Optimization of Machining Parameters for Vibration Assisted Turning of Ti6Al4V Alloy Using Analysis of Variance

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Abstract. In this study, Taguchi-based Analysis of Variance (ANOVA) is adopted for optimization of Vibration Assisted Turning (VAT) process parameters of cutting speed, frequency, amplitude and Feed rate. The machining parameters are analysed by evaluating Maximum cutting force and Tensile maximum circumferential residual stresses (MCRS) in VAT of Ti6Al4V alloy. Finite Element simulations are performed in ABAQUS according to orthogonal array L_{27} to find the optimum condition for Maximum cutting force and MCRS (Tensile). Result shows that the vibrating parameters, frequency and amplitude are most significant for Maximum cutting force and MCRS (Tensile) respectively. The optimum condition is obtained at 30 m/min of cutting speed, 150 μm of amplitude, 600 Hz of frequency and 0.05 mm/rev of feed rate for cutting force while the optimum condition for MCRS(Tensile) is 45 m/min of cutting speed, 50 μm of amplitude, 200 Hz of frequency and 0.15 mm/rev of feed rate.

Keywords: Vibration Assisted Turning; Ti6Al4V alloy; Finite Element Modeling; ANOVA; Optimization.

1. Introduction

Ti6Al4V is the most commonly used material in aerospace, automotive and medical industry due to its inherent properties like high strength to weight ratio and its outstanding corrosion resistance. Machinability of Ti6Al4V alloy in conventional turning (CT) is very poor due to its high chemical affinity with cutting tool materials and low thermal conductivity which results in accumulation of heat generated during machining. Consequently, cutting tool causes rapid tool wear which results in poor surface finish and enhanced cutting forces. Vibration Assisted Turning (VAT) is a promising machining process for high strength materials in which vibrations are superimposed on movement of the cutting tool[1-2]. The fundamental feature of VAT is intermittent contact between tool and the workpiece at periodic intervals. This improves tool life and surface finish of machined component.

The stresses induced during machining remain even after the retrieval of the cutting tool from workpiece are termed as residual stresses. The generation of residual stresses is due to thermoplastic deformation of the workpiece. It may develop due to plastic deformation of material that occurs due to thermo-mechanical loads. The plastic deformation of workpiece and friction between chip tool interface act as main source of mechanical and thermal loads [3]. However, the stresses generated during machining can be either tensile or compressive. The residual stresses developed on machined surface will extend from surface of cut to certain depth will depends upon cutting conditions [4]. The tensile residual stresses generated on machined surface will have detrimental effect by initiating crack propagation. Hence the fundamental mechanism and nature of residual stresses that develop due to VAT should be analysed, to enhance the performance. Few researchers worked to optimize the machining parameters for generation of residual stresses. Fu et al. [5] studied the effect of depth of cut and tool geometry on residual stresses. They found that compressive residual stresses were developed with an increase in nose radius and rake angle. Capello et al. [6] investigated the effect of tool geometry and machining conditions on residual stresses in turning by developing the empirical methodology. In an another attempt, Naresh et al. [7] studied the effect of workpiece hardness on residual stresses and also discussed the variation of residual stresses in machined component from tensile to compressive with an increase in depth direction.

From the literature, it is found that there is no unique agreement between researchers with respect to the effect of machining parameters on the generation of residual stresses. It is also observed that very few works have discussed the optimization of machining parameters for minimum residual stress generation in VAT process. In this study, a 3D FE model is developed in ABAQUS for both CT and VAT. In this work an attempt is made to optimize the machining and vibration parameters for reducing maximum cutting force and tensile maximum circumferential residual stresses (MCRS). Taguchi experimental design is used for to design simulations for VAT of Ti6Al4V alloy. The results obtained from simulations are analysed with Analysis of Variance (ANOVA) to achieve the optimum machining condition. ANOVA is applied to know the most influencing input parameter on output responses. Finally, Confirmation tests i.e. FE simulations are performed at optimum conditions.

