

Performance optimisation of the turning process along with multi-surface heating process

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Materials that are difficult to cut possess excellent qualities and machinability, though conventional machining techniques require additional energy to circumvent the problems associated with the turning process. In this study, heat-assisted turning of duplex stainless steel (SS) was carried out. Various heating techniques such as infrared (IR)-, ultraviolet (UV)- and hot air (HA)-assisted heating were adopted. The experiment used an L_{16} orthogonal array with the most significant parameters such as heating method, feed rate in millimetres per revolution (mm/rev), depth of cut (millimetres [mm]) and cutting speed (metres per minute [m/min]) on the cutting force and surface roughness. The technique for order performance by similarity to ideal solution (TOPSIS) and grey relational analysis (GRA), were used to optimise the output performance. The results of TOPSIS showed that the 16th experimental combination, i.e., the HA heating method, with feed rate = 0.175 mm/rev, depth of cut = 0.1 mm and cutting speed = 150 m/min, required a smaller cutting force and resulted in lower surface roughness. In case of the GRA method, the best output performance was observed for the 15th experimental combination, that is, the HA heating method, with feed rate = 0.15 mm/rev, depth of cut = 0.2 mm and cutting speed = 200 m/min. Compared to the non-heat-assisted turning process, the HA- and UV-assisted processes required 10.25% and 7.69% lesser cutting force, respectively, and the surface roughness in case of the HA method was 15.13% lesser.

Keywords: *ultraviolet, hot air, infrared, turning, surface roughness*

1. Introduction

Duplex stainless steel (SS) is an important material with high corrosion resistance and strength. It is extensively used in industries such as off-shore oil refineries, automobiles, biomedicine and chemical and petrochemical industries for various applications. Due to its composition (>25% chromium and nickel), duplex SS exhibits higher strength than austenitic SS, such as the 304, 308 and 316 grades of SS. This, however, poses challenges for machining through traditional methods [1–3]. Various studies have attempted to resolve this problem. Karabulut et al. [4] investigated preheated titanium alloy workpieces using a conventional machining process; power consumption was 64% lesser with the preheated work material. Moreover, surface roughness of the work material decreased by approximately 15% by sticking on the machined sur-

face. Kim et al. [5] investigated Inconel alloy using plasma heating and conventional machining. The machining rate was three times better and tool life improvement was two times better with the plasma-heated machining than with non-heated machining. Balamurugan et al. [6] investigated the application of thermal energy over the machining zone for die steel work material. They observed that heat energy increased the tool wear due to the high deformation of work material. Lesser speed and feed rate resulted in smaller surface roughness. Rao et al. [7] used plasma on the conventional turning process with American Iron and Steel Institute (AISI) 4340 alloy steel using tungsten tool. Plasma temperature was maintained between 200°C and 400°C, and the surface roughness improved with increase in plasma temperature and decreased tool life. Parida et al. [8] conducted the turning operation on Inconel 718 alloy with the assistance of heat energy. The machining performance im-

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proved significantly under heated conditions than at room temperature. Bharat et al. [9] carried out turning experiments on a nickel-based super alloy in assistance with laser. They maintained the laser temperature at 400°C on the machining zone. The use of laser improved the material removal rate by two times compared to non-laser heating. Olsson et al. [10] investigated the effect of induction heating and cryogenic cooling-assisted machining on tungsten and niobium work materials. The variation in temperature induced phase transformation in the material from ductile to brittle, which contributed towards improving the machining rate. Thus, the machining of metals in heated conditions results in better surface roughness, and under cooling conditions, it improves tool life when machining the tungsten alloy. Parida et al. [11] conducted flame-heated hot machining to study the tool life and surface features on Monel 400 alloy. They used a mixture of oxygen and commercial liquid petroleum gas for producing the flame and applied it over the machining zone. Based on the results of analysis of variance (ANOVA), less tool wear was obtained with this heating technique, along with better surface roughness. Sofuoğlu et al. [12] combined low-frequency ultrasonic vibration and heat-assisted techniques in traditional machining to investigate the surface roughness, tool life and chip morphology on the Hastelloy. The heating technique improved the tool life by softening the metal and improved the surface roughness by eliminating sticking of chips on the machining zone. Parida et al. [13] studied chip morphology using the flame-heating technique for machining Inconel alloys. Comparing the heating and non-heating methods, it was determined that the hot machining method improved the machining performance by two times. Jong-Tae et al. [14] conducted experiments with two different types of heating, namely, induction heating and laser-assisted machining, on nickel-based super alloys in conventional machining. A smaller cutting force was obtained for laser-assisted-machining compared to induction-assisted machining. Asit et al. [15] investigated Monel alloy using the flame-heating technique. Increasing machining cutting speed at higher temperature improved the tool life by approximately 85% com-

