Study on The Effect of Vibration on Surface Quality When High-Speed Machining of H13 Tool Steel

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Abstract

This experimental study presents the effect of vibration on surface quality when end milling of AISI H13 hot work tool steel using vertical CNC milling machine with a high speed adapter. Samples were milled using trochoidal tool path strategy with TiAlN coated flat end mill. Stepover (*So*), trochoidal width (*Tw*) and trochoidal ahead (*Ta*) was determined as three variables of milling parameters. Spindle speed, depth of cut and feed rate was kept constant to better observe the effect of tool path strategy on vibration and surface quality. L16 orthogonal array was selected the most suitable design for the experimental setup using Taguchi method and experiments were performed according to the specified array under dry conditions. Vibration values (G, m/s^2) were recorded simultaneously from both of the workpiece and accelerator adapter during the tests. Besides, vibration measurements were repeated under the same conditions before the milling, without chipping such as simulation, to observe the effect of cutting force on workpiece and adapter behavior. Surface roughness (Ra) were measured from different areas of the milled surface and determined as the average of these values. The optimum tool path parameters providing the minimum vibration and surface roughness values were determined with *the smaller-the better* approach from analysis of the results by using S/N ratio. The minimum surface roughness was measured as 0.2 μm and minimum vibration value was 0.064 mm/s^2. It was concluded that average vibration value increased by %30 for the adapter and %17.3 for the workpiece when tool in chipping. In general surface roughness increased by increasing the vibration values. $So_3Tw_3Ta_4$ and $So_1Tw_4Ta_1$ combinations were found the best trochoidal milling parameters for the minimum vibration and roughness value, respectively. Impact ranking of the parameters was found for vibration as $Ta>Tw>So$ and for surface roughness as $Tw>So>Ta$.

Key words: High-speed machining, Trochoidal tool path, Vibration, Surface roughness

1. Introduction

The main objective of all manufacturing processes is to achieve the desired geometry and precision finishing surface of workpieces. The surface quality depends on the workpiece material, machine tool, cutting parameters, spindle speed, feed rate, depth of cut, stepover ratio and other uncontrollable factors such as vibrations, occurs during the machining process between workpiece and cutting tool. These undesired external factors adversely affect the dimensional accuracy, surface quality and tool life and have a very complicated structure. It is essential to get a lot of experimental data for determine optimum machining parameters and relationships between these parameters correctly during the metal removal process.

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With the development of new technologies in modern metal removal methods such as High-speed machining (HSM), it has become possible to obtain the desired geometry and surface quality by reducing or completely eliminating additional operations especially for the milling of hard materials commonly used in mold manufacturing. It is a well-known fact that the surface quality improves by increasing the cutting speed but there are also negative effects such increasing the vibration stem from many different factors, e.g. longer tool length, multipart tool holder systems, high workpiece hardness, small depth of cut and other imbalances [1]. Vibration is undesirable factor in industrial applications. Especially High-speed machining technology requires high levels of rigidity, rigid spindles with very low vibration characteristics and balanced tool holders [2]. In addition to the adverse effect on the surface quality, tool life is reduced and noise is become when vibration value above certain limit.

So the monitoring and controlling of vibration formation during machining has been the main objective in a number of studies using different materials, tools and analysing methods when the vibration value exceeds a certain limit and influences workpiece surface quality. A finite element model was built by Ostasevicius et al. [3] for comparising the effect of vibration and non vibration milling on finish surface using qualitative and quantitative characterization methods. Surface roughness was found one grade lower in high-frequency vibration milling than the conventional process of difficult to cut materials. Lacerda and Lima [4] applied analytical method to predict the occurrence of chatter vibration between cutter and workpiece. Experimental results were found very compatible with predicted tool behaviour. Toh [5] analysed vibration formation for the different tool path orientations in rough and finish HSM of AISI H13 using fast Fourier transform (FFT) method. For rough milling vibration effect was little or not observed when up milling orientation compared to down milling. Lee et al. [6] simulated the machined surface roughness using acceleration signal in high-speed end milling. Simulated vibration values were found similar with experimental results. From tool to workpiece vibration transmission during chatter formation was analysed by Rubio [7] with accelerometer on the workpiece and inductive sensor near the tool. Shajari et al. [8] investigated the effect of tool path strategies on cutting force and surface quality when milling of convex surfaces. Radial strategy has given the lowest cutting force and best surface, while the spiral one given the highest cutting force and worst surface quality. Toh [9] studied on the tool path strategies in high speed rough machining of AISI H13 tool steel to achieve high volume metal removal. Raster tool path was found the most suitable in terms of the long tool life, high volume metal removal and short machining time. In another sudy Toh [10] examined the effect of tool path orientations on tool life, cutting force and surface quality during the milling of inclined surfaces. Tool life was found longer in the horizontal downward orientation at 45º or above workpiece inclination angle. Yılmaz et al. [11] studied on the optimization of cutting parameters affecting the vibration and surface roughness using Taguchi method. Feed rate was found most dominant variable on quality characteristics. Otkur and Lazoglu [12] modelled the engagement effect in trochoidal milling with analytical approach for defining the cutting forces. Also, double trochoidal milling was analysed and measured forces were compared with predictions. Effects of milling parameters on vibration, cutting forces and surface quality were investigated by Dilipak and Yılmaz [13]. They concluded that vibration has negative effect on surface quality.