2. FE Simulation of Ultrasonic Vibration Assisted Turning

2.1. FE Model

A 3-D FE orthogonal machining model is developed using ABAQUS. The workpiece and cutting tool materials considered for this model are Ti6Al4V alloy and Tungsten carbide (WC) respectively. The workpiece is considered as isotropic plastic material whereas cutting tool is taken as rigid with rake angle 10o and clearance angle 5o.

In FE simulation, the type of element selected is, an eight-node, coupled temperature-displacement, trilinear brick element, C3D8RT in ABAQUS is used to facilitate both mechanical and thermal analysis with reduced integration and hourglass control. The workpiece is meshed with approximately 6800 elements with element deletion. The variation of force is minimum beyond 6800 elements in the developed model. In Vibration Assisted Turning, 20 kHz frequency and 15 µm amplitude is imposed on cutting tool. Figure 1 shows the relative movement between tool and workpiece in FE modelling of VAT process.

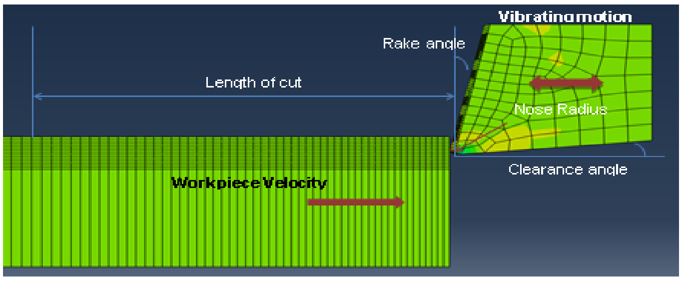

Figure 1: FE Modeling of orthogonal Vibration Assisted Turning

In this FE model, the workpiece moves with cutting speed,Vc is equal to 50 m/min. Kinematic boundary condition are applied to bottom, left and right side of workpiece and top surface is free. The kinematic condition for workpiece at top surface is V_x= V_c and V_y=0.The cutting tool is immovable for conventional turning whereas it vibrates harmonically in cutting velocity direction during ultrasonic vibration assisted turning simulations process as given by

$$v_x = -a\cos\omega t$$

$$v_y = 0$$

where angular velocity ω= 2πf,

The cutting tool vibration velocity = a ω sin ωt and (a ω =1885) > V_c (800 mm/s).This satisfy the condition for separation of cutting tool tip from workpiece chip during each harmonic ultrasonic vibrations.

2.2. Johnson Cook Material model data

The simulated results obtained from Jonson Cook (JC) material model are in close agreement with experimental results. This JC model considers the effect of material hardening at constant strain rate condition and strain rate effect due to thermal softening in an adiabatic heating condition. This JC model represented in Eq. (1) gives relation between the equivalent stress as a function of strain hardening, strain rate and thermal softening [8].

$$\sigma_{eq} = [A + B(\varepsilon)^n]\left[1 + C \times ln\left(\frac{\varepsilon^o}{\varepsilon_0^o}\right)\right][1 - (\frac{T - T_{room}}{T_{Melt} - T_{room}})^m] \tag{1}$$

2.3 Separation criteria and Damage equation

According to JC model, the chip separation and crack initiation in FE model is based on plastic strain at element integration point is given by Eq. (2)

$$\mathrm{D} = \sum\left(\frac{\Delta \epsilon_{\mathrm{p}}}{\epsilon_{\mathrm{f}}}\right) \tag{2}$$

Where D is damage parameters; $\Delta\epsilon_{\mathrm{p}}$ the incremental plastic strain which is updated at every analysis increment; ϵ_{f} is an equivalent plastic strain in damaged element and strain rate ϵ_{P} and temperature T as given by Eq.(3).

$$\epsilon_f = \left[D_1 + D_2\, exp\left(D_3 \frac{p}{q}\right)\right]\left[1 + D_4\, ln\left(\frac{\epsilon_P}{\epsilon}\right)\right][1 + D_5 T *] \tag{3}$$

The ratio of hydrostatic pressure to Von-Mises equivalent stress is p/q, T* is the homologous to the JC model equation. The damage parameters of JC model Di (i=1, 2, 3, 4, 5) for Ti6Al4V alloy are given in Table 1.

