Investigation on Manufacturing of Small-Sized Stepped Rotor Wheel by Engraving Milling Process

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This study aims to explore the potential of the engraving milling process to manufacture 3D structures and layouts like rotor wheels. An experimental study was carried out to manufacture a stepped rotor wheel from EN8 steel blank using a computer numeric control (CNC) engraving milling machine tool. The impact of variable parameters, namely rotational speed (S_R), feed (f), and plunge feed (P_f), on maximum roughness depth (R_t) and material removal rate (MRR) was determined through a total of fourteen tests, each with two replications based on Box-Behnken design (BBD) of the response surface methodology (RSM). The best variable combination was found using desirability functional analysis (DFA) with goals of minimizingRt and maximizing the MRR. The best values achieved at the optimal combination of variable parameters were 2.95 µm as Rt and 43.45 mm3/min as MRR. Micrographs of the rotor wheel blades and cutting tool supported the findings.

Keywords: *Engraving, EN8 Steel, Surface roughness, Optimization, Productivity, Rotor wheel.*

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 EN8 steel. The tensile strength and machinability of EN8 steel are similar to the stainless-steel grade 304 (SS-304). It is an excellent material for applications where higher values of mechanical properties are desirable. Some of the common applications of EN8 carbon steel are in gears, shafts, crankshafts, axles, spindles, hydraulic fittings, machinery parts, fasteners., pins, studs, bolts, keys, and other components.

The rotor wheel is a key component of a pump or turbine system [3]. Rotor wheels have blades with curved wall structures placed on the upper face of the wheel at regular intervals along its periphery. The pur–pose of these blades is to convert the energy into rotational motion. The surface quality of the rotor wheel governs its performance and durability. Casting, depo–sition techniques, Lithographie, Galanoformung, and Abformung (LIGA), extrusion, and electric discharge machining (EDM) are some manufacturing methods of the rotor wheel. However, manufacturing the rotor wheel is difficult due to certain restrictions associated with processes, materials, and cutting tools. Casting and deposition techniques are suitable for high-fluidity materials, whereas extrusion is suitable for non-ferrous materials only. LIGA can produce high aspect ratio micro-sized rotor wheels with superior dimensional accuracy and surface finish. However, the process is highly complex and costly because it requires an X-ray and an ultra-violet light source for the X-ray LIGA and UV LIGA processes, respectively. EDM is a very slow process, requires fabricating a complex shape tool, and is suitable for electrically conductive materials only. Furthermore, these processes are not suitable for the mass production of small-sized rotor wheels [4].

In this work, we attempted to investigate a different method for producing the stepped rotor wheels, called computer numerical control (CNC) engraving milling. Engraving is a machining process of cutting grooves into a hard, usually flat surface to make a 3D pattern [5]. In this process, a set of cutting tools gradually re–moves a small amount of material from a flat surface along a predetermined path. This is a subtractive process that leaves tool marks on the machined surface of the substrate. The CNC engraving milling process is

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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, je–welry 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 preci–sion, (ii) capability to manufacture complex and intri–cate 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 addressed 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 deve–loped 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 eng–raving machine that an Arduino CNC can easily control [7]. That machine was lightweight, simple to use, inexpensive to produce, and portable from one work–station to another, making it perfect for small and me–dium-sized industries. In another study, a router engraving machine for wood based on computer nume–rical control (CNC) was designed and built by Bangse et al. [8]. The developed router engraving machine used a stepper motor driven by the TB 6600 driver coupled with a ball screw on a linear bearing to achieve precise 3-axis motion, ensuring accurate and reliable wood engraving. Their research findings showed that the developed CNC router engraving machine could achi–eve a machining accuracy of approximately 99.5 percent for the X and Y axes and 96% for the Z axis.

Based on an open CNC system, Cao et al. [9] pro–posed a design approach to develop a three-dimensional milling and engraving machine. The developed machine was equipped with a multi-function, high-efficiency numerical control device capable of processing metal and non-metallic components. Experimental results re–vealed that the developed machine could mill and engrave metal as well as non-metallic parts with high efficiency and better quality. Choudhary et al. [10] proposed a venture to develop a CNC milling machine to scratch and penetrate the circuit on the substrate material to make the printed circuit board (PCB) at a reasonable cost.