As seen in the literature review above there are meager study focused on the tool path strategies and effects on the vibration and surface quality. This experimental study intended for better understand the effect and interaction of different trochoidal tool path variables. Having a difference from other studies, AISI H13 samples were subjected to High-speed milling using vertical CNC milling machine, has been gained High-speed machining ability with a high speed adapter. Experimental setup was created using Taguchi method for determining the optimum trochoidal milling variables for better surface. Experiments were performed using trochoidal tool path strategy under dry conditions with TiAlN coated flat end mill.

2. Experimental Procedure

2.1. Workpiece material, tooling and other equipments

AISI H13 hot work tool steel was used as a workpiece material in the experiments for widespread use in die and mold industries at a hardness of approximately 52 HRC. Because of the lower depth of cut was selected, samples were pre-milled to clear the traces of cuts after cutting in the form of a 50x40x30 mm (l-w-t) rectangular prism. Cutting experiments were carried out on Taksan TMC-500 V vertical CNC machine with a maximum spindle speed of 6000 rev/min. High-speed machining ability was obtained by using a BIG/BBT40-GTG5-8-154 high speed tool holder. In this way, performance and productivity of existing conventional machine was increased multiplying the spindle speed by 4.67 times.

A holder apparatus was designed for the coolant inlet of adapter and attached on the CNC machine body as can be seen in the Fig. 1. All tests were done without coolant using 8 mm diameter, TiAlN coated SECO JH930 R020-Mega carbide end mills, and chips were blew out with air.

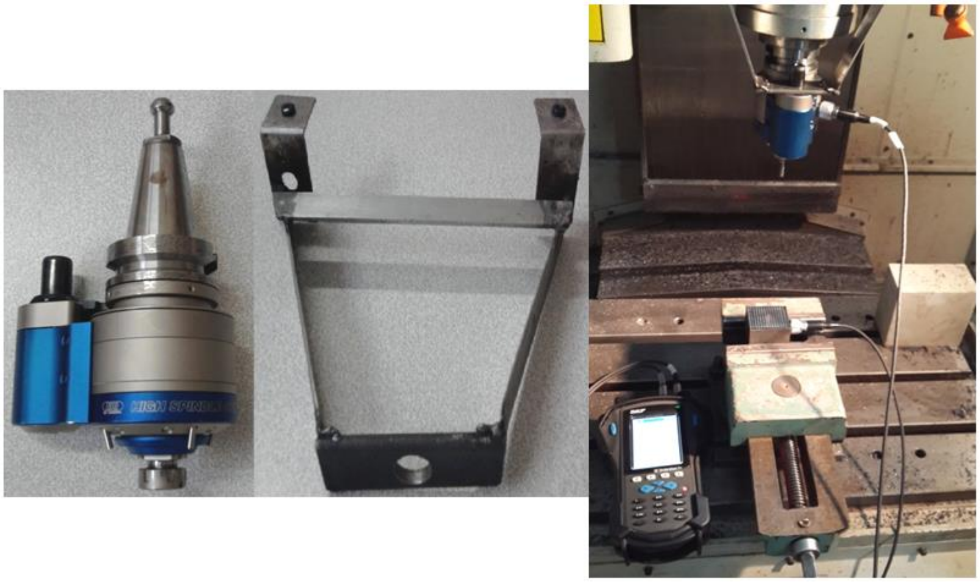


Figure 1. High speed adapter, holder apparatus and vibration measurement.

