Effects of Process Parameters on Machine Vibrations, Cutting Force, Surface Roughness and their Co-Relations in Hard Turning on CNC Lathe

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Abstract

In turning process the vibration is a main concern which occurs due to the lack of dynamic stiffness or rigidity of the machine tool and affects the process in different ways. In this work the effect of machine tool parameters on machining vibration has been experimentally investigated. The process parameters spindle speed, feed, depth of cut, hardness of workpiece and coolant conditions are being varied in order to observe their effect on responses viz. machining vibration, cutting force and torque, surface roughness. Experiments are carried out on CKE6150Z CNC lathe. Regular indexable tool holder of CNC lathe has been removed and specially designed fixture has been mounted to hold dynamometer. Kistler 9257B six component dynamometer has been mounted over the specially designed fixture. Cylindrical bar of diameter 50mm and 160mm length of AISI 52100 bearing steel has been machined by using CBN insert for experimental investigation. Vibration analyser VA-12 has been connected to tool holder in order to record in process vibration variations. Experiments are carried out using Taguchi design of experiments. Statistical analysis for co-relation among the response parameters have been carried out. The process behaviour and optimal setting of process parameters have been investigated and modelled.

Keywords: Hard turning, Vibration, Surface roughness, Cutting force, MQL, Nanofluid.

1. INTRODUCTION

Finish hard turning is the process wherein hard material having hardness beyond 45 HRC, turned to get good surface finish. Traditionally, most of the ferrous metal parts rough turned, heat treated and finished by grinding operation. Finish hard turning process has been developed as alternative to grinding operation to overcome manufacturing cost due to numbers of setup changes and lead time without compromising on surface quality to maintain competitiveness. Due to development in single point cutting tools it is possible to machine very hard material using carbide tool, cubic boron nitride (CBN) and diamond tool. [1]

The dynamic relative motion between cutting tool and workpiece causes generation of forces which gives rise to the vibration in the machine tool. Vibration in turning process affects the cutting tool in various ways such as, increase in tool wear, increase in surface roughness of workpiece and generation of unacceptable noise, reduction in tool life, etc. [2]

The turning operation is the very basic machining operation in the manufacturing industry. In a turning process, three different types of mechanical vibrations are present due to a lack of dynamic stiffness/rigidity of the machine tool system comprising of the tool, tool holder, work piece and the machine tool itself. These are free, forced and self excited vibrations. Free vibrations are generated due to shock and forced vibrations are due to unbalance, misalignment, mechanical looseness and gear defects in the machine tools. The free and forced vibrations can be easily rectified. But self excited vibrations are complex in nature and difficult to understand. The self excited vibrations are of primary and secondary chatter. The primary chatter is caused by friction between the tool and work piece, thermo mechanical effects or by mode coupling. Whereas, secondary chatter caused by the regeneration of a wavy surface on the work piece. Regenerative vibration is the most destructive among all other vibrations. [3]

Vibration generation and its effect on the process parameter need to be studied for successful implementation of hard turning process. Study of cutting forces is critically important in turning operations because cutting forces correlate strongly with cutting performance such as surface accuracy, tool wear, tool breakage, cutting temperature, self-excited and forced vibrations, etc. The resultant cutting force is generally resolved into two components, namely thrust force (FD), and cutting force (Fc or Fz). In three-dimensional oblique cutting, one more force component appears along the third axis. The thrust force FD is further resolved into two more components, one in the direction of feed motion called feed force Fx, and the other perpendicular to it and to the cutting force FC called back force Fy, which is in the direction of the cutting tool axis. [4]

To control the extent of heat produced during machining operations enormous amount of cutting fluid under flood cooling regime has been used throughout the world. But many researchers have criticized the use of flood cooling from environmental, economical and social viewpoints. To reduce the uses of lubrication flood cooling, a technique called minimum quantity lubrication (MQL) has been evolved in machining operations in the last few years. It is also termed as near dry machining (NDM). Due to the use of less amount of cutting fluid (60ml/h to 1000ml/h) the MQL or NDM can be considered as the more sustainable approach as compared to conventional wet machining.