pared with normal machining. Moreover, increasing the temperature and feed rate diminished tool life, producing build-up edges on the machined surfaces. Sanchez et al. [16] used the infrared (IR) ray heating technique for hard metals such as tungsten. The tool life improved by 340% and surface toughness improved by 205% compared to the same in non-heated machining. The machined surface underwent plastic transformation due to the heat, resulting in lesser micro-hardness. Thus, there is scant research on conventional machining of duplex SS using various heating methods. Very few researchers have investigated the heating of the machining zone, and no studies have investigated ultraviolet (UV)- and hot air (HA)-assisted conventional machining. These heating techniques, however, have been successfully used in other manufacturing sectors to improve the machining performance of non-traditional machining processes, such as biomedicine and electrical sectors [17–20]. In this study, UV and IR rays and HA are used to preheat a workpiece, and the results are compared with those obtained under non-heated machining conditions. The experiments were planned with these heating methods, and the specific parameters were feed rate (millimetres per revolution [mm/rev]), depth of cut (millimetres [mm]) and cutting speed (metres per minute [m/min]). Moreover, optimisation techniques, such as the technique for order performance by similarity to ideal solution (TOPSIS) and the grey relational analysis (GRA) method, were used to determine the optimal combination. To achieve better understanding of the heating effect on the work material, analysis using scanning electron microscopy (SEM) was carried out.

2. Experimental work

The turning experiments were conducted on duplex SS using an UNITEC, Rajkot, India TLC360B lathe machine with different heating methods and parameters, such as UV-, IR- and HA-assisted, as well as normal (dry), machining conditions. The machining parameters and their levels are presented in Table 1. The parameters and their levels were identified based on preliminary experi-

Table 1. Machining parameters and ranges

Code	Description	Level 1	Level 2	Level 3	Level 4
A	Heating method	Normal	IR	UV	HA
B	Feed rate, mm/rev	0.1	0.125	0.15	0.175
C	Depth of cut, mm	0.1	0.2	0.3	0.4
D	Cutting speed, m/min	50	100	150	200

HA, hot air; IR, infrared; UV, ultraviolet

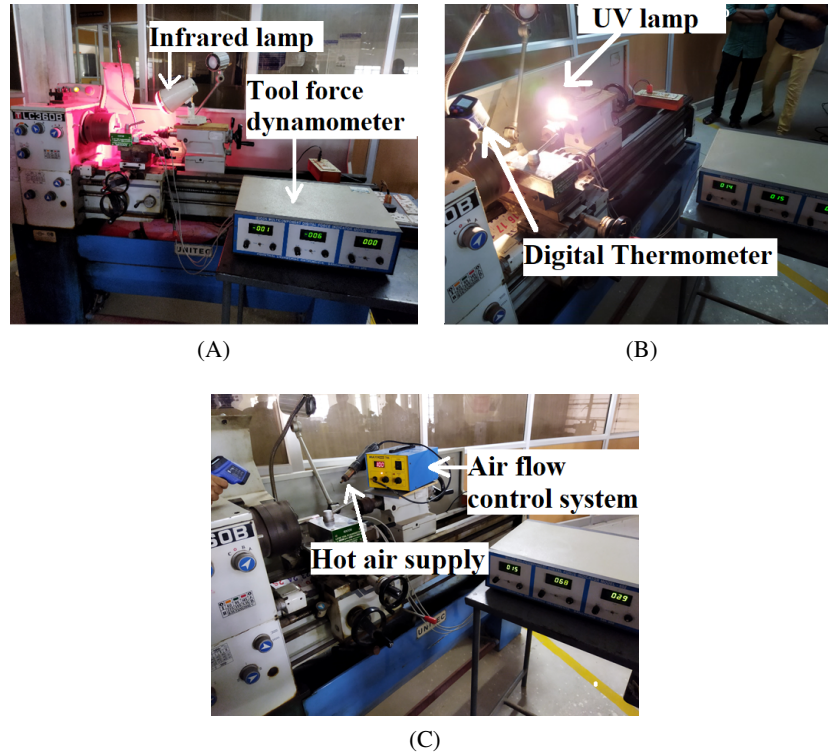


Fig. 1. Experimental setup: (A) IR-assisted machining; (B) UV-assisted machining; and (C) HA-assisted machining.

HA, hot air; IR, infrared; UV, ultraviolet

ments and the literature [21]. The L_{16} orthogonal array (OA) and outcome of experiments are presented in Table 2. Turning operations were carried out by maintaining the workpiece temperature at $120^{\circ}\text{C} \pm 5^{\circ}\text{C}$. The turning operation was initiated as soon as the workpiece temperature reached the desired level, and it was measured using an IR thermometer; no coolant was used for machining under all conditions. Surface roughness of the workpiece was determined using the Surfest S-210 surface roughness measurement instrument (Mitutoyo, Kanagawa, Japan). Five different locations

on the average machined workpiece were considered for the surface roughness measurement. Machining surface defects and tool wear of all states of machining conditions were analysed using SEM images. Figures 1A–1C present the experimental setup of IR-, UV- and HA-assisted workpieces, respectively. An IEICOS, Bengaluru, India 652 tool force dynamometer was used for cutting force measurement during the machining. Figures 2A–2D represent the SEM images of the tool edges for machining under different conditions.