Vibration measurements (RMS G, m/s^2) were taken from both of the adapter and workpiece using two accelerometer sensors with SKF CMXA-45 portable microlog advisor see in Fig. 1 which provide three channels, a frequency range of 40 kHz F_{max} and up to 12800 lines of resolution. Vibration values were also recorded at the same cutting parameters without machining namely unchipping for the comparison and determine the effect of cutting force on vibration.

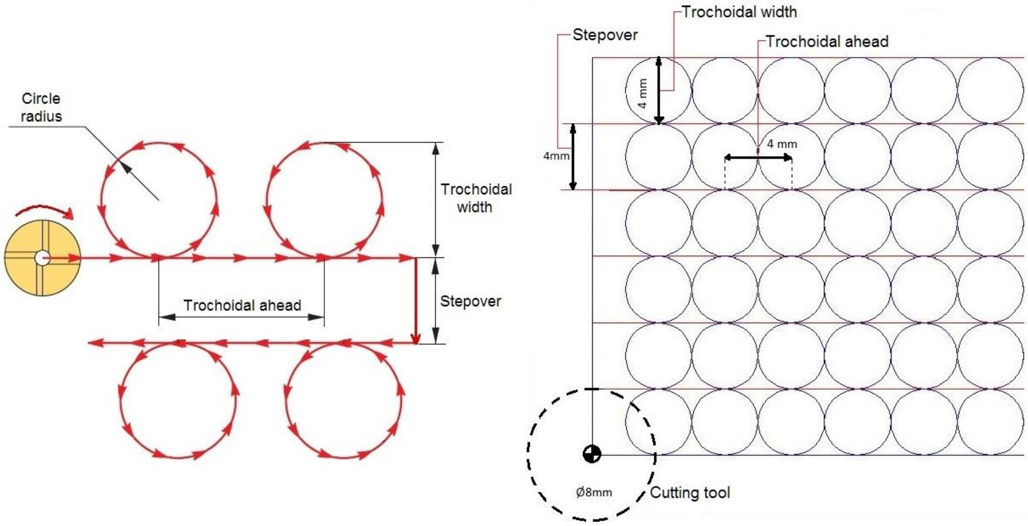


Figure 2. Trochoidal tool path trajectory and an example of 4x4x4mm (*So*-*Tw*-*Ta*).

Surface roughness (Ra) of machined surfaces was measured using a portable Mitutoyo Surftest-201 with 0.8 mm cut-off and 2.4 mm sampling distance. Roughness value was determined as the average of measurements, taken from three different points of same and vertical direction of tool path.

Table 1. Trochoidal tool path variables and levels.

Levels	*Stepover (mm)*	*Trochoidal Width (mm)*	*Trochoidal Ahead (mm)*
1	3.5	2.5	2.5
2	4	3	3
3	4.5	3.5	3.5
4	5	4	4

Trochoidal tool path strategy is important feature in High-speed machining technology to increase the productivity and tool life keeping high volume of the removal chip, especially at high depth of cuts and slots which larger than the cutting tool diameter. In this strategy cutting tool moves on material surface in a sequence of continuous circular direction with a uniform linear motion and constant radius. The geometry of the tool path basically consists of trochoidal ahead (*Ta*), trochoidal width (*Tw*) and stepover (*So*) as seen in Fig. 2 and the effect of different values of these variables on vibration is inevitable. So three variables of milling parameters and four different levels were determined in this study (Table 1) and tool paths were generated by SolidCam commercial software. Spindle speed (16000 rev/min), depth of cut (0.1 mm) and feed rate (3000 mm/min) was kept constant to better observe the effect of tool path strategy.

2.2. Design of experiment

As distinct from conventional method that uses the ‘trial and error’ approach to achieve best surface, making low number of experiment in a short time is possible by Taguchi method. This method based on orthogonal arrays (OAs) and consists of following stages; selecting the suitable OA according to the variables and levels, conducting the experiments, analyzing test results, determining the optimum condition and its confirmation test. L16 (4^3) orthogonal array was defined the most suitable design for this study and experimens were performed as shown in Table 2.

Table 2. Experimental conditions based on L16 orthogonal array.

