In the third case, another series of cutting experiments are carried out on a 1 hp center lathe available in workshop in order to record the static cutting force components, surface roughness of work-piece, flank wear and critical chatter length at selected cutting states. Four different work materials are employed to study the effect of the selected variables. In each case the cutting conditions employed are depicted in Table.

Operating parameters and their levels used in the experiments:

Work-piece Material	Cutting Speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Tool overhang length(mm)
EN24 steel	7,14, 22	0.1 (constant)	0.1,0.2,0.3,0.4,0.5,0.6,0.7	54,57,59,61
EN8 Steel	7,14, 22	0.1(constant)	0.1,0.2,0.3,0.4,0.5, 0.6,0.7	53,57,60,63
Mild Steel	7,14 , 22	0.1, 0.138, 0.175, 0.2, 0.275, 0.35 , 0.5	0.1(constant)	54,57,59,61
Aluminium	7,14, 22	0.1, 0.138, 0.175, 0.2, 0.275, 0.35, 0.5	0.1(constant)	53,56,58,62

IV. EXPERIMENTAL SETUP

This figure shows the experimental set-up employed in the present work. The inward facing is performed from the collar end of the work piece.

The cutting operation is limited to a short range since the structural stiffness rapidly increases as the tool advances inwards. The cutting speed (v),feed rate (f),depth of cut (d) and tool overhang length(*l*) are progressively changed to obtain the cutting forces (Feed force(Fx), Radial force(Fy) and Tangential force(Fz) as well as critical chatter lengths (*l*c).The tool overhang refers to the distance from the tool holder to the end of cutting edge. In the present case the tool overhang lengths are varied between 53 to 63 mm. Overhang lengths of the tool is measured using a milli-meter scale.

An attached tool post strain gauge dynamometer platform is employed to measure the amplitudes of the three cutting forces. Here tool dynometer with strain gauge support (PE1-845122) is mounted on the lathe itself and this strain gauge capacity ranges from 0.1 mV to 3V. Here force values are obtained in terms of voltage and the force in Newton is obtained by the available multiplication factors. Dynamometer is calibrated before applying loads on lathe. Calibration is done individually for horizontal and vertical forces with reference to proving ring and microvolt indicated on bridge balance unit are recorded with respect to definite known loading. A graph is plotted for load verses microvolt in calibration of horizontal and vertical forces separately after multiplying with a factor i.e.1kg equal to 23.4 and 20.3 µv along x and y direction respectively. As one of the output parameter, critical chatter length of work-piece is also measured from the origin of noisy cutting state. During the cutting under the same conditions of operation at some cutting lengths it is found that the magnitudes of cutting forces abruptly increase and these states are referred to as critical states in the present experiments. In fact if a microphone is laid to measure the cutting noise signal, at this length it shows the peak value. The corresponding length is measured from the collar end. The required feed rate is chosen from the lathe preset values. Automatic feed arrangement is engaged in all the cases. The cutting speeds are calculated from the diameters of the work-piece and the set value of the spindle speed from available values.

The flank wear on the tool face is measured before and after the experiments by using tool maker's microscope available in the laboratory. Figure shows the photograph of the tool microscope used in the present work.

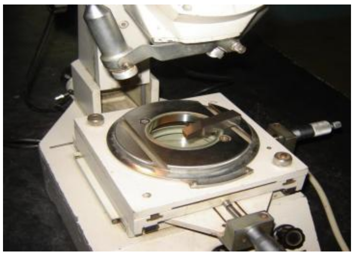

Fig: Tool makers microscope employed (30x Magnification)

It is a high precession versatile microscope as per the international standards and equipped with achromatic optical system to offer an erect image of natural orientation and free from distortion for most diversified jobs. The work is supported over a glass plate while a beam of light transmits the image of the tool face contour on to a line template within the ocular of the microscope. The work table may be rotated or moved transversally or longitudinally for making angular or linear measurements. The linear movements are controlled by micrometer adjustments. Oculars are supplied for threads and general contour inspection. The base of microscope rests on three supports two of which are adjustable for leveling the instrument. The base has an in-built electrical transformer and control panel and transmits illumination with a green filter. The microscope tube is guided by an arm so that its vertical movement can be adjusted by a rack and pinion system. A separate course focusing movement is provided in the microscope tube. The vertical travel or measurements up to 10mm thickness can be read by the depth dial gauge. Thickness is measured as a difference of two different focusing of the object. Least count of the gauge is 0.01. There is an eye piece protractor whose head has been graduated from 0 to 360 degrees with adjustable vernier reading. Two possible range of illuminating system are provided in the instrument. They are operated through 6 volts solid state variable light control built-in transformer.