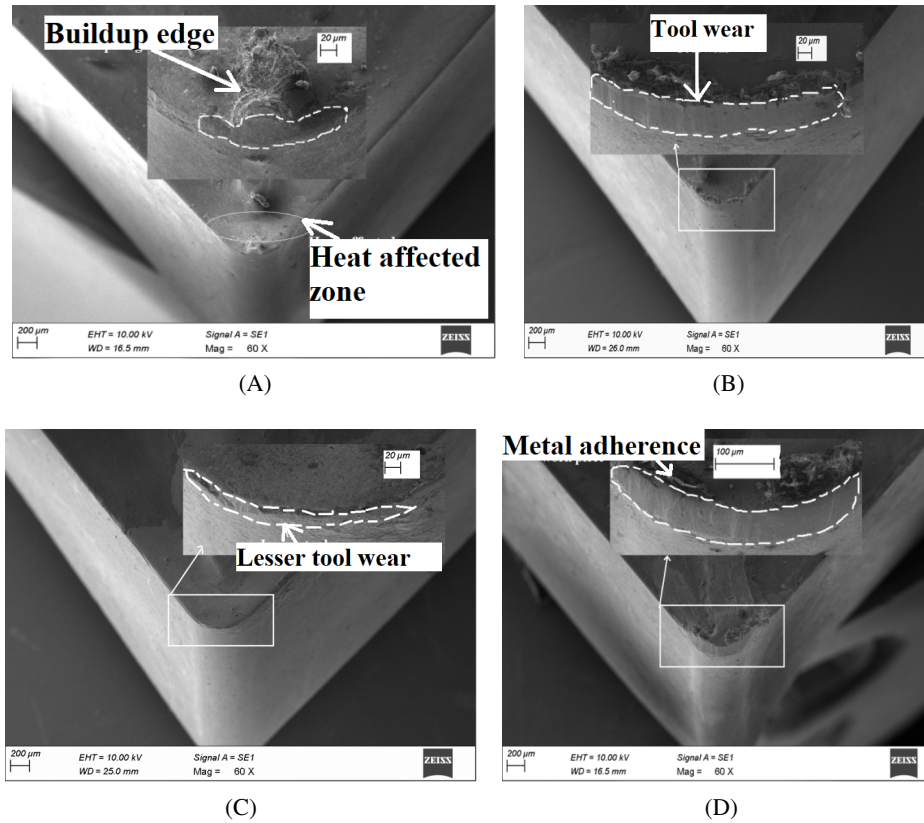


Fig. 2. SEM image of tool edges machined with (A) IR-assisted heating, (B) UV-assisted heating, (C) HA-assisted heating and (D) normal conditions.

HA, hot air; IR, infrared; SEM, scanning electron microscopy; UV, ultraviolet

Table 2. L16 orthogonal array and outcome of machining

Run	A	B	C	D	Cutting force (N)	Surface roughness (μm)
1	Normal	0.1	0.1	50	89	3.18
2	Normal	0.125	0.2	100	84	2.84
3	Normal	0.15	0.3	150	81	3.45
4	Normal	0.175	0.4	200	88	2.97
5	IR	0.1	0.2	150	79	2.17
6	IR	0.125	0.1	200	74	2.97
7	IR	0.15	0.4	50	78	2.84
8	IR	0.175	0.3	100	76	2.34
9	UV	0.1	0.3	200	70	2.38
10	UV	0.125	0.4	150	69	2.27
11	UV	0.15	0.1	100	71	2.14
12	UV	0.175	0.2	50	73	2.17
13	HA	0.1	0.4	100	64	2.18
14	HA	0.125	0.3	50	62	2.07
15	HA	0.15	0.2	200	66	2.12
16	HA	0.175	0.1	150	68	2.01

HA, hot air; IR, infrared; UV, ultraviolet

3. Multi-objective optimisation technique

TOPSIS is a simple and easy to compute method that is able to measure the relative performance for every alternative in a mathematical way. Optimisation of the process parameters through TOPSIS technique is one of the prominent solutions for determining the optimal parameter combination from the experimental plan. The following procedures were considered in TOPSIS [18, 19, 22].

The matrix was framed with 'n' alternatives and 'm' attributes, which is given in Eq. (1).

$$K_m = \begin{bmatrix} l_{11} & l_{12} & l_{13} & \cdots & \cdots & l_{1n} \\ l_{21} & l_{22} & l_{23} & \cdots & \cdots & l_{2n} \\ l_{31} & l_{32} & l_{33} & \cdots & \cdots & l_{3n} \\ \vdots & \vdots & \vdots & \ddots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \ddots & \vdots \\ l_{m1} & l_{m2} & l_{m3} & \cdots & \cdots & l_{mn} \end{bmatrix} \quad (1)$$

where l_{ij} is the result of the i -th alternative corresponding to the j -th attribute.

