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Investigation of Machining Parameters in Thin-Walled Plate Milling Using a Fixture with Cylindrical Support Heads

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Construction, processing, biomedical instruments, electronics, automobiles, and aerospace widely use thin-wall parts. Mostly, these thin-walled parts are machined using either a peripheral milling machine or an end milling machine with the help of fixtures. In this study, three different material thin-walled parts (i.e., Inconel 718, AISI 316L, and Al 6061) are machined in end milling using a newly designed fixture with cylindrical heads, and the surface roughness and deformation with different machining parameters are compared. The optimum values of the machining parameters feed, speed, and depth of cut have been found to improve the surface roughness of thin-walled plates by arresting the deformation using the proposed fixture. Analysis of variance (ANOVA) results show that the speed is the most influential parameter in the case of displacement for AISI 716L and Al 6061, feed is the most influential parameter in the case of surface roughness for Inconel 718 and AISI 716L, and speed is the most influential parameter in the case of displacement and surface roughness for Al 6061. The use of fixtures provides a significant reduction in the deformation and surface roughness during the machining in end milling machine.
Keywords: end-milling, fixture, surface roughness, deformation

Highlights
- *A new milling fixture with sliding jaws was designed and developed to reduce the surface roughness in workpieces.*
- *The experimental model is verified with the three levels of input parameters.*
- *The experimental result values of displacement and surface roughness correlated well with the simulated displacement values.*
- *The cylindrical support heads in the milling fixture reduce the surface roughness to a greater extent.*

0 INTRODUCTION

Thin-walled parts are widely used in the automobile industry, aerospace, precision processing, and medical care to meet specific needs, such as improved performance, aesthetics, and weight. Generally, thin-walled parts are considered to be lightweight and the thickness-to-profile ratio is less than 1:20; they also elastically deform during machining due to low stiffness. The complex geometric shapes of thin-walled parts with significant deformation are no longer machined in milling machine because the surface roughness of thin-walled parts directly impact wear resistance, fatigue strength, corrosion resistance, and friction. The surface roughness of the milled profile is the function of feed and the geometry of the tool profile under ideal circumstances. In actual cases, the deflection, work-tool system vibration, chatter, and built-up edge formation all affect the surface roughness generated in the end milling process. Thus, it is necessary to relate the surface roughness with primary machining parameters, such as speed, feed, and axial depth of cut. The fixtures and jigs are used in the milling operation, which significantly reduce deformation and hence achieve a good surface finish.

Hao and Liu [1] investigated the surface milling of curved thin-walled parts to predict the surface roughness and physical factors. They demonstrated that the surface roughness prediction model had an error of less than 13 %. Cheng et al. [2] explored surface roughness in the feed direction, transverse surface roughness, and deformation while milling Al alloy 5083; they investigated the impact of cutting parameters on both surface roughness and machining deformation. Zahaf and Benghersallah [3] experimentally evaluated the vibration and surface roughness in the end-milling of annealed and hardened bearing steel; they also compared statistical analysis, mathematical modelling, and optimization. They showed the results that the cutting speed and feed per tooth are the influential elements in the milling surface roughness evaluation in the steel workpiece. Sharma and Dwivedi [4] examined the aspects that influence surface roughness in milling; they showed the results that the three primary process parameters that affect the end-milling process of aluminium alloy are feed rate, depth of cut, and spindle speed. Kumar et al. [5] have experimentally determined the effect of machining settings on the surface roughness of aluminium metal matrix composites; the most significant milling parameters, according to their research, are 0.1 mm/rev feed rate, 3000 rpm spindle speed, and 0.2 mm cut depth, with 86.6 %, 9.75 %, and 6.16 % contributions, respectively.

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Lan et al. [6] proposed an intelligent mirror milling machine to mitigate deformation and vibration in the end-milling of large thin-plate workpieces; they have devised a viable way for determining a support head's movement path under a specified cutting path. Bao et al. [7] investigated the forming mechanism of surface topography and the effect of support locations on aircraft skin parts in mirror-milling; they demonstrated that mechanical surface topographies with diverse features may be generated using the same processing parameters by related location between the support head and the milling head. Fei et al. [8] suggested a new method of deformation suppression that involves supporting a fixture element on the back surface of the workpiece at the projection area of the tool-workpiece contact zone; they demonstrated that the method used reduces machining error, improves surface quality, and thus reduces the deformation of low-rigidity workpieces during machining. Bao et al. [9] validated the measurements of milling force for the mirror milling of aircraft skin with the proposed milling force model. They have also developed a finite element m˝SPEEethod (FEM) model to calculate the deformation in the mirror milling of an aluminium plate; they also analysed the position of support heads' locations used in the mirror milling process. Sallese et al. [10] presented the key design considerations and also the characteristics of the black-box control logic employed in the new active fixture; they concluded that the reduction obtained allows for deeper cut depths with lower vibration levels, potentially enhancing production.