Table 1: Material Modeling and JC model parameters used in the simulation model [7]

<table>
<tr><td colspan="5">Density</td><td colspan="2">4420 kg/m^3</td></tr>
<tr><td colspan="5">Conductivity</td><td colspan="2">7.264 W/m-^{o}C</td></tr>
<tr><td colspan="5">Young's modulus</td><td colspan="2">114 GPa</td></tr>
<tr><td colspan="5">Specific heat</td><td colspan="2">526 kJ/kg- ^{o}C</td></tr>
<tr><td colspan="7">JC- Parameters</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td>n</td><td>m</td><td>Melting Temperature</td><td>Strain Rate</td></tr>
<tr><td>724.7</td><td>683.1</td><td>0.035</td><td>0.47</td><td>1</td><td>1650 ^{o}C</td><td>2000 s^{-1}</td></tr>
<tr><td colspan="7">Damage parameters</td></tr>
<tr><td>D1</td><td colspan="2">D2</td><td colspan="2">D3</td><td>D4</td><td>D5</td></tr>
<tr><td>-0.09</td><td colspan="2">0.28</td><td colspan="2">0.48</td><td>0.014</td><td>3.18</td></tr>
</table>

2.4 Model validation

A 3-D FE model developed for VAT process is validated with experimental results available in literature [7]. Variation in cutting force and cutting temperature are observed to be 3.2% and 8.04% respectively in case of CT compared to experimental results, whereas the same are found to be 7.2% for force and 3.1% for temperature respectively in case of VAT. Variation in equivalent stress is observed to be 3.9% for CT and 5.9% for VAT, which is less than 10% in all cases as shown in Table 2.

Table 2. Comparison of results from simulation and experimentation for CT and VAT

Process	Comparison	Stress (MPa)	Force(N)	Temp (^{o}C)
CT	Literature Experiment	-	153	410
	Literature simulation (2D)	1340	160	420
	Present simulation (3D)	1392	158	443
VAT	Literature Experiment	-	110	330
	Literature simulation (2D)	1360	140	265
	Present simulation (3D)	1279	102	340

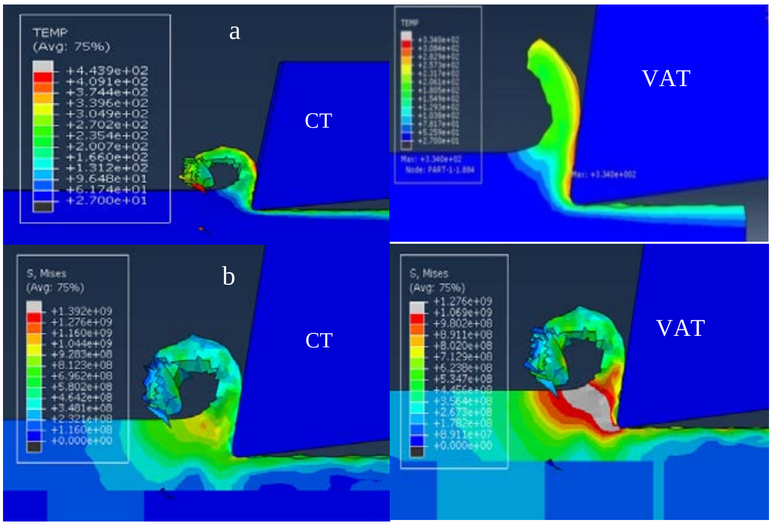

Figure 2: Comparison between CT and VAT (a).Cutting temperature (b). Equivalent stress.