Test Number	*Stepover (mm)*	*Trochoidal Width (mm)*	*Trochoidal Ahead (mm)*
1	5	4	4
2	5	3.5	3.5
3	5	3	3
4	5	2.5	2.5
5	4.5	4	3.5
6	4.5	3.5	4
7	4.5	3	2.5
8	4.5	2.5	3
9	4	4	3
10	4	3.5	2.5
11	4	3	4
12	4	2.5	3.5
13	3.5	4	2.5
14	3.5	3.5	3
15	3.5	3	3.5
16	3.5	2.5	4

In Taguchi methodology, there are three types of quality characteristics, such as smaller-the-better, larger-the-better, and nominal-the-better. For each type of the characteristics, the higher signal to noise (S/N) ratio gives the better results. Therefore the optimum machining parameters are found in the level that has the highest S/N value. Because the purpose of this study is to provide minimum vibration and roughness value, *the smaller-the-better* quality characteristic was defined. The S/N ratio for this characteristic (dB) is calculated as follows:

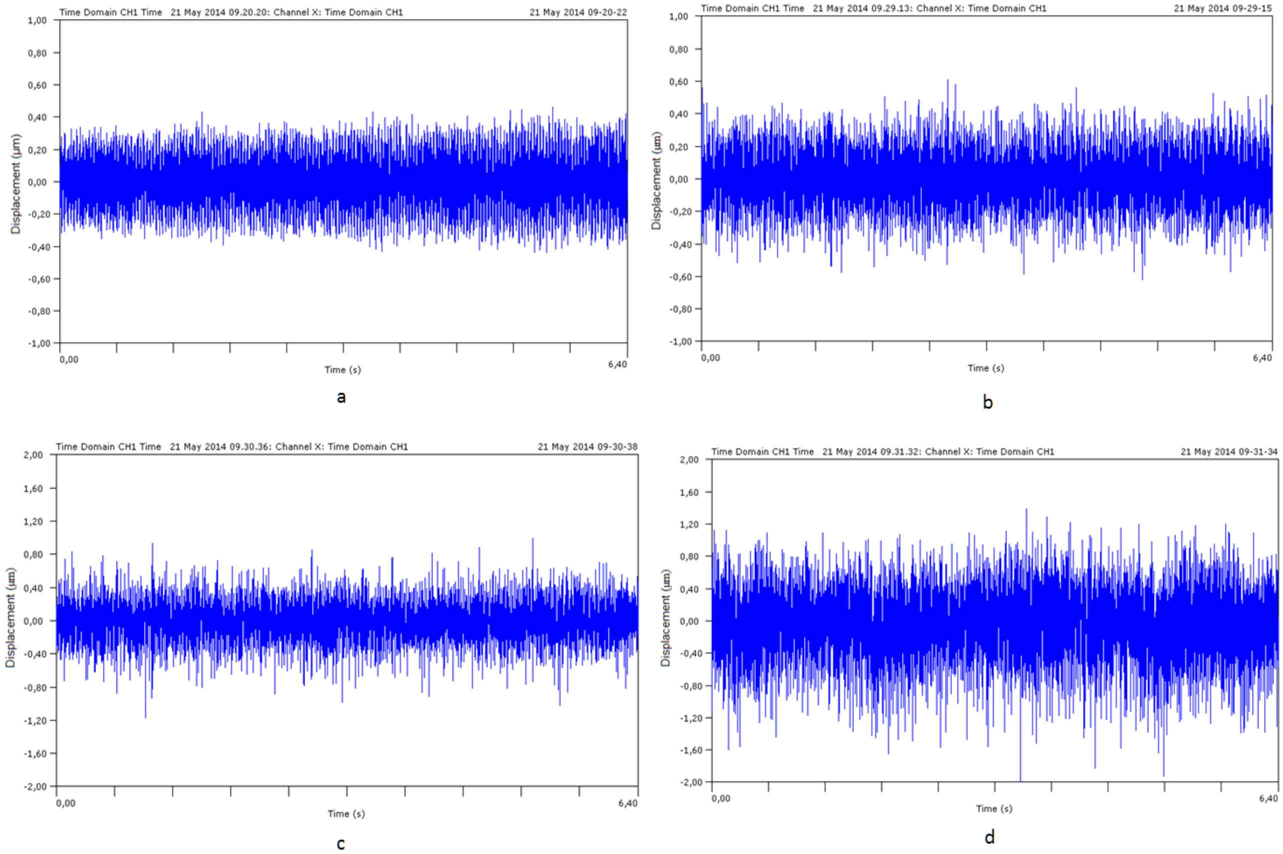
$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^{2}\right)$$

where n is the number of tests, y_i is the measured roughness value for the ith test, and i is the test number.