A multi-point location/support algorithm was developed by Junbai and Kai [11] to solve positions of a flexible tooling system's location and support spheres in order to construct the workpiece's envelope surface while avoiding machine tool interference. The tooling system, which is said to be flexible, meets the needs of large-scale thin-wall workpiece machining in aircraft while minimizing manufacturing error and cycle time. Amaral et al. [12] created an algorithm using ANSYS parametric design language code; they showed that the algorithm optimizes the supports of the fixture, clamp placements, and clamping forces. Also, they showed the results that the reduced deformation improves the machining accuracy. Finite element analysis (FEA) in the computer-aided fixture design environment minimizes the need for extensive "trial and error" experiments on the shop floor. Shi et al. [13] analysed the response of a thin-walled component over the variable thickness in the milling process using the first shear deformation theory and the Lagrange equation. They observed that increasing the slope of the thickness variation, and length and decreasing the width improves the workpiece's dynamic deformation. Chang and Lu [14] presented a feasibility study predicting the surface roughness inside milling operations using different polynomial networks. They concluded that the developed polynomial network models possess promising potential for predicting surface roughness inside milling operations. Yuan et al. [15] presented an accurate surface roughness model based on cutting process kinematics and tool geometry, taking into account the effects of tool run-out and minimum thickness. They demonstrated that the surface roughness model's proposed results could accurately predict the trends and magnitude of surface roughness in micro end-milling.

Xiao et al. [16] performed a turning test on stainless steel using the central composite surface design and the Taguchi design; they suggested that the feed rate impact on surface roughness is highly predominant. They showed the results that the cutting depth ranks second, and cutting speed has the least impact. Yuan et al. [17] studied the auxiliary device capable of providing double-sided support to the tenuously rigid places between the cutter and the workpiece to reduce chatter vibrations in the thin-wall milling of half-opened side walls. They concluded that the quality of the machined surface in the presence of the support device is superior to that of the machined surface in the absence of the support device. Zhao et al. [18] constructed a posture accessibility and a stability diagram based on geometric analysis and machining dynamic analysis by identifying interference and chatter-free cutter postures. Also, they propose a novel surface roughness prediction model by exploring the correlation between surface roughness and maximum cutter deformation force. Maiyar et al. [19] investigated the parameter optimization of Inconel 718 superalloy end milling operations using multi-response criteria based on the Taguchi orthogonal array and grey relational analysis. Jing et al. [20] investigated the effects of micro-end-milling cutting parameters on machined surface roughness to determine the best operating conditions. Muthu Mekala et al. [21] designed and developed a new fixture to minimize the surface roughness in the end milling of Al6061 workpiece. They concluded that the proposed fixture with the support heads greatly reduces the deformation in the work piece, which significantly impacted the surface quality.

Shaik and Srinivas [22] assessed the influence of machining process variables comprising cost, cutting speed, and axial depth of cut on output variables like surface roughness and tool vibration amplitude in an

Al-6061 workpiece; they developed an interactive platform to evaluate the ideal process parameter combination using a multi-objective approach and neural network models. Wanner et al. [23] stated that a well-designed tool-to-workpiece offset geometry could result in a reliable and noise-free operation while milling thin-walled Inconel 718. They proved that adjusting the tool's offset location helped lessen chatter vibrations in the system. Wu and Lei [24] studied the possibility of using signal characteristics in milling vibration measurements and cutting parameters to predict the surface roughness of S45C stee; their experiments revealed that the vibration behaviour affects the surface roughness in addition to cutting parameters. Yue et al. [25] summarised current research on how to achieve stable chatter prediction, chatter identification, and chatter control/suppression during the milling process. They concluded with some reflections regarding possible directions for future research in this field. Alauddin et al. [26] investigated the incorporation of a surface-roughness model for end-milling 190 BHN steel. They observed that the feed effect is predominant in the first- and second-order models.

In the above literature, it is evident that many researchers have test various methods to improve the surface roughness of thin-walled parts by optimizing the machining parameters such as feed, speed, and depth of cut (doc) when machining in end milling. Therefore, the main goal of this research work is to reduce the workpiece deformation with the use of the proposed fixture and also optimizing the machining parameters, including feed, speed, and depth of cut, to improve the surface roughness of thin-walled plates made of three different materials (Inconel 718, AISI 316L, and Al 6061) in a milling machine. Also, the DEFORM 3D model is simulated prior to the experiment, and the significance of variables on the multiple performance characteristics is further investigated using ANOVA results.

1 METHODS

Aircraft wings, automobile bodies, and turbine blades are all machined with computer navigated control (CNC) milling machines. While milling thin-walled components, the milling process causes more deformation, which leads to poor surface roughness. Hence jigs and fixtures are employed to reduce deformation. They minimize the surface roughness in the thin-wall plates during the time of machining. These fixtures will hold the workpiece in place during the machining process, limiting the amount of deformation. The machining settings are critical to achieving surface roughness optimization. The machining parameters are spindle speed, feed rate, depth of cut, coolant flow, drill tool diameter, cutting speed, and the number of passes. Among the input parameters, the speed of the spindle, depth of cut, and the feed rate affect the surface finish to a greater extent. Table 1 gives the detailed required input cutting parameters for machining.