Standardisation by Eq. (2) is as follows.

$$q_{ij} = \frac{l_{ij}}{\sqrt{\sum_{i=1}^m l_{ij}^2}} \quad j = 1, 2, \dots, n \quad (2)$$

Weight assignment to the attribute (equal weights) is done using Eq. (3).

$$B = w_j q_{ij} \quad (3)$$

where $\sum_{j=1}^n w_j = 1$.

Best and worst solutions are obtained using Eqs. (4) and (5), respectively.

$$T^+ = \left(\sum_i^{Higher} B_{ij} \mid j \in J \right), \quad (4)$$

$$\left\{ \left(\sum_i^{Lower} \mid j \in J \mid i = 1, 2, \dots, m \right) \right\}$$

$$= \{B_1^+, B_2^+, \dots, B_n^+\}$$

$$T^- = \left(\sum_i^{Lower} B_{ij} \mid j \in J \right), \quad (5)$$

$$\left\{ \left(\sum_i^{Higher} \mid j \in J \mid i = 1, 2, \dots, m \right) \right\}$$

$$= \{B_1^-, B_2^-, \dots, B_n^-\}$$

The distributions of all alternatives from the best/worst solutions are calculated using Eqs (6) and (7), respectively.

$$V_i^+ = \sqrt{\sum_{j=1}^n (B_{ij} - T_j^+)^2}, \quad i = 1, 2, \dots, m \quad (6)$$

$$V_i^- = \sqrt{\sum_{j=1}^n (B_{ij} - T_j^-)^2}, \quad i = 1, 2, \dots, m \quad (7)$$

The optimal solution is determined through Eq. (8).

$$J_i = \frac{V_i^-}{V_i^+ + V_i^-} \quad (8)$$

The J_i values are ranked to find the optimal combination.

GRA is a portion of the grey system theory, which is fit for solving problems with complex inter-relationships among multiple factors and variables. In GRA, the different units of outcome are standardised, that is, all values were converted into homogeneous values using the following equations [23, 24]. Eq. (9) represents the higher the better and Eq. (10) represents the lower the better; here, Eq. (10) is considered.

$$K_i^*(r) = \frac{g_i(r) - \text{Ming}_i(r)}{\text{Max}g_i(r) - \text{Ming}_i(r)} \quad (9)$$

$$k_i^*(r) = \frac{\text{Max}g_i(r) - g_i(r)}{\text{Max}g_i(r) - \text{Ming}_i(r)} \quad (10)$$

For ($i = 1, 2, \dots, m$; $P = 1, 2, \dots, n$), compute the grey relational coefficient (GRC) using Eq. (11).

$$y_i(r) = \frac{\Delta_{\text{Min}} + \mathcal{L} \Delta_{\text{Max}}}{\Delta_{\text{oi}}(k) + \mathcal{L} \Delta_{\text{Max}}} \quad (11)$$

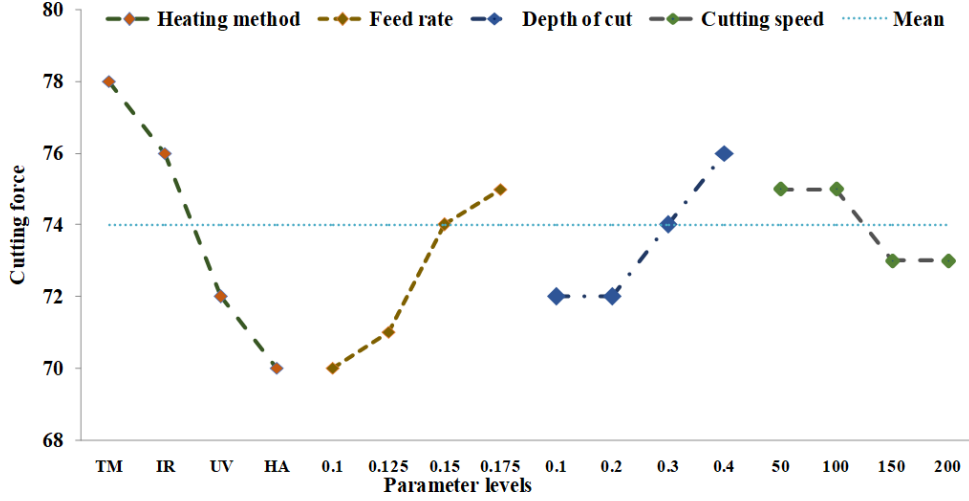


Fig. 3. Effect of input parameters on different parameters

Here $\Delta_{oi}(k)$ is the deviation, $y_0^*(k)$ the orientation and $y_i^*(k)$ is the comparability of the series.

$$Gi = \frac{1}{n} \sum_{p=1}^n \epsilon_i(Y) \quad (12)$$

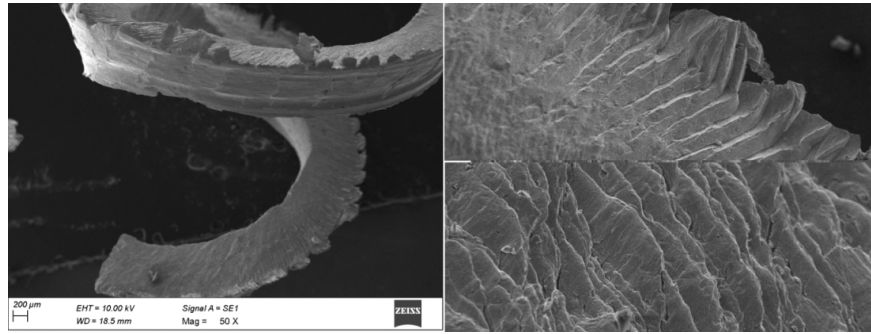
GRG (G_i) is added with the GRC using Eq. 12. ϵ_i yields the situation and comparability values.