Khalid et al. [11] developed a low-cost laser engra–ving machine to engrave desired designs on plastics, acrylic, glass, wood, cardboard, and leather. The 3D modeling and simulation of the apparatus were done using CREO 2.0 software. The performance of the de–veloped laser engraving machine was found satisfactory in terms of machining cost and part quality. Kumar et al. [12] designed and developed a 3-axis CNC milling machine. The deve–loped machine was equipped with Arduino IDE and CNC software. Many components of the developed mac–hine were manufactured using 3D printing. Stepper motors and lead screws were used to achieve precise motion du–ring machining. The developed machine tool was claimed to be used for milling, laser cutting, and engraving for a specific-sized workpiece.

Lei et al. [13] experimentally studied the precision of laser engraving on the quality of UV-coated paper. They reported that the optimal engraving precision can be achieved with a laser power of 11 W and a preset width of 0.26 mm. They also reported achieving higher engraving precision with the increased laser power. In an important study, Lian et al. [14] proposed an open architecture 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 soft–ware. 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 attem–pts 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:

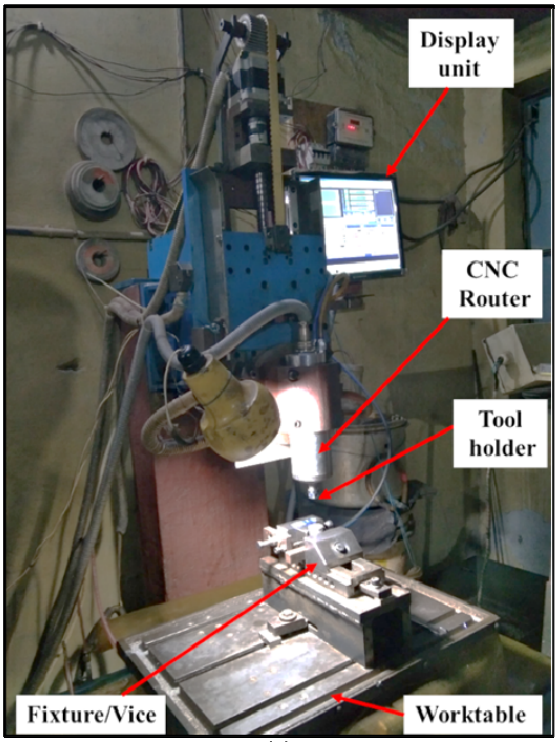
- Manufacturing of the stepped rotor wheel from EN8 steel blank by CNC engraving milling machine.
- Evaluating machinability performance measures for manufacturing small-sized rotor wheels by CNC engraving machine using a tungsten carbide end mill cutting tool.
- Investigations on manufacturing small-sized rotor wheels by CNC engraving milling machine to analyze the effects of rotational speed, feed, and plunge feed on surface quality (maximum roughness depth 'R_t') of the rotor blade and productivity of the process (material removal rate '*MRR*').
- To identify significant process variable parameters affecting R_t 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 Schaftra 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).



(a)


(b)

Figure 1. Machine and cutting used to manufacture stepped rotor wheel: (a) CNC engraving milling machine; and (b) tungsten carbide end-mill cutter

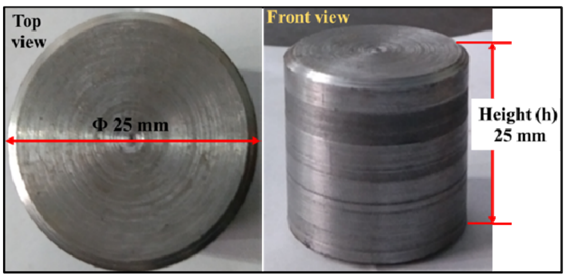


Figure 2. 3D views of the actual EN 8 steel rotor blank with dimensions

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.