Table 1. *Cutting parameters and their ranges*

Parameters	Values		
Speed [rpm]	800	950	1050
Feed rate [mm/rev]	0.05	0.10	0.15
Depth of cut [mm]	0.1	0.2	0.3

In this study, the three different thin-walled plate materials selected are Inconel 718, Stainless steel AISI 316L, and Aluminium alloy Al6061. The requirement of good corrosion-resistant for various applications is the basis for using these materials, but the drawback is more deformation while machining because of low rigidity. This drawback is resolved by the fixture for the milling machine and optimizing the selected machining parameters. The dimensions of all three thin-walled plate materials used for the study are Inconel 718 100 mm × 50 mm × 5 mm, AISI 316L 100 mm × 50 mm × 5 mm, and Al6061 100 mm × 100 mm × 5 mm for the length, width, and thickness, respectively. The chemical compositions of the workpieces play a vital role in selecting the desired input parameters. Fig. 1 shows the nomenclature of the cutting tool. The material of the cutting tool used in this end-milling is high-speed steel (HSS). The width of the cutting tool is 8 mm, and the length is 65 mm.

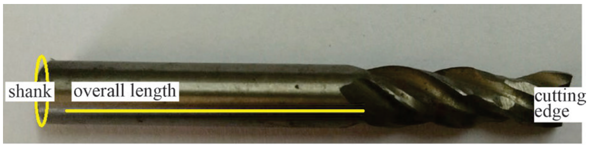

Fig. 1. *Nomenclature of cutting tool*

2.1 Design of Fixture and Simulation of Workpiece Deformation

The main parts of milling fixtures are locators, clamps, and supports or support heads. The milling fixture is designed in such a way as to hold the thin-walled plate and avoids chatter during the milling process. The thin-walled workpieces widely use cylindrical support heads. The high carbon steel is the material used for the attached support heads of the fixtures. Fig. 2 shows the designed fixture with nomenclature and dimensions. This fixture is fixed in the end-milling bed, and the workpiece is subjected to the milling operation. The theoretical values of workpiece deformation are initially predicted with DEFORM 3D simulation software. The simulation uses the same fixture design, end-milling machine, milling cutter, and workpiece similar to the shop floor experiment. The cylindrical support heads in the fixtures reduce the maximum deformation observed during the machining. The input parameters of machining speed, feed rate, and the depth of cut assess the prediction of deformation of the workpiece are the machining speed, feed rate, and the depth of cut, as indicated in Table 1. The parameters are considered to avoid the maximum deformation by reducing the chatter during the milling process.

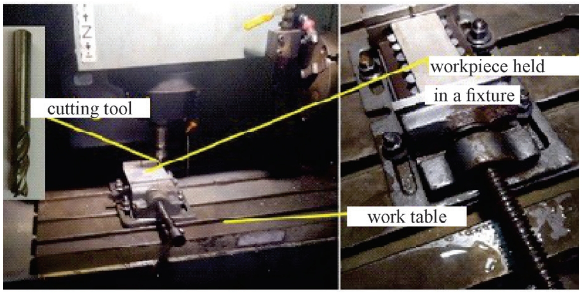

Fig. 2. *Experimental setup*

2.2 Experiment

The vertical milling machine of model Chetak 75M machining centre is employed to perform the end milling operations on the three workpieces. Fig. 3 shows how the proposed newly designed fixture is fixed on the CNC milling machine table using a bench vice. Initially, the thin-walled plate workpiece material of Inconel 718 is fixed on the support heads of the fixture by using various tools and supports. Primarily, the three input parameters considered here for the experiment are feed, depth of cut, and speed. The three different combination values of feed and depth of cut with the different spindle speed values are applied to run the experiments in the end-milling machine. The other workpieces (Stainless steel AISI 316L and the aluminium alloy Al6061) follow a similar experimental procedure. For each experiment, the measurement of the output parameters (surface roughness, displacement, acceleration, frequency, and velocity) is carried out. The SURFTEST SJ-210 portable surface roughness tester measures the average surface roughness for each experiment in the three workpieces under investigation. All other output variables, such as displacement, velocity, acceleration, and frequency, are measured using the HTBB-8215 digital vibration meter. Fig. 4 shows the measuring devices. The fixture usage to reduce the surface roughness in workpieces is evaluated based on the measurements.