4. Results and discussion

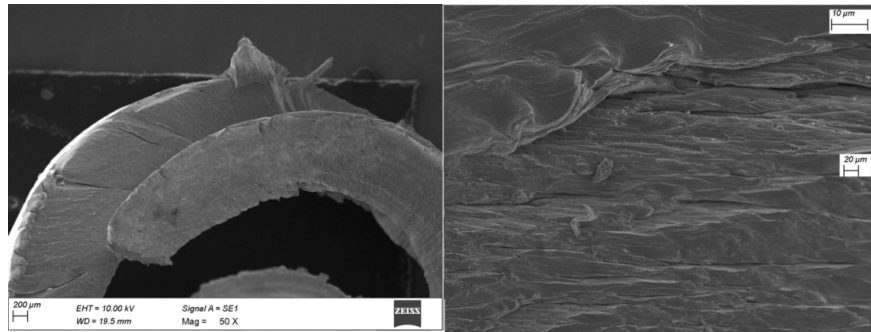
Figure 3 presents the cutting forces of duplex SS under various heating methods. The HA- and UV-assisted heating methods significantly decreased the cutting force. The cutting force also decreased with increase in spindle speed for all heating techniques [24]. The HA-assisted heating method was the best way to produce a smaller cutting force, compared to other methods. Figures 4A–4D present the SEM images of the microstructures of the chips obtained by IR-, UV- and HA-assisted and normal machining, respectively. Compared to normal machining, the HA- and UV-assisted heating methods required 10.25% and 7.69% lesser cutting force. This was because in IR- and UV-assisted heating, the surface of work material was heated extensively to a certain thickness [25]. However, in the HA-assisted heating technique, the work material was heated to a higher temperature than in the UV-assisted heating method. Hence, the cutting force was lesser in the

case of the HA-assisted heating method than with the UV-assisted heating method. At the feed rate of 0.1 mm/rev, the tool required a smaller cutting force than for all other heating techniques. Increasing the feed rate from 0.1 mm/rev to 0.175 mm/rev increased the cutting force (Figure 3). This was because the temperature of the work material spread to the next layer of work material, which resulted in a smaller cutting force at a lower feed rate, and this force increased with the feed rate [26]. As shown in Figure 3, with increase in the depth of cut, the cutting force increases with a change in the temperature. Even under a continuous supply of heat at the machining zone, heat absorption by the work material requires some time to reach the inner layer. Therefore, an increase in the depth of the cut results in a higher cutting force, whereas cutting speed requires almost the same cutting force in all heating methods [27]. Thus, the duration for heating over the work material is comparatively less.

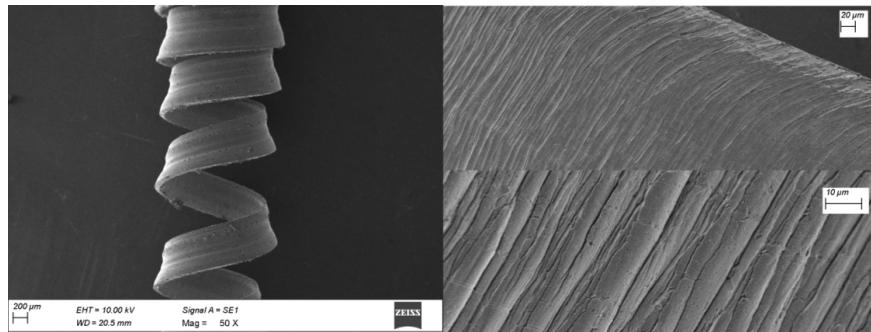
The influence of various input parameters on the surface roughness is displayed in Figure 5. The values of surface roughness were lower for heated machining than for normal machining. Among the heating methods, differences in terms of the final surface roughness were relatively lower for the HA-heating technique and it increased for the UV-assisted heating, IR-assisted heating and normal machining methods. The HA-assisted heating method produced the surface roughness of



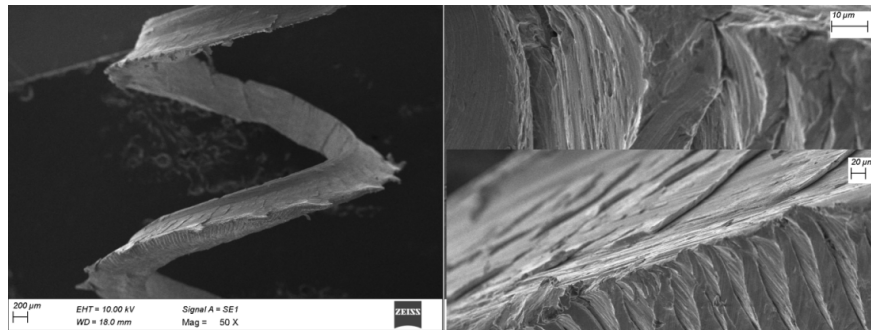
(A)



(B)



(C)



(D)

Fig. 4. SEM image of chip microstructure under (A) IR-assisted machining, (B) UV-assisted machining, (C) HA-assisted machining and (D) normal machining.

