1. INTRODUCTION

Globally, steel is the most demanding material in modern manufacturing industries due to its excellent characteristics. High strength, durability, versatility, excellent wear and corrosion resistance, toughness, good machinability, and weldability are some attractive characteristics of steel [1]. Steel is an alloy of iron and carbon (less than 2%) that is stronger and more fracture-resistant than other types of ferrous alloys. Elements such as nickel, chromium, manganese, silicon, and phosphorus can also be added to produce different grades of steel alloys with different characteristics. Stainless steel, carbon steel, alloy steel, tool steel, and high-speed steel are some popular types of steel widely used in manufacturing industries. EN8 is an unalloyed medium carbon steel, also referred to as 080M40 [2]. It is popularly used in the manufacturing and production industries for general engineering applications as well as automotive applications due to its intermediate strength, toughness, tensile properties, and good machinability. Heat-treated EN8 steel offers stable machining properties due to its homogeneous metallurgical structure and has improved mechanical and wear resistance. It is available in the normalized or rolled conditions. Excellent wear resistance and good surface hardness were shown by induction-hardened rolled conditions. Excellent wear resistance and good machinability, and weldability are some attractive characteristics of EN8 steel [1]. Steel is an alloy of iron and carbon (less than 2%) that is stronger and more fracture-resistant than other types of ferrous alloys. Elements such as nickel, chromium, manganese, silicon, and phosphorus can also be added to produce different grades of steel alloys with different characteristics. Stainless steel, carbon steel, alloy steel, tool steel, and high-speed steel are some popular types of steel widely used in manufacturing industries. EN8 is an unalloyed medium carbon steel, also referred to as 080M40 [2]. It is popularly used in the manufacturing and production industries for general engineering applications as well as automotive applications due to its intermediate strength, toughness, tensile properties, and good machinability. Heat-treated EN8 steel offers stable machining properties due to its homogeneous metallurgical structure and has improved mechanical and wear resistance. It is available in the normalized or rolled conditions. Excellent wear resistance and good surface hardness were shown by induction-hardened EN8 steel.

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commonly used to form 3D structures on the surface of difficult-to-machine materials with a set of engraving tools. In this process, the cutting tool follows the paths generated by CAD-CAM software to form the desired design on the surface of the workpiece. It employs a set of rotary cutting tools to remove materials from the workpiece to form 3D effects. A wide range of 2D and 3D shapes and patterns can be engraved using this process. Drag engravers, small ball nose end mills, and v-bits are common engraving cutting tools.

Several industries have utilized CNC engraving for a wide variety of applications, such as sign-making, jewelry design, and industrial marking. The CNC engraving milling process is widely employed in tool and dies industries. Manual engraving, laser engraving, CNC rotary engraving, CNC engraving milling, and CNC router engraving are some engraving techniques to make 2D and 3D patterns on flat surfaces. These processes can engrave a variety of materials, such as metal, plastic, and wood. Aluminum, steel, gold, brass, copper, and silver are commonly used metallic materials used for engraving. Some benefits of engraving of 3D patterns are (i) a higher degree of accuracy and precision, (ii) capability to manufacture complex and intricate designs, (iii) fast and efficient, (iv) ease of use, (v) ability to engrave a wide range of materials, (vi) better repeatability, (vii) eco-friendly process.

Researchers have made some past attempts at pro–duct development using various engraving techniques. These efforts address the design, development, challenges, and problems related to engraving processes. The following paragraphs discuss some available past research works on engraving processes and fabrication of rotors.

Martinov et al. [6] developed algorithms for the better performance of laser engraving machines to obtain appropriate speed and precision movements. A better synchronization of motion with laser pulses was obtained. According to experimental results, the developed algorithms were found to significantly increase processing speed by up to 30–50% while maintaining machined part quality when compared to the other algorithms used in other laser engraving machines. Kumar et al. designed and built a laser cutting and engraving machine that an Arduino CNC can easily control [7]. That machine was lightweight, simple to use, inexpensive to produce, and portable from one workstation to another, making it perfect for small and medium-sized industries. In another study, a router engraving machine for wood based on computer numerical control of motion and PLC for CNC engraving and milling machine tools that can achieve high performance at high speed with better accuracy, as well as all interpolation movement. In an interesting study, Durna et al. [15] designed a machine by modifying the 3D printing machine with a work head replacement system that enables it for 3D printing as well as for laser engraving. The modified 3D printer could work as a multifunctional CNC laser engraving machine.