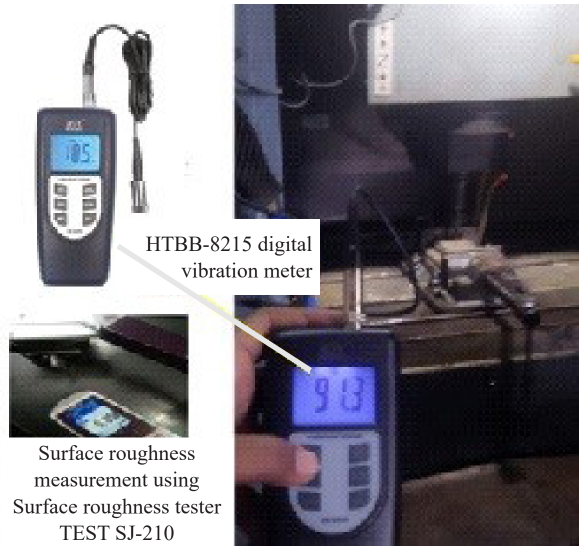

Fig. 3. *Measuring devices: vibration meter and surface tester SJ-210*

2.2.1 Design of Experiments

Taguchi's method carries out the design test, which involves analysing data obtained from surface roughness measurements and instantaneous displacement values on the workpiece. The Taguchi method uses a new orthogonal array design to investigate the whole parameter with fewer experiments. With the newly developed fixture, the Taguchi methodology carries the plan of experiments for three elements in three phases for the three workpieces under investigation. Taguchi's L9 orthogonal array defines the nine trial conditions required for the experiment.

2.2.2 ANOVA (Analysis of Variance)

ANOVA is used to investigate the importance of the output response values regarding surface roughness and displacement of the input parameter. Table 2 shows the procedure's parameters and levels. The present study investigates how different machining parameters affect the machining deformation and surface quality of the product. The present work utilizes MINITAB Software to do experimental data optimization and graphical analysis. The optimal design serves as the basis for the experimental runs, which include nine experiments for each material with the proposed fixture incorporated. The machining parameters used in milling thin-walled plates affect the deformation, quality, and productivity of machined parts.

Table 2. *Input parameters for three different levels*

Input parameters	Unit	Type	Level 1 (L1)	Level 2 (L2)	Level 3 (L3)
Speed	rpm	fixed	800	950	1050
Feed	mm/tooth	fixed	0.05	0.10	0.15
Depth of cut	mm	fixed	0.1	0.2	0.3

3 RESULTS AND DISCUSSION

The Taguchi analysis approach with the values of three levels and three input parameters as shown in Table 1 is employed in the milling operation on three thin-walled plates. Table 2 shows the ranges of input parameters in three different levels (L1, L2, and L3) of experimentation with units and types. A total of nine experiments were carried out on each of three different workpieces using the suggested designed fixture, using the combination of the three machining parameters in MINITAB Software. Table 3 shows the values of simulated displacement found from DEFORM 3D software and experimental values of displacement and surface roughness of the combination of levels by various experimental runs with corresponding input parameters. The following subsections discuss displacement and surface roughness with different outputs from simulation, experimentation, and ANOVA.

Table 3. *Simulation ad experimental values-displacement and surface roughness*

Experiment run	Combination of levels with corresponding input parameters			Material	Experimental displacement [mm]	Displacement simulation [mm]	Surface roughness [μm]
	Speed	Feed	DOC				
1	L1	L1	L1	INCONEL 718	0.019	9.93	0.928
2	L1	L2	L3		0.016	8.44	2.078
3	L1	L3	L3		0.020	9.94	2.768
4	L2	L1	L2		0.014	6.24	2.090
5	L2	L2	L3		0.031	18.5	1.315
6	L2	L3	L1		0.014	4.26	2.485
7	L3	L1	L3		0.025	11.6	2.386
8	L3	L2	L2		0.017	7.19	1.760
9	L3	L3	L2		0.014	4.00	1.552
10	L1	L1	L1	AISI 316L	0.030	20.4	0.565
11	L1	L2	L3		0.026	13.5	1.458
12	L1	L3	L3		0.020	8.54	2.386
13	L2	L1	L2		0.016	6.24	0.958
14	L2	L2	L3		0.020	9.82	0.845
15	L2	L3	L1		0.015	5.99	1.697
16	L3	L1	L3		0.018	9.65	0.428
17	L3	L2	L2		0.022	13.2	1.075
18	L3	L3	L2		0.022	13.7	1.365
19	L1	L1	L1	AL6061	0.030	18.8	1.532
20	L1	L2	L3		0.019	8.6	1.989
21	L1	L3	L3		0.022	12.7	3.090
22	L2	L1	L2		0.016	5.94	2.551
23	L2	L2	L3		0.019	9.62	3.789
24	L2	L3	L1		0.018	9.38	3.620
25	L3	L1	L3		0.016	5.93	3.235
26	L3	L2	L2		0.017	9.80	3.860
27	L3	L3	L2		0.014	4.92	2.719