Surface roughness of the workpieces is measured by using Mitutoyo Tally surf tester (Ra = 3.95μm) which is shown in the Figure

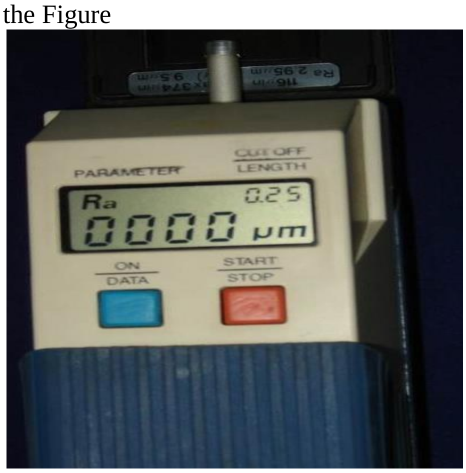

Fig: Mitutoyo Tally Surf Tester

While the sensor (driven by a driver) is making a linear uniform motion along the test surface, the contact stylus in perpendicular with the work surface moves up and down with the work surface. Its motion is converted into electric signals, which are amplified, filtered and transformed into digital signals through A/D convertor. The signals are then processed by the CPU into Ra values before being displayed on the screen. The tester has to be initially calibrated with test specimen provided by the manufacturer. Before starting the sensor, choose the desired parameter Ra and proper sampling length. The Stylus of the tester has to be moved by a standard length on the work specimen and a button is pressed to show the average roughness value on the screen. The roughness is likewise measured at three different positions on the surface. The average of three readings is noted as a final Ra value. In all experiments 50mm diameter work-pieces are employed and tool is HSS S-200. A flow chart of the experiments carried-out in the present case is shown in Table.

Experimental Results carried out on EN8 Steel at different speeds (feed=0.1mm/rev)

S.No	DOC (mm)	TOL (mm)	Cutting Forces(N) V=7m/min			Cutting Forces(N) V=14 m/min			Cutting Forces(N) V=22 m/min		
			F_x	F_y	F_z	F_x	F_y	F_z	F_x	F_y	F_z
1	0.1	53	133	193	294	151	219	334	183	265	396
2	0.2	53	148	217	342	168	242	386	202	288	448
3	0.3	53	231	266	351	251	297	402	284	343	464
4	0.4	53	264	316	417	285	341	458	321	387	520
5	0.5	53	281	351	455	302	384	496	338	430	558
6	0.6	53	331	407	517	352	432	554	385	477	616
7	0.7	53	365	429	568	386	459	606	427	505	668
8	0.1	57	205	263	373	226	296	414	266	342	476
9	0.2	57	241	295	437	264	322	478	307	368	540
10	0.3	57	304	351	486	327	383	528	361	429	590
11	0.4	57	338	390	540	360	420	584	393	466	646
12	0.5	57	396	462	586	411	488	628	444	534	690
13	0.6	57	439	496	647	461	526	686	494	572	748
14	0.7	57	499	542	688	524	573	728	559	619	790
15	0.1	60	262	289	441	285	315	482	321	361	544
16	0.2	60	281	352	493	302	378	534	335	424	596
17	0.3	60	338	433	527	352	458	568	385	504	630
18	0.4	60	361	511	582	386	538	623	420	584	685
19	0.5	60	401	546	657	423	570	702	463	616	764
20	0.6	60	459	574	717	483	599	762	524	645	824
21	0.7	60	539	652	751	562	687	796	596	733	858
22	0.1	63	298	338	483	319	364	524	351	410	586
23	0.2	63	346	428	537	369	458	582	404	504	644
24	0.3	63	394	532	583	411	567	628	446	613	690
25	0.4	63	411	601	647	432	631	692	463	677	754
26	0.5	63	459	636	721	479	658	768	514	704	830
27	0.6	63	508	656	783	529	664	828	562	710	890
28	0.7	63	589	718	851	613	762	896	648	808	958