Vdovin and Smelov [16] designed and manufactured the micro gas turbine engine (GTE) rotor using rapid prototyping technology and a complex investment casting process. The finite element method (FEM) was applied to computer modeling using the ProCast software. The part prototype, also referred to as the master model, was manufactured by additive technologies by utilizing the volume model of the µ-GTE rotor as the initial step in the manufacturing process.

Quatrano et al. [17] developed a control system based on Arduino to transform the 3D printing machine into a CNC milling machine. An ArduinoMega microcontroller was used to control the drivers of the stepper motors of the newly developed machine. The developed system was able to machine wood and polycarbonate materials.

It has been observed from past work that many researchers have attempted to develop control systems and setups and convert different processes to milling and engraving. It has also been identified from past attempts that most of the work was focused only on the laser-based engraving technique. Some previous attempts were mainly focused on using the engraving process to manufacture 2D structures and layouts only. In other
words, a scarcity of work has been found on machining the rotor wheels or any other complex 3D parts and components by the engraving milling processes. The motivation of this study is to explore the potential of the CNC engraving milling process to produce 3D parts and components from a variety of materials.

The following are the major objectives and points of novelty of the current research work:

- Manufacturing of the stepped rotor wheel from EN8 steel blank by CNC engraving milling machine.
- Evaluating machinability performance measures for manufacturing small-sized rotor wheels by CNC engraving machine using a tungsten carbide end mill cutting tool.
- Investigations on manufacturing small-sized rotor wheels by CNC engraving milling machine to analyze the effects of rotational speed, feed, and plunge feed on surface quality (maximum roughness depth ‘R̴’) of the rotor blade and productivity of the process (material removal rate ‘MRR’).
- To identify significant process variable parameters affecting R̴ and MRR.
- To identify the optimal variable combination for manufacturing better surface quality of the stepped rotor wheel without compromising the productivity of the CNC engraving milling machine.
- Micrograph analysis of end mill cutter and stepped rotor wheel manufactured at optimal variable combination.

2. EXPERIMENTATION AND MEASUREMENTS

Using an end mill cutting tool, a computer numerical control (CNC) engraving machine was designed and developed to manufacture small stepped rotor wheels from EN8 steel blanks. Fig. 1(a) shows the developed CNC engraving milling machine. This machine is equipped with drives for the linear movement of the workpiece in X and Y directions and the rotation of the cutting tool in clockwise and anticlockwise directions. The CNC router firmly holds the cutting tool and can move up and down in the Z direction. The cutting tool rotates at a given speed during machining.

The four flutes and 4 mm diameter end mill tungsten carbide tools (Fire-VHM Schafta DIN 6527l R-N HRC 56; Manufacture: Gurhing; Country of origin: Germany) with a hardness of 56 HRC on the Rockwell scale were used for manufacturing the stepped rotor wheels from EN8 steel cylindrical bars by CNC engraving milling machine using suitable coolant. The end mill cutting tools have a right-hand helix and four cutting edges. The cutting tool surface is coated with tungsten titanium aluminum nitride (TiAlN) with the help of CVD or PVD processes. Fig. 1(b) shows the end mill cutting tool used in this study.

A 450 mm long and 28 mm diameter round bar made of EN8 stainless steel was used to prepare fifteen cylindrical blanks having 25 mm diameter and 25 mm height, as shown in Fig. 2. After that, turning and drilling were performed to prepare the stepped blank to manufacture the stepped rotor wheel with the hub (17 mm diameter), blind bore (9 mm diameter and 10 mm long) and screw hole (4 mm diameter).
Table 1: Details of selected engraving milling variables and their levels, constant parameters, considered responses, specification of end mill and rotor wheel, chemical composition of rotor blank material, and experimental combinations.