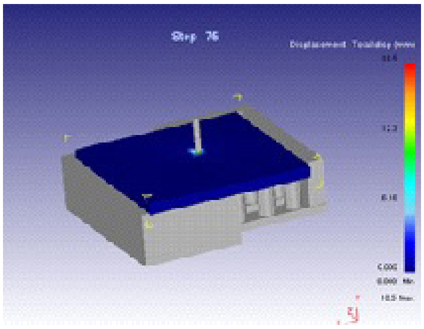

Fig. 4. *Simulation results for Inconel 718 workpiece*

3.1 Comparison of Displacement and Surface Roughness

Fig. 5 shows the comparison of experimental displacement values and surface roughness of three thin-walled plates machined in end-milling machine using the proposed fixture with cylindrical support heads. Nine experiments were carried out on each thin-walled plate with different input parameter combinations. Fig. 5a shows that the displacement trend curve has different behaviour for Inconel when the other two materials show similar trends for the corresponding experimental runs. From Fig. 5b, the minimum surface roughness value of 0.928 µm is measured for the combination of same level's (L1, L1, L1) parameter values. Similarly, for AISI 716L, the minimum surface roughness value measured is 0.565 µm and for AL6061; it is 1.532 µm. For the first three experimental runs, the surface roughness shows a similar trend for all three metals, and then different behaviour is observed for the rest of the experimental runs.

Fig. 6 shows the correlation of experimental displacement, simulated displacement, and surface roughness. It is seen that the displacement trend is similar in both the experimentation and simulation. Also, the surface roughness reduces with the corresponding reduction in displacement values. As seen from the figure, for the experimental samples 6, 11 and 20, the deformations are the peak, as compared to other samples and the corresponding reduction in surface roughness. Hence, the use of fixtures is valid for reducing the deformation in terms of displacement values and the corresponding improvement in surface roughness.

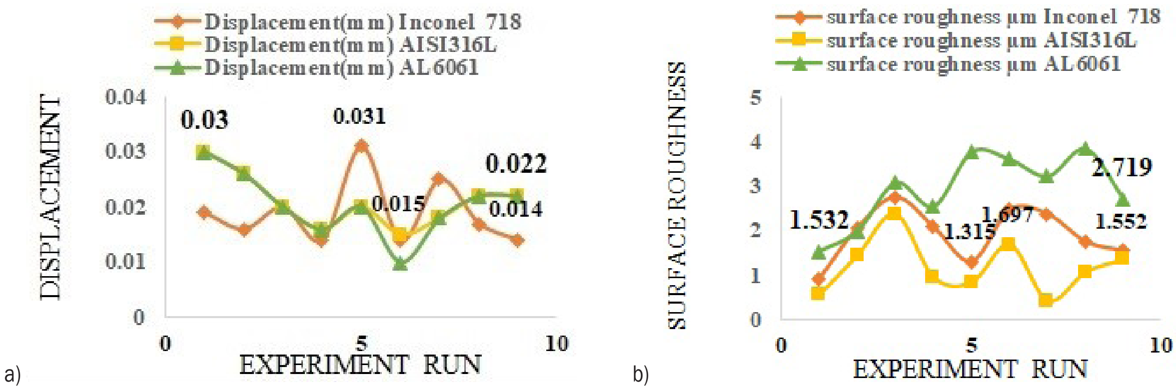

Fig. 5. *Comparison of a) displacement, b) surface roughness in three different thin-walled plates*

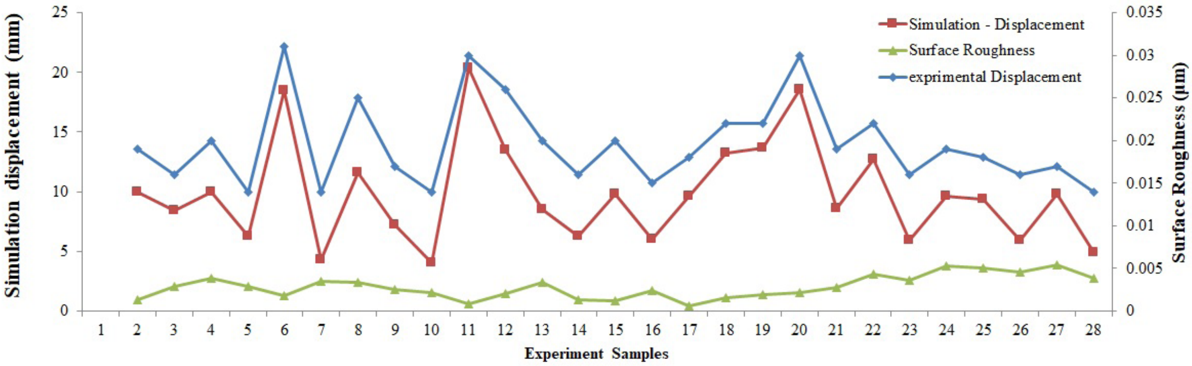

Fig. 6. *Correlation of simulated displacements, experimental displacements, and surface roughness*