3. Results

3.1. Vibration and roughness results

Vibration measurement was taken from adapter at four different spindle speeds at constant axis to observe vibration behavior in the face of incremental spindle speed before the machining tests. Displacement was increased with the incerasing values of spindle speed which was found at 1000 rev/min as 0.4 µm, at 2000 rev/min as 0.6 µm, at 3000 rev/min as 0.9 µm and at 4000 rev/min as 1.4 µm. It was observed in Figure 3 that the patterns formed in each period are non-repetitive and dissimilar. Therefore the source of vibration is not only from the rotation of the shaft, mainly other disruptive surrounding factors (e.g. mechanical slackness or gaps between the planet gears). A constant spindle speed (3426x4.67=16000 rev/min) was selected during the experiments for reducing the effect of these negative factors and provide the low displacement value.



a b c d

Figure 3. Waveform graphs at different spindle speeds a)1000, b)2000, c)3000, d)4000 rev/min.

An example spectrum graphs in Figure 4 project the alteration of vibration values during chipping and unchipping conditions for test number 8. Figure 4-a illustrates unchipping, c-chipping condition for high speed adapter and b-unchipping, d-chipping condition for workpiece. At the begining of the graph c and d, vibration values have the highest value just before the cutting tool in chipping and then reducing slowly because the tool start to chip removal and resulting cutting forces play a little role for balancing.