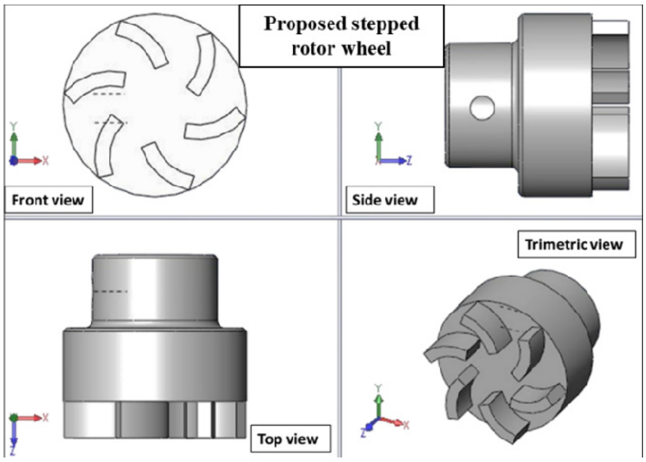
E.No.	BBD-RSM-based experimental runs			Details of experimentation			
	Engraving milling variable combinations			Variables	Levels		
	Rotational speed 'S_R'(rpm)	Feed '*f*' (mm/min)	Plunge feed '*Pf*' (mm/min)		*L (-1)*	*M(0)*	*H(1)*
1	5500 (-1)	800 (-1)	125 (0)	'S_R' (rpm)	5500	6000	6500
2	5500 (-1)	900 (0)	150 (1)	'*f*' (mm/rev)	800	900	1000
3	5500 (-1)	900 (0)	100 (-1)	'*Pf*' (mm)	100	125	150
4	5500 (-1)	1000 (1)	125 (0)	***Constant parameters***			
5	6000 (0)	800 (-1)	150 (1)	Blank size; Blank and cutting tool materials; Coolant; Plunge down			
6	6000 (0)	800 (-1)	100 (-1)				
7	6000 (0)	900 (0)	125 (0)	***Machinability performance measures***			
8	6000 (0)	900 (0)	125 (0)	Maximumroughness depth 'R_t' and Material removal rate '*MRR*'			
9	6000 (0)	1000 (1)	100 (-1)				
10	6000 (0)	1000 (1)	150 (1)	***Specifications of end mill cutting tool***			
11	6500 (1)	800 (-1)	125 (0)	Manufacturer: Gurhing; Dia.: 4 mm Flute: 4; Cutting edge: 4; Helix: Right hand; Cutting direction: Clockwise; Material: Carbide; Coated material: TiNAl (VHM)			
12	6500 (1)	900 (0)	150 (1)				
13	6500 (1)	900 (0)	100 (-1)				
14	6500 (1)	1000 (1)	125 (0)				
Specifications of the stepped rotor wheel							
Material: EN8 steel; Rotor Type: Semi-open; Diameter: 25mm; 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							
Chemical composition (%) of EN8 blank							
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							

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-dimen–sional 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.

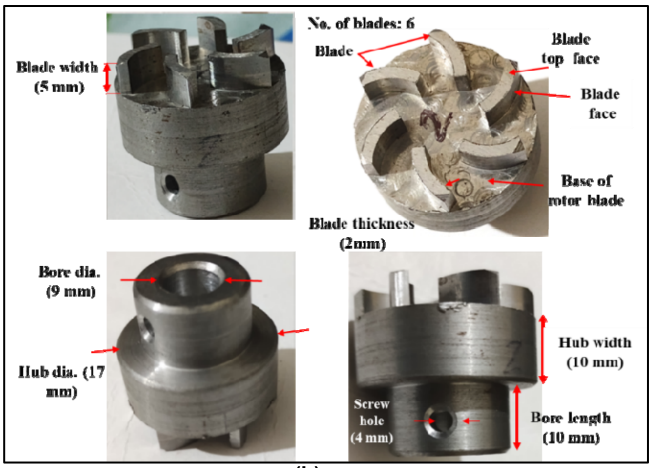
Table 1 presents the detailed specifications of the manufactured EN8 steel stepped rotor wheel along with its chemical composition.