3.2 Identification of Influential Parameters by ANOVA

ANOVA helps predict the most influential parameter in the machining with the proposed fixture. The schematic of ANOVA for the displacement of three different materials is given in Table 4. It also shows the most influential input parameters for displacement-measured output responses of the milling process with the use of proposed fixtures for three workpieces. It is inferred from this table that the depth of cut is the most influential input parameter with a contribution of 71.48 % in controlling the displacement for Inconel 718; speed is the most influential input parameter in controlling the displacement by 58.01 % and 58.42 % for AISI 316L and AL6061, respectively. The schematic of ANOVA for the surface roughness of three different materials is given in Table 5. It also shows the most influential input parameters for surface roughness measured output responses of the milling process with the use of proposed fixtures for three workpieces. It is inferred from this table that the feed is the most influential input parameter with contributions of 71.03 % and 70.02 % in controlling the surface roughness for Inconel 718 and AISI 316L, respectively. Speed is the most influential input parameter in controlling the surface roughness by

Table 4. *Scheme of ANOVA for displacement of three different materials*

Material	Source	DF	Adj SS	Adj MS	F-value	P-value	% of contribution	Influential parameter
Inconel 718	Speed	2	0.000003	0.000001	0.10	0.911	1.11	insignificant
	Feed	2	0.000044	0.000022	1.47	0.404	16.30	significant
	Depth of cut	2	0.000193	0.000096	6.53	0.133	71.48	significant and most influential
	Error	2	0.000030	0.000015	-	-	11.11	admissible
	Total	8	0.000269					
AISI 316L	Speed	2	0.000105	0.000052	2.57	0.280	58.01	significant and most influential
	Feed	2	0.000041	0.000020	0.51	0.663	22.65	significant
	Depth of cut	2	0.000014	0.000007	0.34	0.744	7.73	less significant
	Error	2	0.000021	0.000010	-	-	11.60	admissible
	Total	8						
AL6061	Speed	2	0.000104	0.000052	5.57	0.152	58.42	significant and most influential
	Feed	2	0.000013	0.000006	0.68	0.596	0.07	insignificant
	Depth of cut	2	0.000043	0.000021	2.29	0.304	24.16	significant
	Error	2	0.000019	0.000009	-	-	10.67	admissible
	Total	8	0.000178					

Table 5. *Scheme of ANOVA for surface roughness for three different materials*

Material	Source	DF	Adj SS	Adj MS	F-Value	P-Value	% of Contribution	Influential parameter
Inconel 718	Speed	2	0.00623	0.00312	0.00	0.997	0.22	insignificant
	Feed	2	2.00296	1.00148	0.26	0.791	71.03	significant and most influential
	Depth of cut	2	0.52832	0.1411	0.14	0.877	18.74	less significant
	Error	2	0.28220	-	-	-	10.01	admissible
	Total	8	2.81971	-	-	-	-	-
AISI 316L	Speed	2	0.45050	0.000020	0.89	0.530	15.30	less significant
	Feed	2	2.06114	0.000010	4.58	0.179	70.02	significant and most influential
	Depth of cut	2	0.03208	0.000007	0.08	0.928	1.09	insignificant
	Error	2	0.40004	0.000052	-	-	13.5	admissible
	Total	8	2.94676	-	-	-	-	-
AL6061	Speed	2	2.3885	0.000052	5.57	0.152	45.71	significant and most influential
	Feed	2	1.0980	0.000006	0.68	0.596	21.01	significant
	Depth of cut	2	1.3820	0.000009	2.29	0.304	26.45	significant
	Error	2	0.3570	0.127449	-	-	6.83	admissible
	Total	8	-	-	-	-	-	-

45.71 % for AL6061. The contribution factor is the speed for both the displacement and surface roughness from ANOVA in Tables 4 and 5.

Fig. 7 shows the ANOVA graphs for the main plot of the means for displacement and surface roughness for Inconel 718, AISI 316L and Al6061, respectively. From Fig. 7a, the main effect plot for means, for Inconel 718, the optimum parameter conditions are L2L2L3 (speed 950 rpm, feed rate 0.10 mm, and depth of cut 0.3 mm) for displacement and L2L3L3 (speed 950 rpm, feed rate 0.15 mm, and depth of cut 0.3 mm) for surface roughness, as identified from the plots.

From Fig. 7b for AISI 316L, the optimum parameter conditions are L1L2L1 (speed 800 rpm, feed rate 0.10 mm, and depth of cut 0.10 mm) for displacement and L1L3L2 (speed 800 rpm, feed rate 0.15 mm, and depth of cut 0.2 mm) for surface roughness. From Fig. 7c, the optimum parameter conditions are L1L1L1 (speed 800 rpm, feed rate 0.05 mm, and depth of cut 0.1 mm) for displacement and L2LB2C3 (speed 950 rpm, feed rate 0.10 mm, and depth of cut 0.3 mm) for surface roughness.