Experimental Results carried out on EN24 Steel at different Speeds

S.No	DOC (mm)	TOL (mm)	Cutting Forces(N) V=7m/min			Cutting Forces(N) V=14 m/min			Cutting Forces(N) V=22 m/min		
			F_x	F_y	F_z	F_x	F_y	F_z	F_x	F_y	F_z
1	0.1	52	155	239	362	183	284	425	204	321	475
2	0.2	52	170	263	410	196	311	471	217	347	523
3	0.3	52	252	312	419	279	362	484	304	398	537
4	0.4	52	284	362	485	310	411	546	331	447	597
5	0.5	52	305	397	523	328	441	587	350	477	644
6	0.6	52	357	453	585	387	501	649	409	535	707
7	0.7	52	392	475	636	418	519	701	441	557	755
8	0.1	55	236	309	441	261	358	506	283	394	565
9	0.2	55	264	341	505	296	391	569	316	429	626
10	0.3	55	329	397	554	357	443	617	378	483	673
11	0.4	55	365	436	608	391	482	671	412	520	727
12	0.5	55	420	508	654	444	553	719	462	590	775
13	0.6	55	464	542	715	491	585	780	513	623	837
14	0.7	55	523	588	756	552	634	816	571	670	872
15	0.1	59	288	335	509	316	381	575	338	419	629
16	0.2	59	307	398	561	336	444	627	357	481	683
17	0.3	59	357	479	595	385	525	662	407	561	718
18	0.4	59	383	557	650	412	603	713	432	641	767
19	0.5	59	428	592	725	454	639	784	476	675	839
20	0.6	59	488	620	785	517	668	848	539	706	904
21	0.7	59	562	698	819	592	746	886	616	786	942
22	0.1	62	321	384	551	347	433	616	371	473	672
23	0.2	62	370	474	605	397	524	665	422	562	719
24	0.3	62	422	578	651	452	626	712	477	666	768
25	0.4	62	435	647	715	461	693	774	483	731	829
26	0.5	62	484	682	789	513	730	851	537	767	908
27	0.6	62	535	702	851	566	748	912	589	788	969
28	0.7	62	612	764	919	641	812	984	664	850	1032

V. FLANK WEAR

The flank wear is caused by the abrasive and adhesive actions between the cutting tool and the machined surface. It starts at the cutting tip and then widens as the contact area increases, thus forming the wear land. The width, shape and growth rate of the wear land depend on the tool material, workpiece material and cutting parameters. Variation of flank wear with speed is shown in Figure: 5 (a). It can be very clearly seen that the flank wear increases with speed. The effect of feed and depth of cut on flank wear can be seen from Figures: (b) and (c) respectively.

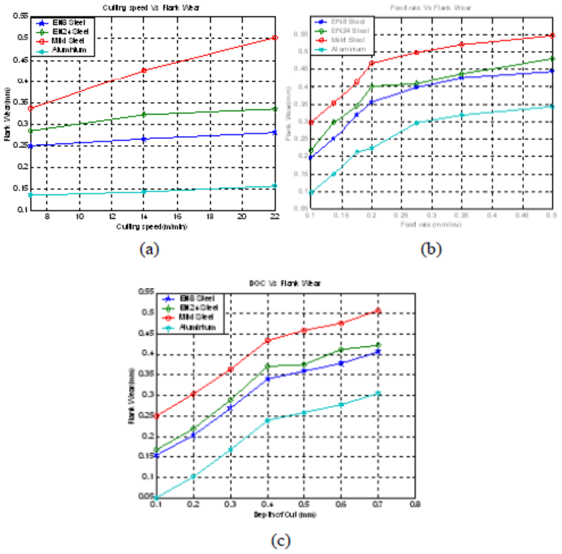

Fig: Variation of flank wear with cutting parameters

VI. CRITIVAL CHATTER LENGTH

The next output parameter considered is critical chatter length. There are different ways to record the chatter signatures (abnormal) during cutting. The critical chatter length is the work length from tailstock support at which the cutting force readings have a sudden increase. The variation in critical chatter length for work-pieces of EN8 steel, EN24 steel, mild steel and aluminium as a function of cutting speed, feed rate and depth of cut are shown in Figure: (a)-(c).

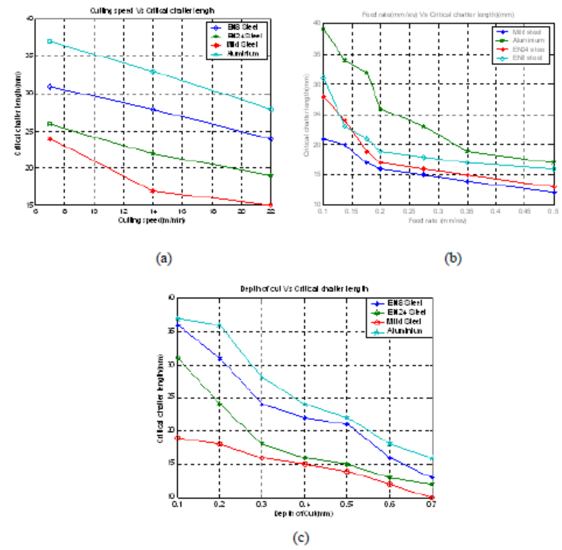

Fig: Variation of critical chatter length with cutting parameters

VII. TOOL OVERHANGING LENGTH

Figure (a)-(d) shows the variation of cutting forces against the different tool overhang lengths for four work piece materials. It is observed that radial cutting force sharply increases when tool overhanging length exceeds 59mm. It is also observed that, the cutting force increases along X, Y and Z directions with overhanging length.