HA, hot air; IR, infrared; SEM, scanning electron microscopy; UV, ultraviolet

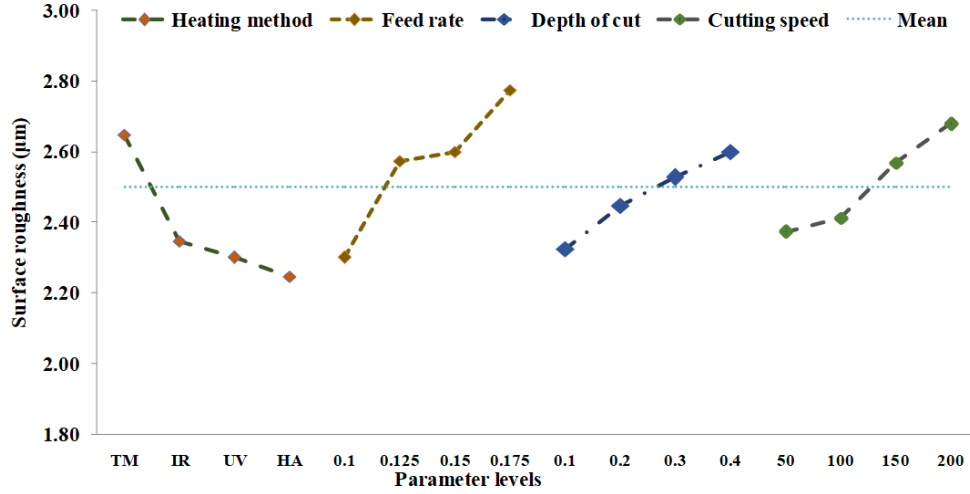


Fig. 5. Effect of input parameters on surface roughness

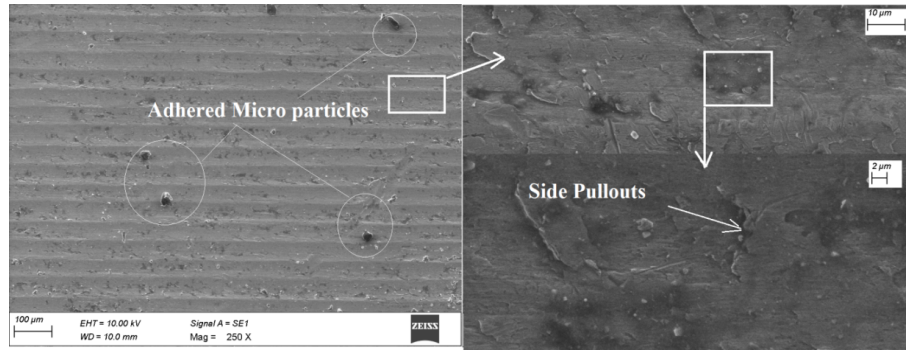
2.2436 μm , which was 15.13% lesser than that obtained with normal machining. This was because the microstructure of the metal was elongated due to the application of heat over the surface, softening the surface [28]. This method also heated the work material faster than other heating techniques. Therefore, the HA-assisted heating method resulted in lesser cutting effects and lesser surface roughness. The UV-assisted heating method produced the surface roughness of 2.312 μm , which was the second-smallest value, and it was 13.14% lesser than that obtained for normal machining. The next lower surface roughness was acquired with the IR-assisted heating method, which produced a surface roughness of 2.346 μm , which was 11.41% lesser than that obtained for normal machining. Other parameters (such as feed rate, depth of cut and cutting speed) showed increasing trends with increases in different parameters. All these methods produced surface roughness values in the range of 2.3–2.775 μm . This was because applying external load against the rotating parts induced surface damages, resulting in higher surface roughness [29]. Figures 6A–6D show the surface of machined metals obtained using different heating methods.