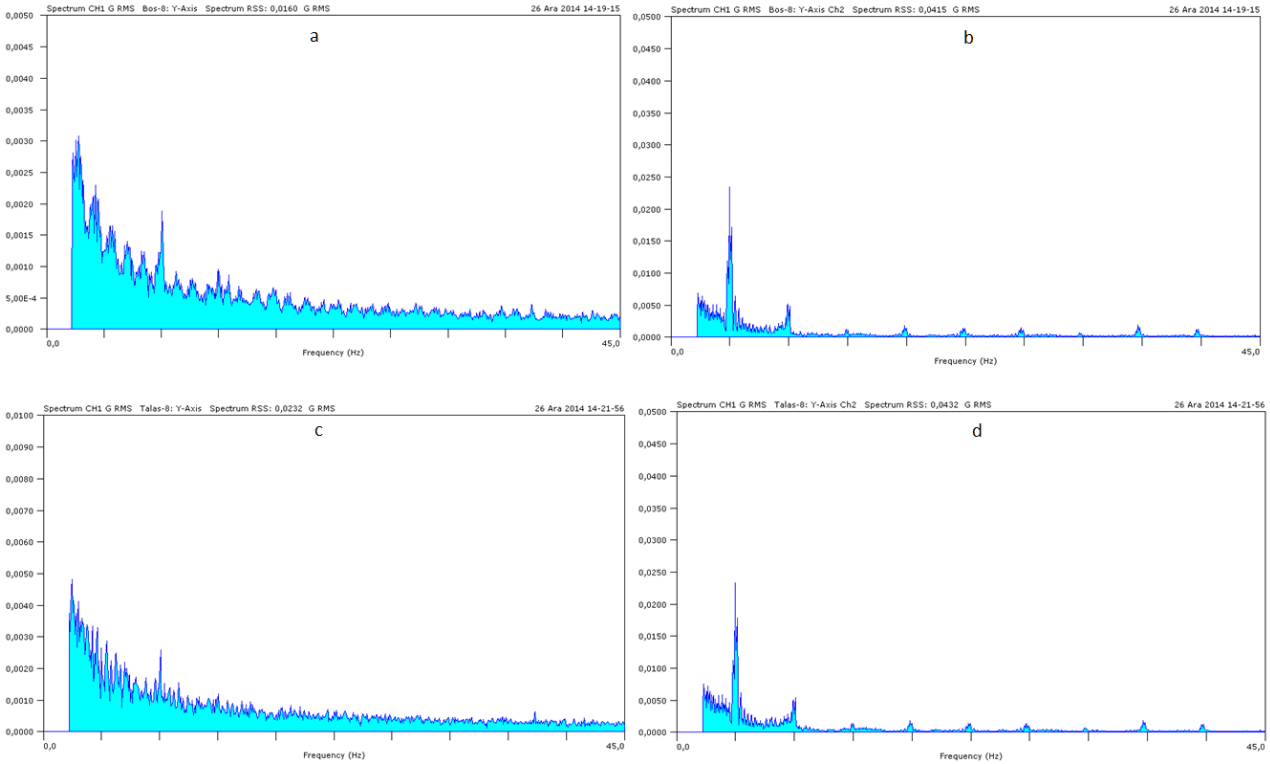


Figure 4. Vibration graphs of test number 8 for high speed adapter (a,c) and workpiece (b,d).

Table 3. S/N results of workpiece vibration (x10^{-2} m/s^{2}) and roughness values.

Test number	*Adapter (unchipping)*	*Workpiece (unchipping)*	*Adapter (chipping)*	*Workpiece (chipping)*	*S/N ratio dB*	*Surface Roughness µm*	*S/N ratio dB*
1	0.0468	0.0255	0.0603	0.0713	62.9333	0.231	12.7278
2	0.0344	0.0327	0.0366	0.0845	61.4660	0.298	10.5157
3	0.0370	0.0998	0.0201	0.0390	68.1809	0.341	9.3449
4	0.0359	0.1212	0.0582	0.1638	55.7121	0.341	9.3449
5	0.0211	0.0740	0.0215	0.0895	60.9674	0.230	12.7654
6	0.0272	0.0565	0.0212	0.0064	83.8764	0.310	10.1728
7	0.0236	0.0781	0.0503	0.1314	57.6301	0.305	10.3140
8	0.0391	0.1316	0.1442	0.1833	54.7349	0.398	8.0023
9	0.0321	0.0628	0.0282	0.0896	60.9500	0.260	11.7005
10	0.0381	0.1055	0.0511	0.1595	55.9464	0.288	10.8122
11	0.0184	0.1033	0.0209	0.1162	58.6959	0.335	9.4991
12	0.0197	0.1052	0.0216	0.1110	59.0928	0.393	8.1121
13	0.0224	0.0705	0.0233	0.0949	60.4519	0.201	13.9361
14	0.0213	0.1019	0.0197	0.1111	59.0849	0.266	11.5024
15	0.0219	0.1140	0.0183	0.0520	65.6783	0.315	10.0338
16	0.0355	0.0893	0.0219	0.1040	59.6568	0.325	9.7623

Similar situation, occurred in unchipping condition (graph a and b) can be explain as the reduction in deflection and vibration values by increasing of spindle speed from steady state after exceed the critical speed. In Table 3 average vibration values were noted down taken from adapter and workpiece in each chipping and unchipping conditions only except for initial highest values, because the first plunge of the tool into the workpiece have little effect on the surface quality. Higher vibration values were observed in chipping condition than unchipping. Average unchipping vibration value of adapter taken from all experiments was found as 0,297 mm/s^2 and 0,386 mm/s^2 for chipping condition. Unchipping workpiece vibration was found as 0,857 mm/s^2 and 1,005 mm/s^2 for chipping conditions. So it was concluded that average vibration value increased by %30 for the adapter and %17.3 for the workpiece when tool in chipping. These rates were too high when the lower depth of cut is considered.