Now days, along with MQL Nanoparticles are added as additive to increase the thermal conductivity of cutting fluid. The mixture of base fluid (water, vegetable oil) with Nanoparticles (ceramic, metal, CNT, aluminium oxide (Al203) particles) is called Nanofluid. The nanoparticles are mixed with base fluid in different percent by weight of base fluid depending on the physical properties of base fluid and nanoparticles. [5]

Dr. Deng in 1982 proposed Grey analysis to fulfill the crucial mathematical criteria for dealing with poor, incomplete, and uncertain system. As the name itself indicates that a shade between the absolutes of black and white, the black is represented as lack of information and the white is full of information. Thus, the information that is either incomplete or undetermined is called Grey. A system having incomplete information is called Grey system. Grey analysis can effectively recommend a method of optimizing the complicated inter-relationships among multiple performance characteristics. Grey analysis has been broadly applied in evaluating or judging the performance of a complex project with incomplete information. The data to be used in Grey analysis must be preprocessed into

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quantitative indices for normalizing raw data for another analysis. Grey relational analysis is in impacting measurement method in grey systems theory that analyzes uncertain relations between one main factor and all other factors in a given system. When the experiments are ambiguous or when the experimental method cannot be carried out exactly, Grey analysis helps for the shortcomings in statistical regression. Grey relational analysis is actually a measurement of the absolute value of data difference between sequences, and it could be used to measure the approximate correlation between the sequences. [6]

In this work attempt has been made to investigate the finish hard turning process on AISI 52100 bearing steel using CBN inserts. The objective of this work is to study and analyse the vibration and cutting forces generated during the hard turning process. Material hardness cutting speed, feed, depth of cut and cutting conditions (Dry, MQL and MQL with Nanofluid) are used as process parameters. Taguchi orthogonal array L18 has been used for conducting the experiments. Surface Roughness of the turned component, Resultant forces (Fx, Fy and Fz) and Vibration generated during the process have been measured and analyzed by Taguchi method. Finally the multi criteria decision making tool Gray Relation Analysis has been applied to optimize the process parameters.

2. EXPERIMENTAL DETAILS

2.1 Machine tool details

The experiments were performed on CKE6150z CNC lathe of Dalian machine tool (10HP, 7- 2200 rpm range). Regular indexable tool holder of CNC lathe has been removed and specially designed fixture mounted to hold tool force dynamometer. Kistler 9257B tool force dynamometer is mounted on specially designed fixture and tool holder is fixed over it. The dynamometer is connected with the charge amplifier for signal conditioning which in turn is connected to the computer for real time monitoring of the process. To measure the vibration generated during the turning process, vibration analyzer VA-12 is connected to tool holder. In this experiment indigenously designed and fabricated MQL system has been used to control the coolant flow rate. Commercially available twin fluid siphon nozzle is used for the mist generation. The MQL system has been set to supply the coolant with different flow rates. The distance between the cutting insert and the nozzle has been decided according to the distance of the far field from the nozzle. The detailed experimental set up is shown in Figure 2.1