The turning process for duplex SS was optimised for output responses, such as cutting force and surface roughness, with different heating techniques using the TOPSIS method. Based on

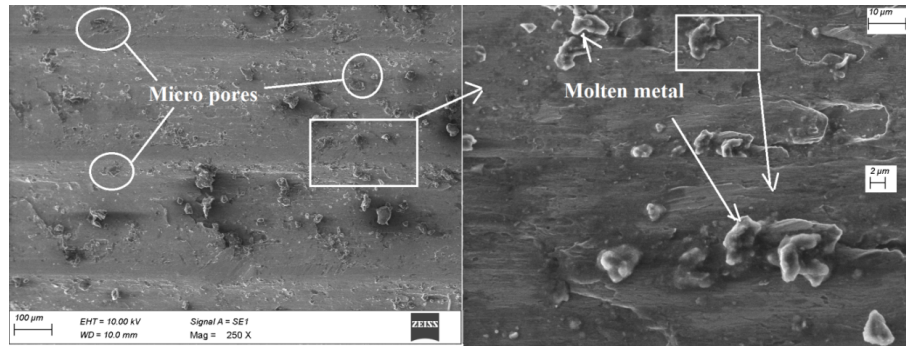
Eqs. (1)–(8), the optimal values were determined. The outcomes of machining were allocated equal weights to obtain an appropriate parameter combination. The calculated preference values are presented in Table 3. The largest or uppermost preference values were considered as the appropriate parameter combination for lesser cutting force and higher surface quality and ranked as the first. According to Table 2, Experiment 16 showed the highest preference value (0.7132) and was ranked the first, and the experimental combination was the HA-assisted heating method, with a feed rate = 0.175 mm/rev, depth of cut = 0.1 mm and cutting speed = 150 m/min as the optimal solution using the TOPSIS method. Experimental runs 15 and 12 provided the second and third optimal combinations, respectively.

To determine the significant factor and its contribution to machining performance, ANOVA was performed [30]. The preference values of TOPSIS were computed and are presented in Table 4. According to Table 4, the heating method and cutting speed significantly influence the output responses, and its values were 26.16% and 30.33%, respectively. The depth of cut contributed 22.23% to machining performance.

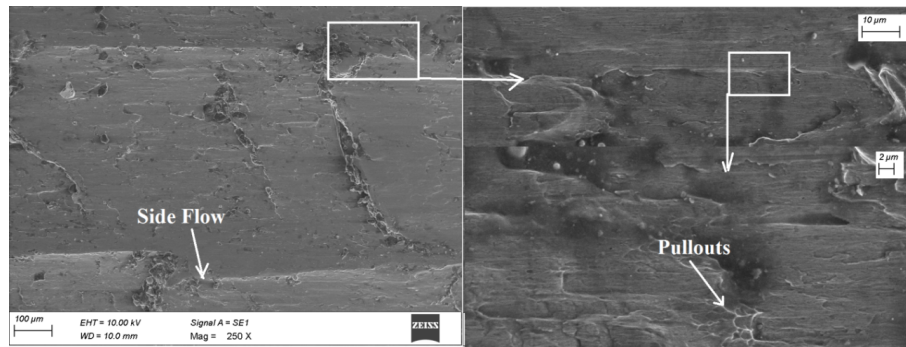
The outcomes of machining, such as cutting force and surface roughness, for different parameters were standardised using Eqs. (9) and (10). The GRC and GRG values were calculated us-



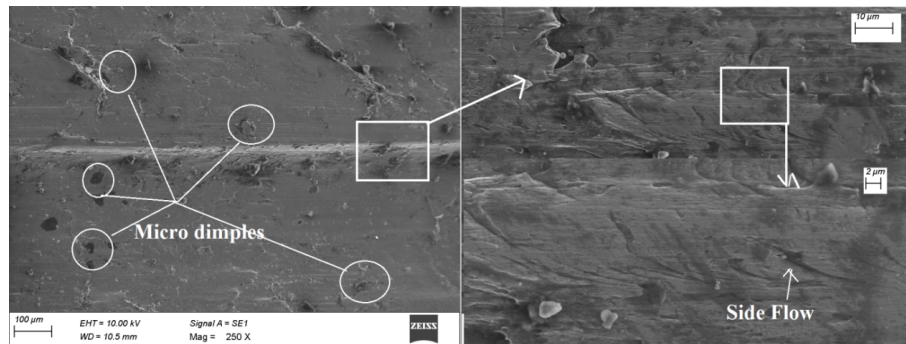
(A)



(B)



(C)



(D)

Fig. 6. SEM images of machined surface obtained under (A) IR-assisted machining, (B) UV-assisted machining, (C) HA-assisted machining and (D) normal machining.
HA, hot air; IR, infrared; SEM, scanning electron microscopy; UV, ultraviolet

Table 3. TOPSIS ranking

Experiment no.	V_i^+	V_i^-	J_i (preference) value	Rank
1	0.0584	0.0313	0.3489	16
2	0.0425	0.0337	0.4425	15
3	0.0485	0.0429	0.4695	13
4	0.0404	0.0378	0.4833	11
5	0.0267	0.0503	0.6528	6
6	0.0387	0.0354	0.4779	12
7	0.0381	0.0336	0.4687	14
8	0.0399	0.0404	0.5032	10
9	0.0287	0.0462	0.6166	8
10	0.0253	0.0531	0.6775	4
11	0.0289	0.0500	0.6342	7
12	0.0230	0.0533	0.6986	3
13	0.0284	0.0594	0.6766	5
14	0.0337	0.0536	0.6136	9
15	0.0258	0.0621	0.7063	2
16	0.0243	0.0605	0.7132	1