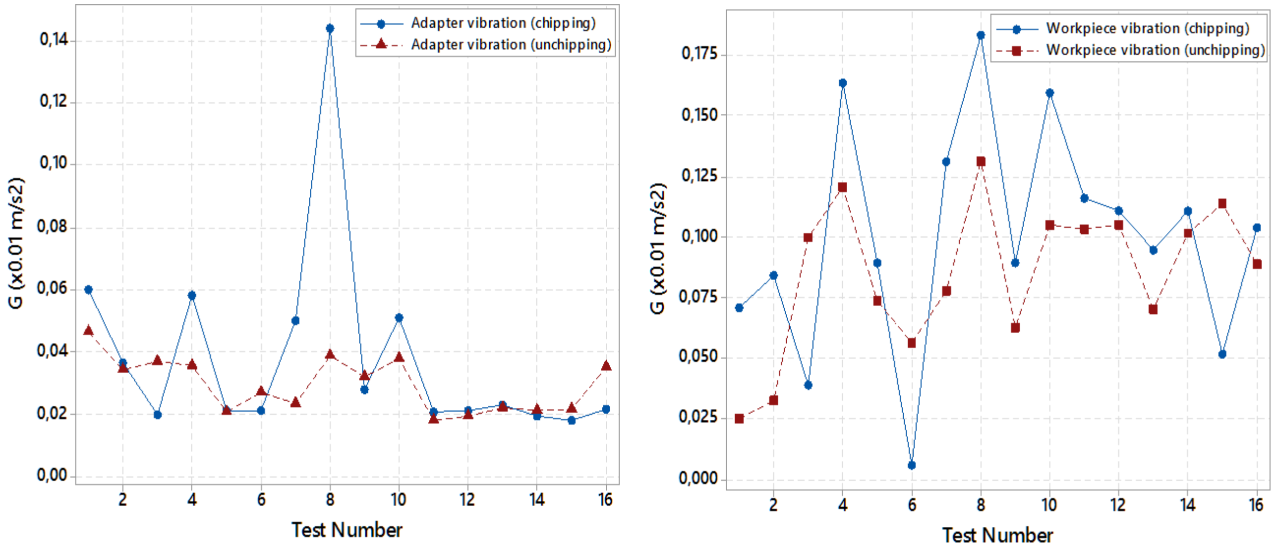


Figure 5. Comparison of vibration conditions for adapter and workpiece.

There was close correlation observed between vibration and surface quality for workpiece and adapter. Because the rate of increment was lower, workpiece vibration values in chipping condition were taken into account for calculating the S/N ratios and results of vibration and surface roughness were shown in Table 3. Maximum vibration was measured 1.833 mm/s^2 from test number 8 and minimum was 0.064 mm/s^2 from test number 6. Maximum surface roughness was measured 0.398 µm from test number 8 and minimum was 0.201 µm from test number 13. It can be seen very close relationship between the adapter vibration and surface quality for test number 8. Other vibration conditions for adapter and workpiece were compared in Figure 5 and Figure 6. In general it was observed surface roughness increased by increasing the vibration values. For the test number 8, maximum vibration caused to maximum roughness value. Lower trochoidal width and higher values of stepover and trochoidal ahead were caused to higher vibration and roughness values. There are some reasons such as increasing the volume of removal chip and the effect of sudden deceleration and acceleration between transitions of the tool paths that more evident especially at higher values of *So* than tool radius. Surface quality was improved when the tool is passed over and milled again on a machined area at lower *So, Ta* and *Tw* values.

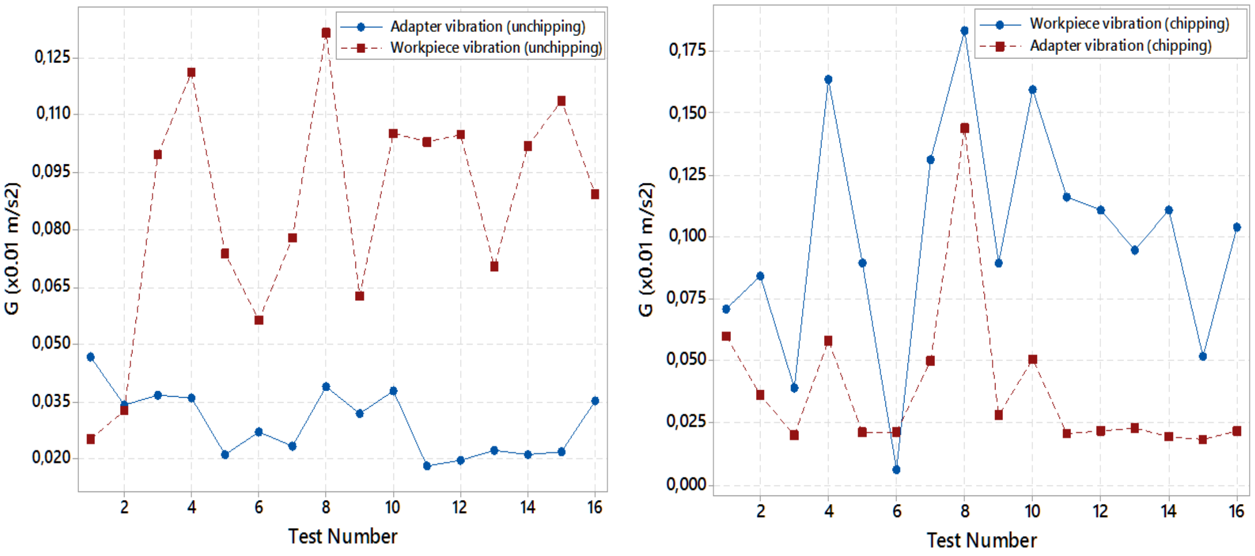


Figure 6. Chipping and unchipping vibration conditions for adapter and workpiece.