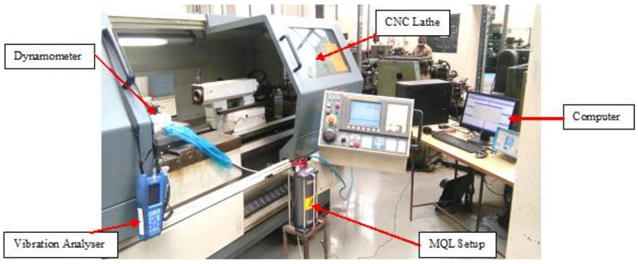

Figure 2.1 Experimental Setup

2.2 Work and tool materials

Experiments are conducted on AISI 52100 bearing steel material with different hardness 35 HRC and 60 HRC. The length of the rod was 160 mm with diameter of 50 mm. Due to its wear resistance property this material is commonly used for components subjected to severe abrasion, wear or high surface loading. Typical applications include Ball and Roller Bearings, Spinning Tools, Beading Rolls, CV Joints, Gauges, Knife, Punches and Dies. It contains 0.5-1.1% of Carbon, 1.3 -1.5% of Chromium. It has very good physical properties, like it is very lustrous, good conductors of heat and electricity, high melting point, high density, malleable and ductile. CBN inserts CNGA120408S01030A 7025 uncoated of Sandvik Coromant make were used for the turning process. For each and every experiment a fresh cutting edge was utilized. The right hand style tool holder PCLNR 2525 M12 RH designated by ISO is used to hold the inserts.

2.3 Preparation of Nanofluid

Addition of Nanoparticles in base fluid is termed as Nanofluid. There are two methods for preparation of Nanofluid, the single-step preparation process and the two-step preparation process. In single step preparation method Al_2O_3 Nanoparticles 4% by weight of palm oil are added to vegetable base oil (palm oil) and ultrasonication process carried out for 6 hours to avoid agglomeration in Nanofluid. Surfactant added to increase the surface tension property of Nanofluid .In this work palm oil has been used as base oil and aluminum oxide (Al_2O_3) nanoparticles are added as additives. Palm oil has good thermal conductivity, low viscosity, environmental friendly and easily available with low cost hence used as the base oil. Nanoparticles as additives in cutting fluid base oil can increase the thermal conductivity of the coolant due to convective heat-transfer enhancement by solids.[19] Nanoparticles have efficient lubrication features in addition to their satisfactory cooling performance.

2.4 Design of Experiments

Taguchi's orthogonal and balanced array provides prominent test procedure capable of reducing the noise and making robust design. This array determines the number of experiments to be performed, ensuring that all levels of all factors are tested at equal number of times. The Experiments are conducted using the Taguchi L18 orthogonal array for turning of AISI 52100 Bearing Steel using CBN inserts. Taguchi L18 array is a mix array which can be used to test one factor at two levels and up to 7 factors at three levels. The factors and their levels are selected through detailed literature survey, preliminary experimentations and by referring the standard insert catalogue. This work involves the study of process parameters Viz. cutting speed, feed, depth of cut, machining condition and material hardness. The output parameters taken into considerations are cutting force (Fz), thrust Force (Fy), feed force (Fx), surface roughness (Ra) and vibration. Process parameters and their levels are shown in Table 2.1 and the Taguchi L18 orthogonal array is shown in Table 2.2.

Table 2.1 Process Parameters and their Levels

Factors	Unit	Levels		
		1	2	3
Hardness	HRC	35	62	-
Cutting Speed	m/min	63	95	126
Feed Rate	mm/rev	0.05	0.1	0.15
Depth of Cut	mm	0.1	0.3	0.5
Cutting Condition		Dry	MQL (Oil)	MQL (Nanofluid)

Table 2.2 Taguchi L18 orthogonal array

Exp No.	Hardness (HRC)	Speed (Rpm)	Feed (mm/rev)	DOC (mm)	Machining Conditions
1	35	400	0.05	0.1	DRY
2	35	400	0.1	0.3	MQL(oil)
3	35	400	0.15	0.5	NANOFLUID
4	35	600	0.05	0.1	MQL(oil)
5	35	600	0.1	0.3	NANOFLUID
6	35	600	0.15	0.5	DRY
7	35	800	0.05	0.3	DRY
8	35	800	0.1	0.5	MQL(oil)
9	35	800	0.15	0.1	NANOFLUID
10	62	400	0.05	0.5	NANOFLUID
11	62	400	0.1	0.1	DRY
12	62	400	0.15	0.3	MQL(oil)
13	62	600	0.05	0.3	NANOFLUID
14	62	600	0.1	0.5	DRY
15	62	600	0.15	0.1	MQL(oil)
16	62	800	0.05	0.5	MQL(oil)
17	62	800	0.1	0.1	NANOFLUID
18	62	800	0.15	0.3	DRY