<table>
<thead>
<tr>
<th>E.No.</th>
<th>BBD-RSM-based experimental runs</th>
<th>Details of experimentation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Engraving milling variable combinations</td>
<td>Variables</td>
</tr>
<tr>
<td></td>
<td>Rotational speed ( 'S_R' (\text{rpm}) )</td>
<td>( S_R ) (rpm)</td>
</tr>
<tr>
<td></td>
<td>Feed ( 'f' (\text{mm/min}) )</td>
<td>( f ) (mm/rev)</td>
</tr>
<tr>
<td></td>
<td>Plunge feed ( 'P_f' (\text{mm}) )</td>
<td>( P_f ) (mm)</td>
</tr>
<tr>
<td>1</td>
<td>5500 (-1) 800 (-1) 125 (0)</td>
<td>( 'S_R' (\text{rpm}) )</td>
</tr>
<tr>
<td>2</td>
<td>5500 (-1) 900 (0) 150 (1)</td>
<td>( 'f' (\text{mm/rev}) )</td>
</tr>
<tr>
<td>3</td>
<td>5500 (-1) 900 (0) 100 (-1)</td>
<td>( 'P_f' (\text{mm}) )</td>
</tr>
<tr>
<td>4</td>
<td>5500 (-1) 1000 (1) 125 (0)</td>
<td>( Constant parameters )</td>
</tr>
<tr>
<td>5</td>
<td>6000 (0) 800 (-1) 150 (1)</td>
<td>Blank size; Blank and cutting tool materials; Coolant; Plunge down</td>
</tr>
<tr>
<td>6</td>
<td>6000 (0) 800 (-1) 100 (-1)</td>
<td>Machinability performance measures</td>
</tr>
<tr>
<td>7</td>
<td>6000 (0) 900 (0) 125 (0)</td>
<td>Maximum roughness depth ( 'R_t' ) and Material removal rate ( 'MRR' )</td>
</tr>
<tr>
<td>8</td>
<td>6000 (0) 900 (0) 100 (-1)</td>
<td>Specifications of end mill cutting tool</td>
</tr>
<tr>
<td>9</td>
<td>6000 (0) 1000 (1) 100 (-1)</td>
<td>Manufacturer: Gurhing; Dia.: 4 mm Flute: 4; Cutting edge: 4; Helix: Right hand; Cutting direction: Clockwise; Material: Carbide; Coated material: TiNAl (VHM)</td>
</tr>
<tr>
<td>10</td>
<td>6000 (0) 1000 (1) 150 (1)</td>
<td>Specifications of the stepped rotor wheel</td>
</tr>
<tr>
<td>11</td>
<td>6500 (1) 800 (-1) 125 (0)</td>
<td>Material: EN8 steel; Rotor Type: Semi-open; Diameter: 25 mm; Shroud width: 10 mm; Hub diameter: 17 mm; Hub width: 10 mm; Bore type: Blind; Bore diameter: 9 mm; Bore length: 10 mm; Blade type: Curved; Number of rotor blade: 6; Blade width: 5 mm; Blade thickness: 2 mm; Blade profile: curved type; Rotor eye diameter: 10 mm</td>
</tr>
<tr>
<td>12</td>
<td>6500 (1) 900 (0) 125 (0)</td>
<td>Chemical composition (%) of EN8 blank</td>
</tr>
<tr>
<td>13</td>
<td>6500 (1) 900 (0) 100 (-1)</td>
<td>C: 0.36-0.44; Si: 0.1-0.4; Mn: 0.6-1.0; P: 0.05; S: 0.05; Cr: 0.3; Ni: 0.25; Rest: Fe</td>
</tr>
<tr>
<td>14</td>
<td>6500 (1) 1000 (1) 125 (0)</td>
<td>No. of Blades: 6</td>
</tr>
</tbody>
</table>

Fig. 3 (a) shows the schematic 3D views of the proposed stepped rotor wheel to be manufactured by a CNC engraving milling machine. Whereas, Fig. 3(b) presents detailed specifications and actual 3-dimensional views of the manufactured stepped rotor wheel having a curved profile blade, 25 mm outer diameter, 5 mm blade face width, 2 mm blade thickness, 17 mm hub diameter, 9 mm bore diameter, 10 mm bore length and 4 mm screw hole in this study.

Table 1 presents the detailed specifications of the manufactured EN8 steel stepped rotor wheel along with its chemical composition.