3.2. Optimization of tool path variables

According to the results in Table 3, optimum trochoidal tool path variables were determined where the highest value of S/N ratio indicates the optimum level of variables as seen in Figure 7. $So_3Tw_3Ta_4$ combination was found for minimum vibration and $So_1Tw_4Ta_1$ combination was found for minimum surface roughness as the best tool path parameters. Because of these optimum levels have already done with test number 6 and 13 there was not need to perform the confirmation test. Impact ranking was found for vibration as $Ta>Tw>So$ and for surface roughness as $Tw>So>Ta$, shows that the order of most effective parameters on aimed outputs.

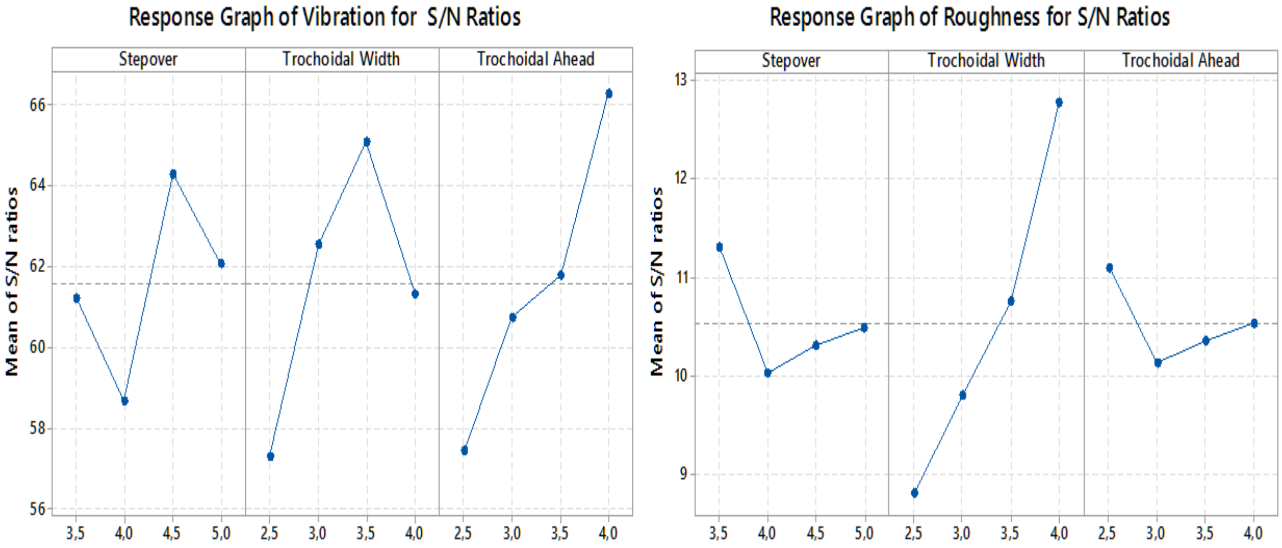


Figure 7. S/N response graph of vibration and surface roughness.

4. Conclusions

In this study trochoidal tool path variables were optimizated in terms of the vibration which an important issue for surface quality of high speed machined parts. It was observed that displacement value of adapter increased by nearly %50 at the each 1000 rev/min increment of spindle speed. The highest vibration values were obtained when tool in chipping especially at the first plunge into the workpiece. Average vibration value increased by %30 for the adapter and %17.3 for the workpiece when tool in chipping because increasing of the probable cutting forces. Close correlation was observed between vibration and surface quality and surface roughness were increased with increasing the vibration. $So_3Tw_3Ta_4$ and $So_1Tw_4Ta_1$ combinations were found the optimum levels of trochoidal tool path variables for the minimum vibration and roughness value, respectively. Impact ranking of the trochoidal parameters was found for vibration as $Ta>Tw>So$ and for surface roughness as $Tw>So>Ta$.

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