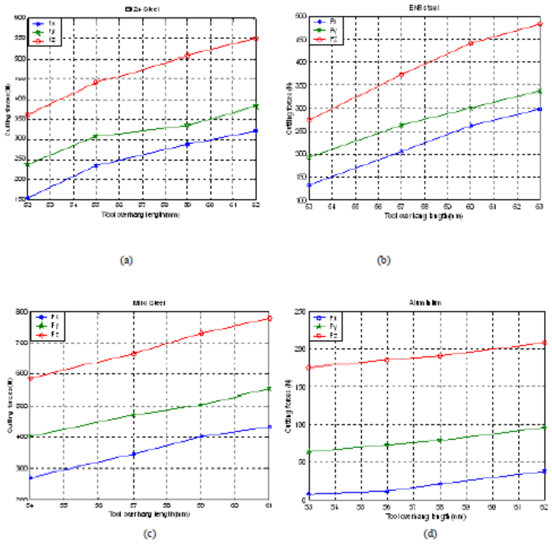

Fig: Variation of cutting forces with tool overhang length

Large amount of positive radial force (Fy) is undesirable and it causes the work piece to deflect and there by surface finish deteriorates. As tool overhanging is increased, the maximum roughness height increases which means that the quality of surface deteriorates as shown in Figure (a) for EN24 steel. Figures (b), (c) and (d) show the similar variation of surface roughness against the tool overhanging lengths for other three work piece materials.

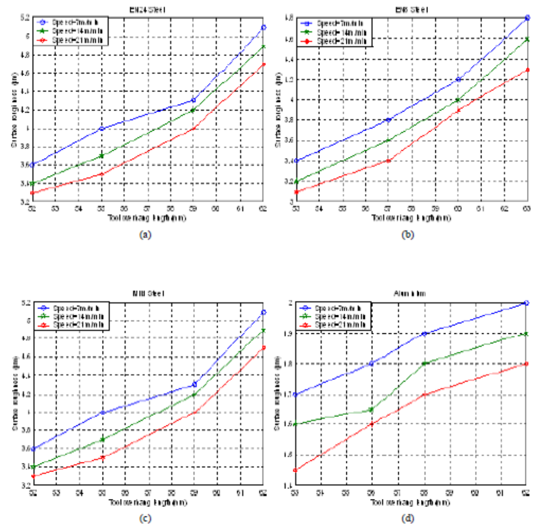

Fig: Variation of cutting forces with tool overhang length

As seen from the Figures: (a) - (d), with an increase in tool overhang, critical chatter length decreases for all the work materials.

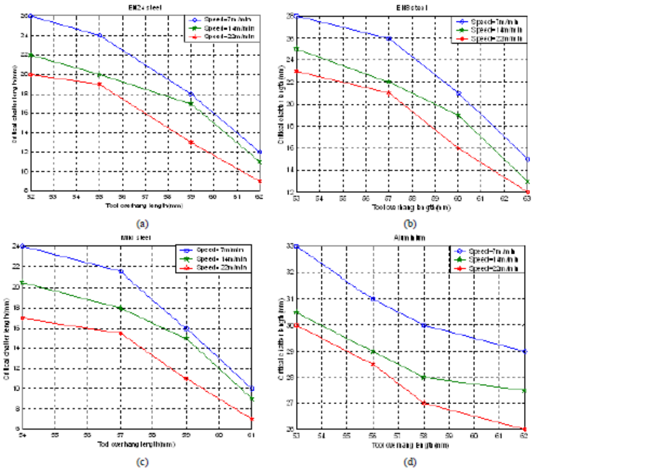

Fig: Variation of critical chatter length with tool overhang length

VIII. VARIATION OF FLANK WEAR WITH TOOL OVERHANG LENGTH

Figures: (a) - (d) show the variation of flank wear versus tool overhang length at different cutting speeds.