A grey relational analysis of three metals is given in Table 6, which also gives the optimum machining conditions L2L2C3 for Inconel 718, L1L1L1 condition for AISI 316L and AISI 316L. Based on the ANOVA, the predominant input parameters are speed and feed in the case of milling of AISI 316L, and speed and feed in the case of milling of Al 6061. Hence the optimum speed for the Inconel milling using the fixture is 950 rpm. The surface roughness value measured for Experiment Run 5 with the optimum conditions gives less value around 1.315 µm.

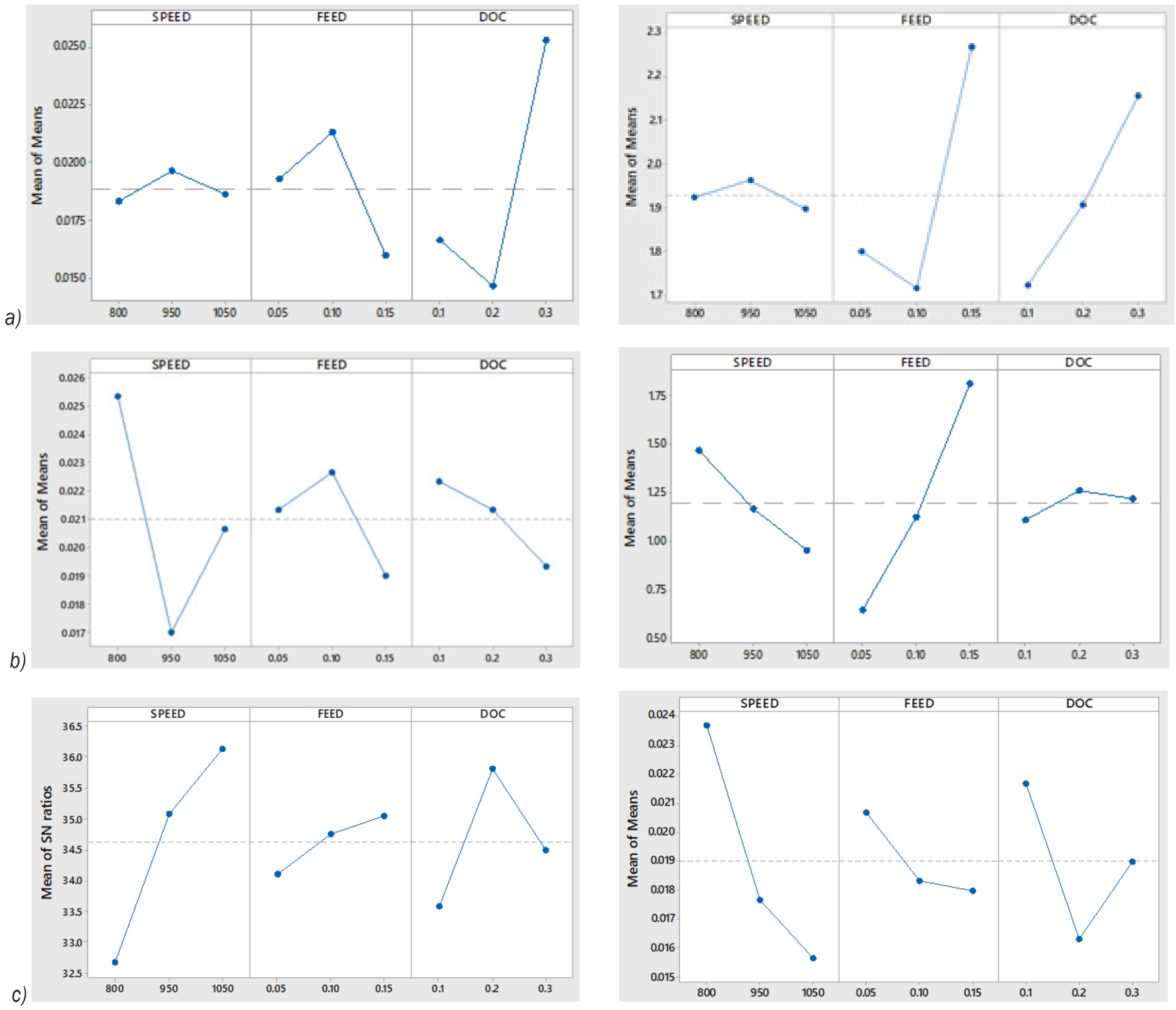

Fig. 7. *Main effect plots for means; a) displacement and surface roughness for Inconel 718, b) displacement and surface roughness for AISI 316L, and c) displacement and surface roughness for Al6061*