3. RESPONSE MEASUREMENTS

3.1 Cutting forces measurements

Cutting forces during machining are measured by using Kistler 9257B Dynamometer. The dynamometer has a great rigidity and consequently a high natural frequency. Its high resolution enables the smallest dynamic changes in large forces to be measured. The dynamometer consists of four three-component force sensors fitted under high preload between a base plate and a top plate. Each sensor contains three pairs of quartz plates, one sensitive to pressure in Z-direction and the other two responding to shear in the X and Y directions respectively. The force components are measured practically without displacement. The outputs of four built in force sensors are connected inside the dynamometer in such a way to allow multicomponent measurements of forces and moments to be performed. Force measurement is carried out and monitored through charge amplifier and on board computer system. The real time measurement of Fx, first experiment is shown in Figure 3.1

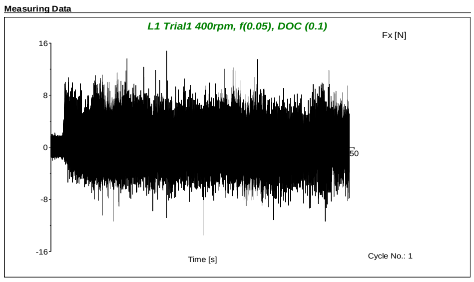

Figure 3.1 Measurement of Fx

3.2 Vibration measurements

Vibration during the machining is measured using VA-12 portable vibration analyzer. The VA-12 is a portable vibration analyzer with FFT analysis function specially designed for in field measurements. It comes with the Piezoelectric Accelerometer PV-57I equipped with magnetic attachment. The VA-12 offers three analyzer modes: vibration meter mode, time waveform mode, and FFT mode. In vibration meter mode, acceleration, velocity, displacement, acceleration peak, and acceleration crest factor can be measured simultaneously. In time waveform mode, the waveform of acceleration, velocity, displacement or acceleration envelope cure can be displayed with up to 8192 samples. In FFT mode, the frequency analysis of acceleration, velocity, displacement or acceleration envelope curve can be displayed with up to 3200 spectral lines.

3.3 Surface Roughness measurements

The surface roughness of turned components are measured using stylus type surface roughness tester, Surftest SJ410, Mitutoyo make. According to JIS-1994 standard, cut off length and sampling length of 0.8 mm and 4 mm respectively were selected to evaluate the surface texture. The surface roughness were measured at three locations and then, the average surface roughness (Ra) calculated. Measured responses Fx, Fy, Fz, Ra and Vibration are given in table 3.1.

Table 3.1 Experimental Results for L18

Exp No.	Avg Ra (µm)	Fx (N)	Fy (N)	Fz (N)	Vibration (m/s^2)
1	1.0250	25.82	50.96	159.32	0.0525
2	0.9877	38.69	90.45	140	0.03271
3	0.9562	47.34	89.32	162.47	0.0966
4	0.5676	32.36	63.85	111.3	0.09396
5	0.4043	27.36	45.63	98.89	0.1002
6	0.9871	80.42	126.52	247.67	0.2333
7	0.7582	62.84	86.45	167.52	0.1236
8	0.8617	64.87	91.2	159.49	0.1987
9	0.3321	38.94	58.72	141.1	0.1844
10	0.9864	51.23	67.47	140.21	0.1136
11	1.1530	35.08	75.96	187.5	0.04146
12	1.0210	49.05	102.5	203.7	0.03437
13	0.5180	38.28	81.7	162.8	0.1214
14	0.9887	81.47	143.1	256.8	0.2415
15	0.9640	52.41	93.71	168.5	0.0974
16	0.4920	66.9	124.87	205.32	0.1785
17	0.4373	42.76	85.3	174.25	0.1652
18	0.9877	63.28	164.7	254.12	0.1745

4. RESULTS AND DISCUSSION

The Finish turning of AISI 52100 with CBN inserts using Taguchi's orthogonal array L18 has been carried out. The experimental results are measured with various measuring instruments discussed in previous section. The response parameters Fx, Fy, Fz, Ra and Vibration are corresponding to the Lower the Better quality characteristics, therefore Lower the Better quality characteristics is used to calculate the S/N ratios of the response variables. The experiment which has highest S/N ratio is considered as the more robust and less prone to noise. Therefore process optimization involves, maximization of S/N ratios. The Taguchi analysis for all the responses are carried out using Minitab 17 software.