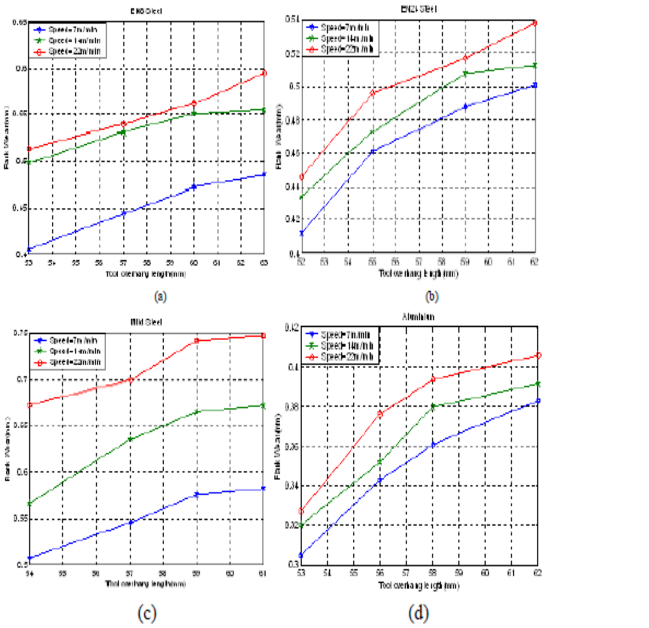

Fig: Variation of flank wear with tool overhang length

Variation of cutting force components with flank wear is shown in Figures: (a) - (d). It is clearly seen that the cutting force components increase with flank wear.

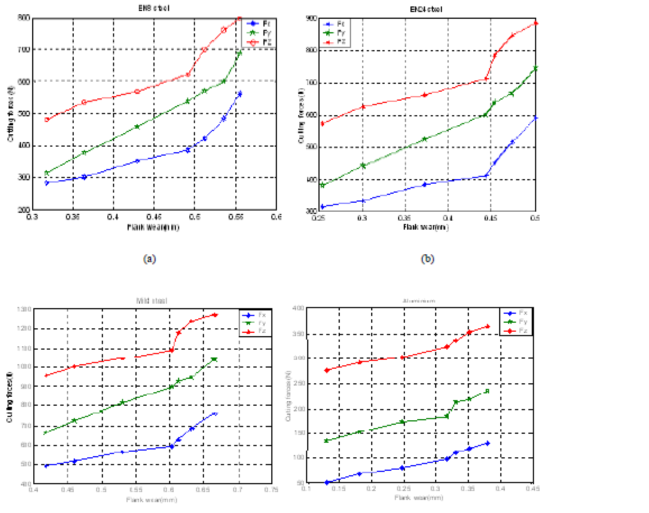

Fig: Variation of cutting force with flank wear

The variation of critical chatter length with flank wear is represented graphically in the Figures: (a) - (d). It is observed that critical chatter length is decreases with increase in flank wear.

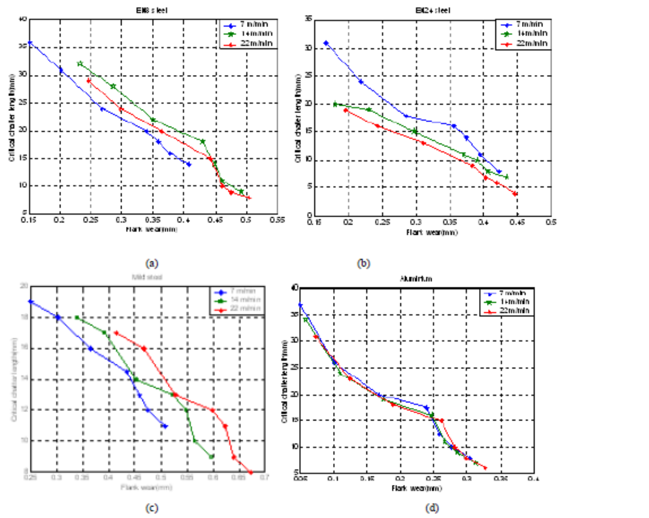

Fig: Variations of flank wear with tool overhang length

IX. CONCLUSION

At low speed, cutting forces increases gradually with overhanging lengths and at high speeds initially forces increase slowly at low overhanging lengths and at high overhanging length forces increase very rapidly. The static forces generally increase with the subsequent increase in feed rate. This has been attributed to the fact that the area of cut subsequently increased per cycle of cut, hence more shearing had to be done which required more force. Increasing the DOC generally resulted in a proportional increase in the static cutting forces. The fresh (sharp) tool static cutting forces increased linearly when overhanging length increases, forces increase both in X , Y and Z Direction at low overhanging length forces increases slowly and at high over hanging length increases very rapidly. Above all parameters effects on critical chatter lengths i.e. by increasing above all parameters chatter lengths decreases.

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