Rotational speed \( 'S_R' \), feed \( 'f' \), and plunge feed \( 'P_f' \) are available parameters in the CNC engraving milling machine. These parameters were considered as machining variables, while maximum roughness depth \( 'R_t' \) and material removal rate \( 'MRR' \) were selected as machinability performance measures. Each machining variable has three levels. The machining variables and levels were selected with the view of CNC machine and end-mill cutting tool constraints, design of experiments (DoE), and preliminary experiments (PE).

A single rotor blade was manufactured in preliminary experiments using the one-variable-at-time approach of DoE by CNC engraving milling machine using suitable coolant. It was found that better surface quality (roughness), dimensional accuracy, the profile of the rotor blade, minimum tool wear, and productivity can be achieved at machining variables varying from 6000 to 9000 rpm as rotational speed of the cutting tool, 800 to 1000 mm as feed, and 100 to 150 mm as plunge feed. Tool wear can be easily identified by manual observation during machining, such as excessive noise and chattering, and visual inspection, such as burr formation at the corner edge (Fig. 4) and the machined surface of the manufactured rotor blades.

![Figure 3. 3D views and specifications of the stepped rotor wheel: (a) schematic 3D CAD views of the proposed stepped rotor wheel; and (b) specifications of actual manufactured stepped rotor wheel](image-url)
Excessive tool wear is the reason behind the abnormal noise during machining. Over this range of machining variables, excessive noise was noticed during the milling of the single blade of the rotor.

On the other hand, when the machine variables were beyond the range during the machining of the single rotor blade, excessive tool wear and burr formation were observed on the edges of the blade and the perimeter of the rotor wheel.

A manual examination can easily detect poor surface quality (tool marks and burrs) on the manufactured rotor blade. The productivity of the CNC engraving milling machine was drastically reduced below the indicated range of machine variables. On the other hand, rotor blade surface quality was considerably diminished at rotating speeds below range.

Figure 4. Burr formation at the corner edge of the rotor due to tool wear

In this study, fourteen distinct combinations of machining variables (i.e., rotational speed ‘\(S_R\)’, feed rate ‘\(f\)’, and plunge feed ‘\(f_p\)’) were designed using the Box-Behnken design (BBD) of response surface methodology (RSM). Each combination of machining variables indicates the experimental run. Therefore, a total of fourteen experimental runs were conducted to manufacture small-sized rotor wheels by a CNC engraving milling machine using end mill cutters with 4 mm diameter and 4 flutes.

In each experimental run, different end-mill cutters of the same specifications were used to manufacture small-sized rotor wheels with the help of a CNC engraving milling machine. Every run was conducted twice to reduce the error of the chosen machinability performance measures, namely maximum roughness depth (\(R_a\)) and productivity (\(MRR\)) caused by uncontrolled variation during the machining, and to enhance the statistical precision of the experimental runs. Thus, twenty-eight small-sized rotor wheels were manufactured by the CNC engraving milling machine used in this study.

Taguchi designs are available in L9, L17, and L27. However, it is difficult to obtain valuable information using the Taguchi L9 experimental design. Whereas L17, L27, and factorial design significantly increase the number of experiments compared to BBD and convey similar information. Hence, keeping the above experimental comparative evaluation, BBD of RSM was selected for conducting fourteen experiments to manufacture small-sized rotor wheels in this study. Table 1 shows the BBD of RSM-based fourteen combinations of machine variables, including two center points, selected machine variables, their levels, constant parameters, specifications of end mill cutter and manufactured wheel, and chemical composition of EN8 steel bar. Two experimental runs (i.e., experimental runs 7 and 8), corresponding to the center point design, are similar and have the same values of machine variables.