Rotational speed 'R_S', feed '*f*', and plunge feed 'P_f' are available parameters in the CNC engraving milling machine. These parameters were considered as machi–ning variables, while maximum roughness depth 'R_t' and material removal rate '*MRR*' were selected as mac–hinability performance measures. Each machining vari–able 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 prelimi–nary experiments using the one-variable-at-time appro–ach 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.



(a)



(b)

Figure 3. 3D views and specifications of the stepped rotor wheel: (a) schematic 3D CAD views of the proposed step–ped rotor wheel; and (b) specifications of actual manufac–tured stepped rotor wheel

Excessive tool wear is the reason behind the abnor–mal noise during machining. Over this range of machi–ning 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.

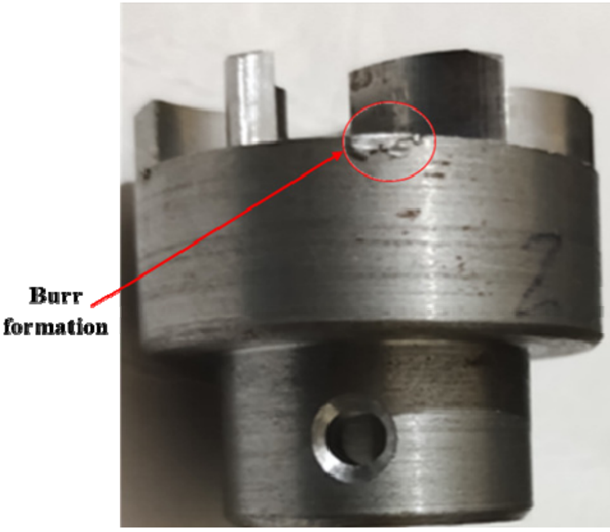


Figure 4. Burr formation at the corner edge of the rotor due to tool wear

In this study, fourteen distinct combinations of machining variables (i.e., rotational speed 'S_R', feed rate 'f', and plunge feed 'P_f') were designed using the Box-Behnken design (BBD) of response surface metho–dology (RSM). Each combination of machining varia–bles indicates the experimental run. Therefore, a total of fourteen experimental runs were conducted to manufac–ture 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, diffe–rent 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_t) 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 L_9, L_{17}, and L_{27}. However, it is difficult to obtain valuable information using the Taguchi L_9 experimental design. Whereas L_{17}, L_{27}, 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 combi–nations of machine variables, including two center points, selected machine variables, their levels, constant parameters, specifications of end mill cutter and manu–factured 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.

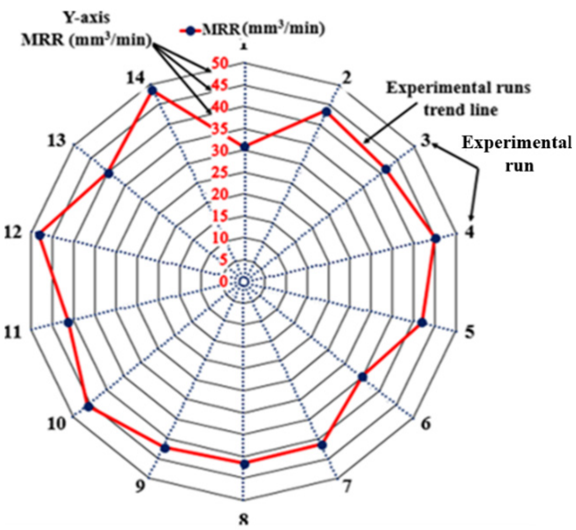
Material removal rate *'MRR'* indicates the produc–tivity of the machine. The material removal rate is de–termined by the volume of material (in grams) removed and the total amount of time (in minutes) required for the CNC engraving milling machine to machine the rotor wheel. Equation 1 was used to calculate the mate-rial 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.