Table 6. *Grey relational analysis (GRA)*

Material	Experiment run	Grey relational coefficient for experimental displacement	Grey relational coefficient for displacement simulation [mm]	Grey relational coefficient for surface roughness [μm]	Grey relational grade	Rank
Inconel 718	1	0.414634	0.550076	1	0.235772	2
	2	0.361702	0.620188	0.444444	0.134358	8
	3	0.435897	0.549659	0.333333	0.128205	9
	4	0.333333	0.763962	0.441883	0.129203	6
	5	1	0.333333	0.703902	0.283984	1
	6	0.333333	0.965379	0.371417	0.117458	4
	7	0.586207	0.488215	0.38688	0.162181	7
	8	0.377778	0.694444	0.525114	0.150482	5
	9	0.333333	1	0.595855	0.154865	3
AISI 316L	1	1	0.333333	0.87724	0.368429	1
	2	0.652174	0.489636	0.487307	0.27152	6
	3	0.428571	0.738596	0.333333	0.250083	8
	4	0.348837	0.966465	0.648774	0.327346	3
	5	0.428571	0.652923	0.701289	0.297131	4
	6	0.333333	1	0.435498	0.294805	5
	7	0.384615	0.663139	1	0.341292	2
	8	0.483871	0.499827	0.602091	0.264298	7
	9	0.483871	0.483071	0.51096	0.246317	9
AL6061	1	1	0.333333	1	0.388889	1
	2	0.421053	0.65019	0.718075	0.29822	3
	3	0.5	0.467852	0.427627	0.23258	6
	4	0.363636	0.870229	0.533211	0.294513	4
	5	0.421053	0.592721	0.340251	0.225671	8
	6	0.4	0.60531	0.357934	0.227207	7
	7	0.363636	0.871338	0.405999	0.273496	5
	8	0.380952	0.583618	0.333333	0.216317	9
	9	0.333333	1	0.495108	0.30474	2

Table. 7. *Consolidation of influential input parameters on output results*

Workpiece	Output			
	Displacement		Surface roughness	
	Most influential input parameter	Range of the input factor	Most influential input parameter	Range of the input factor
Inconel 718	Depth of cut	L2L2L3 (speed 950 rpm, feed rate 0.10 mm, and depth of cut 0.3 mm)	feed	L2L3L3 (speed 950 rpm, feed rate 0.15 mm, and depth of cut 0.3 mm)
AISI 316L	Speed	L1L2L1 (speed 800 rpm, feed rate 0.10 mm, and depth of cut 0.10 mm)	feed	L1L3L2 (speed 800 rpm, feed rate 0.15 mm, and depth of cut 0.2 mm)
Al6061	Speed	L1L1L1 (speed 800 rpm, feed rate 0.05 mm, and depth of cut 0.1 mm) for displacement	speed	L2L2l3 (speed 950 rpm, feed rate 0.10 mm, and depth of cut 0.3 mm)

Table 7 gives the consolidation of the influential input parameters on the output results. It has been construed from Table 7 that the speed is the most influential parameter in the case of displacement for AISI 716L and Al 6061. Feed is the most influential parameter in the case of surface roughness for Inconel 718 and AISI 316L. Speed is the most influential parameter in the case of displacement and surface roughness for Al 6061.

5 CONCLUSIONS

The proposed fixture with a cylindrical support head is used in an end-milling machine to produce three thin-walled plates made with three different materials (Inconel 718, AISI 316L, and Al 6061) to reduce the deformation and hence minimize the surface roughness. The cylindrical support heads in the proposed fixture reduce the chatter and vibration during the milling of thin-walled plates. The author proposes the new fixture design to improve the surface quality by minimizing the deformation caused due to low rigidity. The workpiece-fixture system also suppresses the vibration of thin-walled parts.

The optimum machining parameters (feed, speed, and depth of cut) have been found to improve the surface roughness of thin-walled plates by arresting the deflection using the proposed fixture. ANOVA is performed to investigate the more influential parameters on multiple performance characteristics.

The following conclusions are via simulation and experimentation.

- For Al 6061, speed is the most influential parameter in controlling the displacement and surface roughness, contributing around 58 % and 45 %, respectively.
- The optimum machining conditions for Inconel 718: speed 950 rpm, and depth of cut 0.3 mm. The feed rate range is 0.10 mm to 0.15 mm for the displacement and surface roughness model. It is evident that the grey relational analysis results match with ANOVA in terms of speed and feed rate. The depth of cut is the most influential parameter.
- The optimum machining condition for AISI 316L: speed 800 rpm, feed rate 0.10 mm, depth of cut 0.1 mm for displacement and speed 800 rpm, feed rate 0.15 mm, and depth of cut 0.2 mm for surface roughness.
- Hence, care has been taken to reduce the displacement and surface roughness with the use of the proposed fixture.
- The speed is the most influential parameter in the case of displacement for AISI 716L and Al 6061, feed is the most influential parameter in the case of surface roughness for Inconel 718 and AISI 716L, and speed is the most influential parameter in the case of displacement as well as surface roughness for Al 6061.
- Therefore, the speed and feed are the two most influential parameters (not the depth of cut) to reduce the deformation and the surface roughness using the proposed fixture with cylindrical support heads.

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