4.1 Analysis of Fx, Fy, Fz:

It can be seen from the graphs that cutting forces Fx, Fy and Fz exhibits the same pattern for change in Material hardness, Speed, Feed, Depth of cut and Machining conditions. Cutting forces are found to be steadily increasing with Material Hardness, Speed, Feed, and Depth of cut however it is observed that the cutting forces are highest for dry machining, medium for MQL and lowest for MQL with Nanofluid which justifies the use of Nanofluid in hard turning operation. Addition of solid particles as an additive suspended into the base fluid is a technique for the heat transfer enhancement. Nanoparticles present into base fluid acts as solid additive which increases the thermal conductivity of nanofluid and results to lower the cutting forces. From S/N ratio plot of Fx, it is observed that Fx is least when Hardness is 35 HRC, 400 RPM Speed, 0.05 mm/rev Feed, 0.1 mm DOC and Nanofluid as a coolant condition. This same pattern is found to be valid for Fy and Fz. The relative importance of input parameters affecting the Fx can be judged by computing the response table for means which ranks the process parameters according to their individual effect on the response. In this work it is found that, the factor which affects the Fx most is Machining conditions, followed by Speed, Feed, DOC and material hardness respectively. Same ranking has been observed for Fy and Fz. The S/N ratio plots for Fx is shown in figure 4.1.

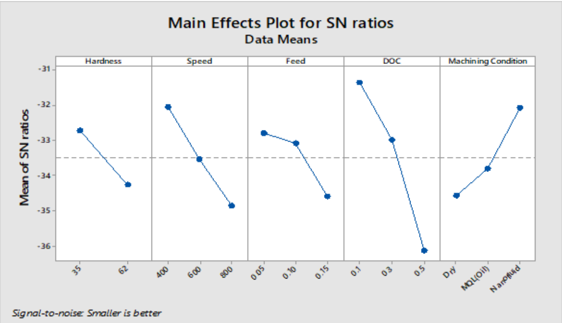

Figure 4.1 S/N ratio plot for Fx

4.2 Analysis of Ra:

Main Effects Plot of SN ratios for Average Ra shows that, good surface finish is obtained for the material with lower hardness i.e. 35 HRC. Surface roughness found to be improving with increase in speed form 400 RPM to 600 RPM. Surface roughness found to be increasing with increase in feed and DOC for hard turning of AISI 52100. The surface roughness Ra is less for 0.05 mm/rev feed and 0.1 mm DOC. Also it is evident that machining condition of MQL with Nanofluid is best in order to improve the surface finish of the turned components. The main effects of SN ratios of surface roughness are shown in figure 4.2.

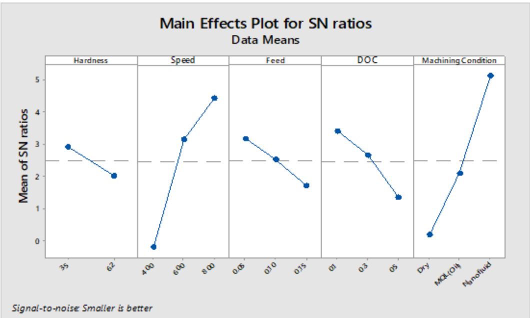

Figure 4.2 S/N ratio plot for Ra

4.3 Analysis of Vibration:

Main Effects Plot of SN ratios for vibration acceleration (mm/sec^2) shows that, vibration acceleration is less for the material with lower hardness i.e. 35 HRC. Vibration acceleration found to be worsening with increase in speed form 400 RPM to 600 RPM. Vibration acceleration found to be optimal at the feed of 0.10 mm/rev. The vibration acceleration is found to be optimal for 0.3 mm DOC. Also it is evident that machining condition of MQL is best suited in order to reduce the vibration acceleration of the turned components. The main effects plot of S/N ratios of vibration acceleration is shown in figure 4.3.