2.5 Taguchi Experimental Design

Taguchi experimental design is an efficient and easy approach for process optimization and uses orthogonal array to analyse the machining parameters. The levels of machining parameters such as cutting speed, frequency, amplitude and feed rate are selected to cover wide range of machining conditions as given in Table 3. The selected parameters have no interaction among them. The response parameters considered for this work are maximum cutting force and tensile maximum circumferential residuals tresses (MCRS-Tensile). According to Stephanie Fraley et al. [8], Taguchi L27 (34) array with 4 control parameters with 3 levels is used for this study.

Table 3: Machining parameters and their levels for simulation with Ti6Al4V alloy

Parameters	Level 1	Level 2	Level 3
Cutting speed (A), m/min	30	45	60
Amplitude (B), µm	50	100	150
Frequency (C), Hz	200	400	600
Feed rate (D), mm/rev	0.05	0.1	0.15

3. Results And Discussion

The 3-D FE model is developed in ABAQUS and simulations are conducted to study the machining parameters such as cutting speed, frequency, and amplitude and feed rate on Max. Cutting force and MCRS (Tensile) in VAT of Ti6Al4V alloy. Table 4shows the simulation results of 27 trails from L27 array.

Table 4: Simulation results for Max. Cutting force and MCRS (Tensile) at various machining conditions

Trial no.	Speed (m/min)	Amplitude (μm)	Frequency (Hz)	Feed (mm/rev)	Max. Cutting Force (N)	MCRS (Tensile) (MPa)
1	30	50	200	0.05	190	410
2	30	50	400	0.1	180	435
3	30	50	600	0.15	172	445
4	30	100	200	0.1	175	431
5	30	100	400	0.15	180	436
6	30	100	600	0.05	150	449
7	30	150	200	0.15	165	435
8	30	150	400	0.05	151	460
9	30	150	600	0.1	145	462
10	45	50	200	0.1	210	374
11	45	50	400	0.15	182	388
12	45	50	600	0.05	162	402
13	45	100	200	0.15	187	405
14	45	100	400	0.05	177	429
15	45	100	600	0.1	168	440
16	45	150	200	0.05	175	401
17	45	150	400	0.1	168	407
18	45	150	600	0.15	158	416
19	60	50	200	0.15	224	358
20	60	50	400	0.05	174	378
21	60	50	600	0.1	165	381
22	60	100	200	0.05	228	477
23	60	100	400	0.1	215	475
24	60	100	600	0.15	200	452
25	60	150	200	0.1	193	385
26	60	150	400	0.15	178	397
27	60	150	600	0.05	150	422

3.1 Analysis of process parameters

In this technique, the output responses are transformed to average signal to noise ratio, delta, rank and optimum level. The average S/N is used to measure the deviation of the response from the mean value. The response that is to be maximized is called larger-the-better and response that is to be minimized is called smaller-the better. Rank is assigned to each factor according to its delta value. SNR characteristics, larger the better and smaller the better are calculated using Eqs. (4) and (5).

$$\eta = -10 \log_{10} \left(\frac{1}{n}\right) \sum_{i=1}^{n} \frac{1}{\sigma_i^2} \quad (4)$$

$$\eta = -10 \log_{10} \left(\frac{1}{n}\right) \sum_{i=1}^{n} {\sigma_i}^2 \quad (5)$$

where n represents the average SNR of simulated values indicates the simulated value of the i_{th} simulation. In order to observe the practical significance of machining parameters on responses Max.cutting force and MCRS (Tensile), ANOVA is performed at 95% confidence level. The larger value of percentage contribution indicates the most significant on output parameters.

3.1.1 Effect of parameters on maximum cutting force

The response data for SNR and ANOVA of maximum cutting force is presented in Table 5 and 6. From ANOVA results, it is observed that the influence of frequency (35.12% of contribution) on cutting force is more whereas the influence of amplitude (21.63% of contribution) and cutting speed (20.63% of contribution) is less on cutting force. Figure 3 shows the variation of cutting force with cutting speed, feed rate, amplitude and frequency.