V_i^+ , Positive ideal solution; V_i^- , negative ideal solution

TOPSIS, technique for order performance by similarity to ideal solution

Table 4. ANOVA for TOPSIS

Machining parameter	Degree of freedom	Sum of the squares	Mean square	F-value	% Contribution
A	3	0.076439	0.0255	1.308	26.16
B	3	0.048701	0.0162	0.833	16.67
C	3	0.064954	0.0217	1.112	22.23
D	3	0.088611	0.0295	1.517	30.33
Error	3	0.013443	0.0045	0.230	4.60
Total	15	0.2921	0.0195		100

ANOVA, analysis of variance; TOPSIS, technique for order performance by similarity to ideal solution

ing Eqs. (11) and (12), respectively, for all the experiments. The outcomes were assigned equal weightage and their grade rankings are presented in Table 5. The highest GRG was considered as the best parameter combination for better machining. Experimental run 15 showed the highest grade (0.8230) rank, and it was selected as the best machining parameter for the turning process of duplex SS. Experimental runs 16 and 13 showed the next-highest grey grades, and these were considered the second and third optimal combinations for better machining. Hence, as per the GRA method, experimental combination 15 under HA-assisted heating with feed rate = 0.15 mm/rev, depth of cut = 0.2 mm and cutting speed = 200 m/min was determined as the optimal solution using the GRA method.

The calculated GRG values were used to frame the ANOVA table (Table 6). Cutting speed and depth of cut contributed 25.67% and 25.40%, respectively, towards machining performance. The feed rate had the lowest contribution among the three parameters on machining performance (~22.73%) under different heating methods. Based on the analysis, it can be concluded that the HA-assisted heating method, with feed rate in the range of 0.15–0.175 mm/rev, depth of cut in the range of 0.1–0.2 mm and cutting speed of 150–200 m/min, is suitable for obtaining lower cutting force and surface roughness.

Table 5. GRC and GRG values

Experiment no.	GRC		GRC	Rank
	y_0^*	y_i^*		
1	1.0000	0.5517	0.6839	13
2	0.8438	0.6344	0.6853	12
3	0.7714	0.5000	0.7127	10
4	0.9643	0.6000	0.7328	9
5	0.7297	0.9000	0.7599	5
6	0.6429	0.6000	0.6619	16
7	0.7105	0.6344	0.6650	15
8	0.6750	0.8136	0.6806	14
9	0.5870	0.7956	0.7085	11
10	0.5745	0.8471	0.7534	6
11	0.6000	0.9172	0.7338	8
12	0.6279	0.9000	0.7642	4
13	0.5192	0.8944	0.7922	3
14	0.5000	0.9600	0.7343	7
15	0.5400	0.9290	0.8230	1
16	0.5625	1.0000	0.8097	2

GRC, grey relational coefficient; GRG, grey relational grade

Table 6. ANOVA for GRG

Machining parameter	Degree of freedom	Sum of the squares	Mean square	F-value	% Contribution
A	3	0.618799	0.2063	0.842	16.84
B	3	0.835593	0.2785	1.137	22.73
C	3	0.933500	0.3112	1.270	25.40
D	3	0.943359	0.3145	1.283	25.67
Error	3	0.344308	0.1148	0.468	9.37
Total	15	3.6756	0.2450		100

ANOVA, analysis of variance; GRG, grey relational grade

5. Conclusions

The turning process of duplex SS was performed using different heating techniques, and the following conclusions were obtained. The HA- and UV-assisted heating methods significantly decreased the cutting force and the HA-assisted heating method was found to be the best method for producing lesser cutting force among all the considered methods. The HA- and UV-assisted heating methods produced surface roughness = 2.2436 μm and 2.312 μm , respectively, which were 15.13% and 13.14%, respectively, lesser than the roughness obtained with normal machining. For experimental run 16, for the HA-assisted heating method with feed rate = 0.175 mm/rev, depth of cut = 0.1 mm

and cutting speed = 150 m/min was the optimal solution obtained using the TOPSIS method. Based on the ANOVA for TOPSIS, the cutting speed significantly influenced the outcomes approximately 26.16% and 30.33%, respectively, with different heating methods. As per the GRA method, for experimental combination 15 under the HA-assisted heating method, with feed rate = 0.15 mm/rev, depth of cut = 0.2 mm and cutting speed = 200 m/min, the optimal solution was obtained using the GRA method. As per the ANOVA for GRG, the cutting speed and depth of cut showed the highest contribution, that is, 25.67% and 25.40%, respectively. Hence, based on the study, the HA-assisted heating method showed the most significant contribution on the turning process of duplex SS. The

suitable range of parameters for obtaining lower cutting force and surface roughness is HA-assisted heating method with a feed rate range of 0.15–0.175 mm/rev, depth of cut in the range of 0.1–0.2 mm and cutting speed in the range of 150–200 m/min. The future scope of work is to develop passive layer by including electrochemical treatment in the turning process.

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