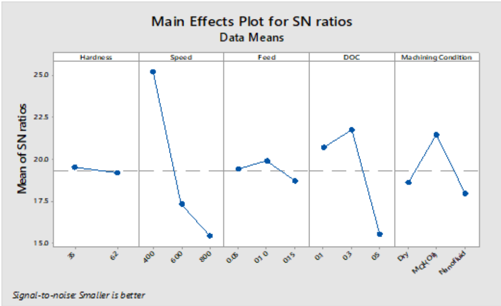

Figure 4.3 S/N ratio plot for Vibration acceleration (mm/sec^2)

5. OPTIMIZATION OF PARAMETERS USING GRG

Grey Relation Grade analysis is used to optimize the process parameters for the Finish turning of AISI 52100. GRG analysis is the effective tool for multi attribute decision making which converts the multiple responses into a single grade. Following steps are followed to calculate the GRG and multi attribute decision making:

Step 1: Calculation of S/N ratio for given observations. In turning process, the objective is to reduce the cutting forces, vibrations, and surface roughness. Hence smaller the better criteria has been applied for cutting forces, vibrations, and surface roughness.

Step 2: Normalization of data.

Step 3: Computation of Grey Relation co-efficient

Step 4: Computation of Grey Relational Grade.

Step 5: Taguchi analysis of GRG to get the optimal parameter setting.

The main effects plot for SN ratios of GRG is shown in the Figure 4.4. From the main effects plot it is observed that the optimal parameter setting in finish turning of AISI 52100 is hardness at 35 HRC, speed at 400 RPM, feed at 0.05 mm/rev, DOC of 0.1 mm and cutting conditions of MQL with Nanofluid produces the optimal GRG.

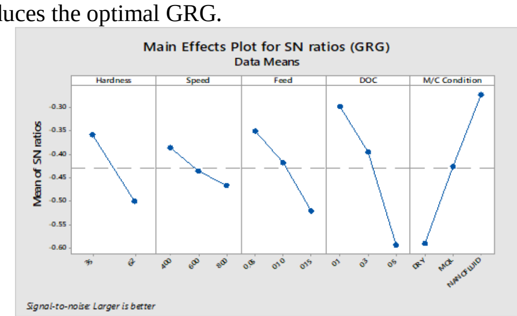

Figure 4.4 S/N ratio plot for GRG

6. CONCLUSION

In this work experimental analysis of finish turning of AISI 52100 has been carried out using Taguchi method to study the effect of process parameters on cutting forces, surface roughness and machine vibration. Taguchi orthogonal array L18 has been used for conducting the experiments and responses are measured using standard measuring instruments and response data is analyzed. Optimal setting of process parameters has been found out by Grey analysis. Following conclusions have been drawn from this study.

- The Feed Force (Fx) is strongly affected by machining conditions, followed by speed, feed, DOC and material hardness. Same pattern has been observed for Fy and Fz.
- The best surface finish was achieved at lower feed rate, highest cutting speed and machining conditions of MQL with Nanoparticles.
- It is found that the cutting speed, depth of cut, and machining conditions have greater influence on machine vibration.
- Addition of solid Nanoparticles as an additive suspended into the base fluid found to be effective to reduce the cutting forces and to improve the surface finish of turned components.

Optimal parameter setting for finish turning of AISI 52100 has been found out by Taguchi analysis of GRG. It is observed that process parameters setting of hardness at 35 HRC, speed at 400 RPM, feed at 0.05 mm/rev, DOC of 0.1 mm and cutting conditions of MQL with Nanofluid produces the highest GRG.

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