Table 5: Response table for SNR of Max.Cutting Force

	Factors			
Level	Cutting speed (m/min)	Amplitude (µm)	Frequency (Hz)	Feed rate (mm/rev)
1	-44.45	-45.27	-45.71	-44.69
2	-44.90	-45.36	-44.99	-45.04
3	-45.58	-44.30	-44.22	-45.20
Delta	1.13	1.05	1.49	0.51
Rank	2	3	1	4
Optimum	1	3	3	1

Table 6: ANOVA table for Max. Cutting force using SN data

Factors	DOF	SSTR	MSTR	F – Test	% Contribution (P)
Cutting Speed	2	5.862	2.9310	10.25	20.69
Amplitude	2	6.128	3.0642	10.72	28.63
Frequency	2	9.950	4.9752	17.40	38.12
Feed rate	2	1.248	0.6239	2.18	4.40
Error	18	5.146	0.2859		8.16
Total	26	28.334			100.00

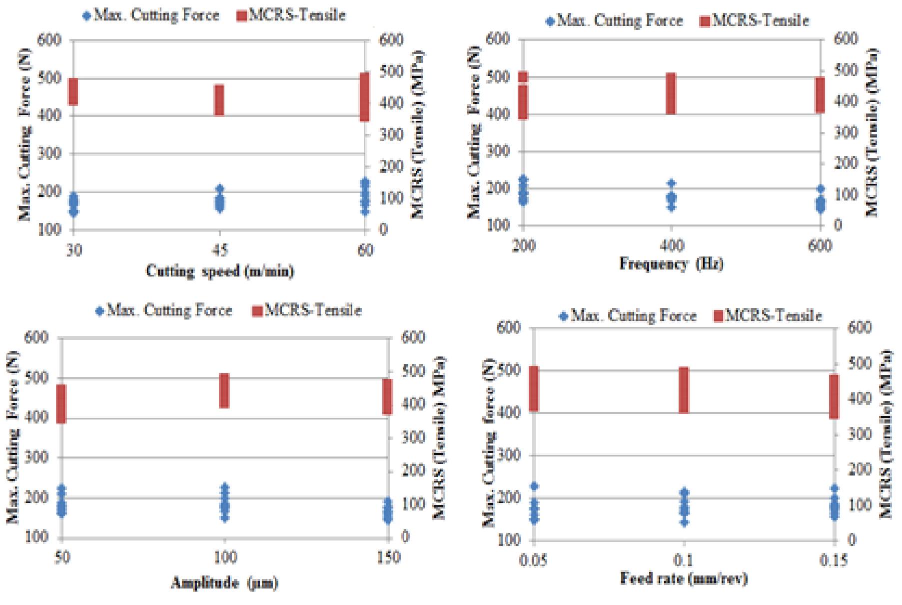

Figure 3: Variation of Max.cutting force and MCRS (Tensile) with (a). Feed rate (b). Cutting speed (c). Amplitude (d).Frequency

As the frequency increased, it causes reduction in force due to less time of contact which allows the reduction in friction due to the pulsating characteristics of VAT. Hence, in VAT process frequency is more influencing parameter compared to other parameters. As the cutting speed increases, the rate at which workpiece interacting with the cutting tool also increases which in turn increases the friction and so the cutting force. Therefore, lower value of cutting speed is preferred for low cutting force. As the amplitude value increases, the time of lapse also increases which allows the workpiece to relieve its stresses causing less cutting force. Therefore higher value of amplitude is preferred. As the feed increases, the cutting force increases due to the higher interaction time at certain positions. So, lower value of feed is preferred.

3.1.2 Effect of machining parameters on MCRS (Tensile)

Table 6 and 7 depicts the influence of each process parameter on MCRS (Tensile). From ANOVA results, it is observed that the influence of amplitude (37.74% of contribution) is more on MCRS (Tensile). Figure 3 shows the variation of MCRS on cutting speed, feed rate, amplitude and frequency. The lower values of MCRS (Tensile) are obtained at lower values of Cutting speed and amplitude whereas these are obtained at higher values of frequency and feed rate.