Material removal rate ‘\(MRR\)’ indicates the productivity of the machine. The material removal rate is determined by the volume of material (in grams) removed and the total amount of time (in minutes) required for the CNC engraving milling machine to machine the rotor wheel. Equation 1 was used to calculate the material removal rate. Both before and after machining, the stepped blank was weighed using precision weighing equipment (Model: DS852G from Essay Group firm, India) with an accuracy of up to 0.01 g. The total time taken for the machining of the rotor wheel was directly recorded from the CNC engraving milling machine’s display screen.

\[
MRR = \frac{\text{Weight of material lost during machining of stepped blank}}{(\text{Density of EN8} \times \text{Total machining time \(\min\)})} \left(\frac{\text{mm}^3}{\text{min}}\right) (1)
\]

The LD-130 3D roughness contour tracing machine, manufactured by Mahr Metrology (Germany), was utilized to measure the roughness of the machined surface of rotor wheels using a 2 µm diameter probe. Roughness measurements were carried out in accordance with ISO 4287, using a Gaussian filter, 0.8 mm cut-off length, and 2 mm evaluation length. Roughness measurements were taken at two distinct locations on the machined surface of the blade, along the opposite direction of the tool movement. Roughness measurements were made on the two opposing blades of each rotor wheel. Thus, four roughness measurements were made for each rotor wheel, and the average of those readings was taken into account for data analysis. A field-emission scanning electron microscope (FE-SEM) SUPRA 55 from Carl Zeiss (Germany) was also used for capturing micrographs of the cutting tool and the rotor wheel produced in the best possible variable combination.

3. RESULTS AND DISCUSSION

This section presents the results obtained from experimental runs by manufacturing EN8 small-sized stepped rotor wheels by CNC engraving milling machine using a 4 mm diameter tungsten carbide end mill cutter. Multi-objective optimization and FE-SEM analysis of the cutting tool and rotor wheel manufactured at optimum variable combinations are also discussed in this section. Table 1 summarizes the fourteen experimental runs, i.e., combinations of machining variables with their actual values and coded levels.
Figure 5. Variation of considered machinability measures with experimental runs: (a) material removal rate and (b) maximum roughness depth.

Fig. 5 illustrates how the two responses under consideration i.e. \( R_t \) and \( MRR \), vary across the experimental runs. It also indicates the values of \( R_t \) and \( MRR \) of each experimental run. It can be observed from Fig. 5 that the experimental run 14 has maximum values of \( R_t \) and \( MRR \). Whereas, experimental runs 11 and 6 have a minimum value of \( MRR \) and \( R_t \), respectively.

3.1 Effects of machine variables on machinability performance measures

Figures 6-8 depict the influence of engraving variables, namely rotational speed \( 'SR' \), feed \( 'f' \), and plunge feed \( 'Pf' \), on machinability measures, namely maximum roughness depth \( (R_t) \) and material removal rate \( (MRR) \). The purple line in these graphs indicates the maximum roughness depth, and the dark red line indicates the material removal rate. The response axis, or Y-axis, is represented by the orange line, and the Y-axis gridlines are represented by the light blue dotted line. It can be observed from Fig. 6 that rotational speed has a negligible impact on machinability measures, i.e., \( MRR \) and \( R_t \). These machinability performance measures are slightly increased with rotational speed. Whereas it can be seen from Figs. 7 and 8, feed and plunge feed significantly influence both \( MRR \) and \( R_t \).

3.2 Other machine variables on machinability performance measures

\( MRR \) and \( R_t \) increase linearly with an increase in feed and plunge feed. The feed impacts \( MRR \) and \( R_t \) more than rotational speed and plunge feed. Rotational speed indicates the rotation of the cutting tool in clockwise directions along the downward Z axis. It doesn't move along X and Y directions except for upward and downward Z directions. Feed indicates the movement of the workpiece in X and Y with respect to the cutting tool according to the part program. Therefore, higher feed values result in faster removal of materials from the workpiece in the predefined path according to the part program. Hence, the plunge feed indicates the speed at which the cutting tool moves to its initial position, including the plunge up and down after each step of cutting to perform the next step.
In this study, each rotor wheel blade was manufactured in a hundred steps of cutting tool in the first stage of engraving. The 50 µm, 100 µm, and 100 µm are the values of plunge down in stage and stage 2 and 3, respectively. In the engraving process, the cutting tool left the tool marks in each step. Therefore, the higher value of the plunge feed reduces the machining time, increasing the material removal rate and the roughness.

The success of any machining operation like engraving milling cannot be determined solely by analyzing how machining variables affect machinability measures. Multi-response optimization is necessary to ensure the optimum performance of any machining operation. Therefore, the machining variables must be optimized using an appropriate technique to obtain the optimum machinability measures. The statistical technique known as desirability function analysis (DFA) has been employed with objective functions to minimize maximum roughness depth (i.e., smaller-the-better type) and maximize the material removal rate (i.e., higher-the-better type) [18]. The equal weightage (0.5) has been assigned to both machinability measures. Equations 2 and 3 were used to compute the desirability of $R_t$ and $MRR$.

For minimization of the maximum roughness depth ‘$R_t$’ (i.e., smaller-the-better type)

$$d_{W_j} = \left( \frac{R_{t,\text{max}} - R_{t,j}}{R_{t,\text{max}} - R_{t,\text{min}}} \right)^{0.5}$$  \hspace{1cm} (2)

For maximization of the material removal rate ‘$MRR$’ (i.e., higher-the-better type)

$$d_{W_j} = \left( \frac{MRR_{j} - MRR_{\text{max}}}{MRR_{\text{max}} - MRR_{\text{min}}} \right)^{0.5}$$  \hspace{1cm} (3)

where $R_{t,\text{max}}$, $MRR_{\text{max}}$, $R_{t,\text{min}}$, and $MRR_{\text{min}}$ indicate the highest and lowest values of maximum roughness depth and material removal rate within experimental runs. The highest values used for maximum roughness depth and material removal rate are 4.86 µm and 48.56 mm³/min, respectively. At the same time, the corresponding lowest values are 1.26 µm and 30.92 mm³/min, respectively.

Equations 4 and 5 can be used to calculate the overall desirability function ‘$D_j$’ for the $j^{th}$ combination of the considered machinability performance measures.
\[ D_j = \left[ \left( \frac{d_{R_j}}{d_{MRR_j}} \right)^{0.5} \right]^{0.5} \]

\[ D_j = \left[ \left( \frac{d_{R_j}}{d_{MRR_j}} \right)^{0.5} \right]^{0.5} \]

The optimum results (i.e., 2.82 µm \( R_t \) and 41.36 mm³/min \( MRR \)) predicted from the best desirability (i.e., 0.761) were validated by conducting two confirmation experiments (CEs) at optimal variables combination (i.e., 6496 mm/min as \( SR \); 898 mm/min as \( f \); and 100 mm/min as \( Pf \)) as given in Table 2. The percentage difference of \( R_t \) and \( MRR \) obtained from DFA and CEs was computed using the average values of \( R_t (2.70 + 3.20 = 2.95 \mu m) \) and \( MRR (43.1 + 43.8 = 43.45 \text{ mm}^3/\text{min}) \) of CEs. The CEs and DFA results differ by less than 5%, indicating a good agreement between predicted and actual values.

### Table 2: Results of optimization and confirmation experiments.

<table>
<thead>
<tr>
<th>Machining details</th>
<th>Optimal results (DFA)</th>
<th>Confirmation results CE1</th>
<th>Confirmation results CE2</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine variables</td>
<td>Rotational speed ( 'SR' ) (rpm)</td>
<td>6496</td>
<td>6496</td>
<td></td>
</tr>
<tr>
<td>Feed ( 'f' ) (mm/min)</td>
<td>898</td>
<td>898</td>
<td>898</td>
<td></td>
</tr>
<tr>
<td>Plunge feed ( 'P_f' ) (mm/min)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Machinability measures</td>
<td>Maximum roughness depth ( R_t ) (µm)</td>
<td>2.82</td>
<td>2.70</td>
<td>3.20</td>
</tr>
<tr>
<td>Material removal rate ( MRR ) (mm³/min)</td>
<td>41.36</td>
<td>43.1</td>
<td>43.8</td>
<td>43.45</td>
</tr>
</tbody>
</table>

#### 3.2 Analysis of rotor wheel manufactured at optimum variables combination

A total of two small-sized rotor wheels were manufactured using the optimum variables of a combination of CNC engraving milling machines obtained from multi-objective optimization using a 4 mm diameter carbide end mill cutter. Fig. 9 depicts the captured 2D roughness profile (for CE1 value of \( R_t \) as given in Table 2) for the small-sized rotor wheel manufactured at optimum variables combination. It was found from roughness measurement that the best optimum rotor wheel has maximum roughness depth \( R_{max} = 2.95 \mu m \); average roughness \( R_a = 0.28 \mu m \); mean roughness \( R_{\text{mean}} = 1.6 \mu m \); Skewness- 0.25; and Kurtosis- 4.034. The positive value of Skewness indicates the higher peak distribution on the machined surface of the rotor blade, which indicates better tribology behavior. The value of kurtosis greater than 3 indicates good bearing strength of the machined surface rotor blade.