Table 6: Response table for SNR of Max.Cutting Force

	Factors			
Level	Cutting speed (m/min)	Amplitude (μm)	Frequency (Hz)	Feed rate (mm/rev)
1	-52.87	-51.95	-52.19	-52.55
2	-52.18	-52.93	-52.50	-52.46
3	-52.29	-52.46	-52.65	-52.33
Delta	0.69	0.98	0.46	0.22
Rank	2	1	3	4
Optimum	2	1	1	3

Table 7: ANOVA table for cutting force Fc using SN data

Factors	DOF	SSTR	MSTR	F – Test	% Contribution (P)
Cutting Speed	2	2.4657	1.2329	6.34	21.42
Amplitude	2	4.3448	2.1724	11.17	37.74
Frequency	2	0.9809	0.4904	2.52	29.52
Feed rate	2	0.2212	0.1106	0.57	1.92
Error	18	3.4996	0.1944		9.40
Total	26	11.5121			100

MCRS (Tensile) mostly occurs in the forward movement of cutting tool onto the workpiece. If the amplitude is low, the speed with which it comes would be lower causing less impact on the workpiece there by lowering the MCRS (Tensile). For minimizing MCRS, lower speeds are preferred as the heat generated in the workpiece is less which is the main source for generating tensile MCRS.

3.2 Optimum Design

The SSTR is used to quantify the variation between the treatment groups and error sum of squares (SSE) which is calculated from Eq. (4) [4].

$$\mathrm{SSE} = (y_1 - 1)x_1^2 + (y_2 - 1)x_2^2 + \cdots + (y_n - 1)x_n^2 \tag{6}$$

where ‘‘n” indicates each individual factor, ‘‘x2” indicates variance and ‘‘y” indicates number of observations in the nthfactor. The optimum levels of machining parameters are calculated with the help of response data from S/N ratio. The predicted output responses at optimum levels of control parameters are obtained by using the Eq. (5).

$$\mathrm{X} = \overline{\mathrm{X}} + (\overline{\mathrm{A_o}} - \overline{\mathrm{X}}) + (\overline{\mathrm{B_o}} - \overline{\mathrm{X}}) + (\overline{\mathrm{C_o}} - \overline{\mathrm{X}}) + (\overline{\mathrm{D_o}} - \overline{\mathrm{X}}) \quad (7)$$

Maximum Cutting force $$\mathrm{F_c} = 10^{\frac{-\mathrm{x}}{20}} \quad (8)$$

MCRS (Tensile) $$\sigma_{\mathrm{TR}} = 10^{\frac{-\mathrm{X}}{20}} \quad (9)$$

3.3 Confirmatory test

The confirmatory test is conducted through FE simulation model which is already validated through experimental values. These simulations are done at optimum machining parameters i.e V= 30 m/min, a= 150 μm F=600 Hz and f=0.05 mm/rev of feed rate for maximum cutting force and V=45 m/min, a=50 μm, F=200 Hz and f=0.15 mm/rev for MCRS(Tensile) for output responses. Then the predicted values from Eqs. (5) to (7) are compared with simulated values as shown in Table 8.

Table 8: Predicted and simulated results

	Predicted value	Simulated value	% error
Max cutting force	151.2	137.2	9.1
MCRS (Tensile)	424.1	395.3	8.7

4. Conclusions

The influence of cutting speed, frequency, amplitude and feed rate on Maximum cutting force and MCRS (Tensile) are analysed using ANOVA and following conclusions are drawn from this study. Cutting force, cutting temperature and equivalent stress developed in VAT process are less when compared to CT due to relaxation between tool and workpiece in VAT

ANOVA at 95% confidence level, gives frequency as the most significant parameter for maximum cutting force while amplitude as most significant parameter for MCRS (tensile).

The optimum condition is obtained at 30 m/min of cutting speed, 150 μm of amplitude, 600 Hz of frequency and 0.05 mm/rev of feed rate for maximum cutting force while the optimum condition for MCRS (tensile) is 45 m/min of cutting speed, 50 μm of amplitude, 200 Hz of frequency and 0.15 mm/rev of feed rate.

5. References

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