Figures 10 and 11 illustrate scanning electron microscopic (SEM) micrographs of cutting tools and rotor blades. Figure 10(a) shows the micrograph of the end-mill cutter at 25x after manufacturing the stepped rotor wheel at machining combination 14 (i.e., exp. run 14: \( 'SR': 6500 \text{ rpm}; \text{feed}: 1000 \text{ mm/min}; \text{and} \ P_f: 150 \text{ mm/min} \)) having maximum roughness and material removal rate. Fig. 10(b) depicts the micrograph of the end mill cutter at 50x after manufacturing the rotor wheel at optimum variables combination.

![SEM micrograph of rotor wheel](image_url)

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deposition of removed fine particles of the blank and tool materials on the top surface of the rotor blade can be observed in Fig. 11(a). This happened due to excessive heat formation and faster material removal from the rotor blank at maximum values of machine variables. Whereas a comparatively smoother surface with minimum burr formation can be observed in Fig. 11(b) due to minimum tool wear and heat generation at optimum variables combination.

Fig. 11: SEM micrographs of CNC engraved rotor blades machined at (a) experimental run 14 (i.e., max. Rt and MRR) and (b) at optimum variables combination.

4. CONCLUSIONS

In this research, the small-sized stepped rotor wheels have been successfully manufactured from EN8 steel cylindrical blank by a CNC engraving milling machine using a tungsten carbide end mill cutter of 4 mm diameter. Detailed investigations on CNC engraving milling machine with carbide end mill cutter were carried out to manufacture the stepped rotor wheel from EN8 steel blank. Multi-objective optimization was employed to find the optimum variable combination, i.e., rotational speed, feed, and plunge feed, to secure the best surface quality of the rotor wheels using the developed CNC engraving milling machine with higher productivity. The conclusions drawn from this investigation are as follows:

- Successfully manufactured the stepped rotor wheel by engraving milling process using a CNC machine tool.
- The feed and plunge feed of the engraving milling machine tool has significantly influenced the maximum roughness depth 'Rt' and material removal rate 'MRR'.
- Feed was observed as the most significant variable compared to plunge feed and rotational speed.
- $R_t$ and MRR increased linearly with an increase in feed rate and depth of cut.
- Rotational speed has a negligible impact on $R_t$ and MRR compared to feed and plunge feed.
- Maximum $R_t$ and MRR were reported at high values of engraving variables, i.e., 6500 rpm as rotational speed, 1000 mm/min as feed, and 125 mm/min as plunge feed (experimental run 14).
- Optimum values of $R_t$ and MRR can be achieved at 6496 rpm as rotational speed, 898 mm/min as feed, and 100 mm/min as plunge feed.
- 2.95 µm as $R_t$ and 43.45 mm³/min as MRR were obtained at optimum variables combination.
- SEM micrographs of the cutting tool revealed tool wear and deposition of fine particles of the blank on the cutting tool face when the process was performed at high values of engraving variables (experimental run 14).
- SEM micrographs of the rotor blade manufactured at optimum variables combination showed a uniform and accurate geometrical profile of the rotor blade along with the burr formation on the corner edges of the blade and deposition of fine particles on the top surface of the blade.
- The experimental values of $R_t$ and MRR are close to their corresponding predicted values, with a deviation of less than 5%.
- Potential directions for future study on the CNC engraving milling process include (i) fabrication of miniature rotor wheels made from other difficult-to-machine materials; (ii) measurement of micro- and macro-geometry parameters of the rotor blade such as blade profile, blade thickness, blade gap, surface topography, and wheel diameter; (iii) tool wear and tribological analysis (i.e., wear and hardness); and (iv) manufacturing of gears from difficult-to-machine materials using CNC engraving milling process.

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