$$MRR = \\ = \frac{\begin{pmatrix} \text{Weight of material lost during} \\ \text{machinig of stepped blank} \end{pmatrix}}{(\text{Density of EN8} \times \text{Total machining time})} \left(\frac{mm^3}{\text{min}} \right) \quad (1)$$

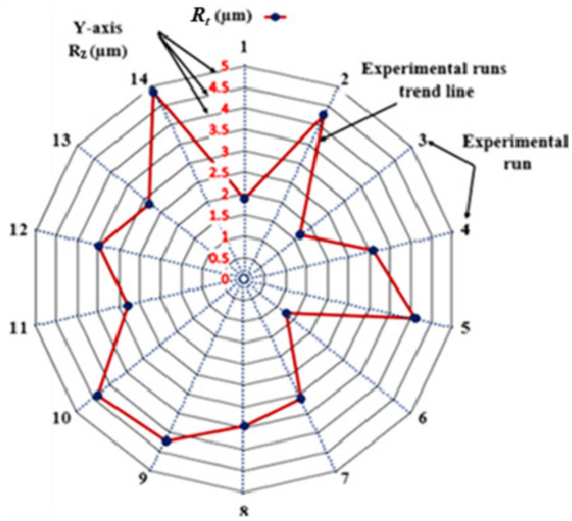
The LD-130 3D roughness cum contour tracing machine, manufactured by Mahr Metrology (Germany), was utilized to measure the roughness of the machined surface of rotor wheels using a 2 µm diameter probe. Roughness measurements were carried out in accor–dance with ISO 4287, using a Gaussian filter, 0.8 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 measure–ments 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 experi–mental 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.



(a)



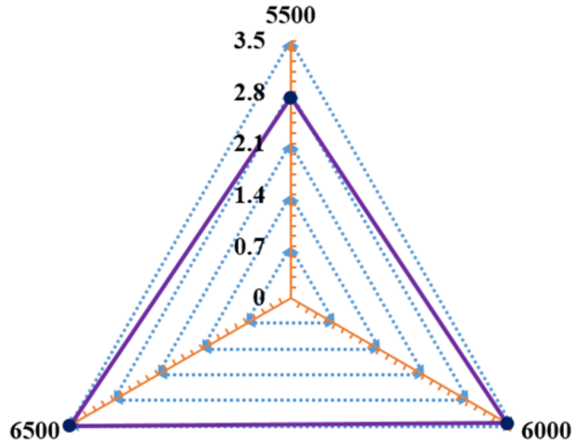
(b)

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 consi–deration 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 'S_R', feed *'f',* and plunge feed *'P_f',* 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* andR_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* andR_t.


(a)

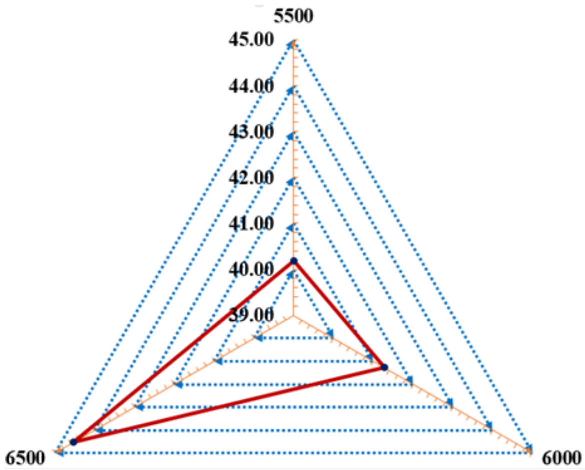

(b)

Figure6. Variation in machinability measures with rotational speed: (a) maximum roughness depth and (b) material removal rate

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. Higher values of materials removal from the stepped rotor blank also increase the roughness of the machined surface. In the engraving process, the cutting tool removes the material from the workpiece layer by layer in several steps to bring it to the desired shape and size. The cutting tool moves upward after each step of cutting, goes back to its initial position, and then moves downward at a certain depth known as plunge down, as given in 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.

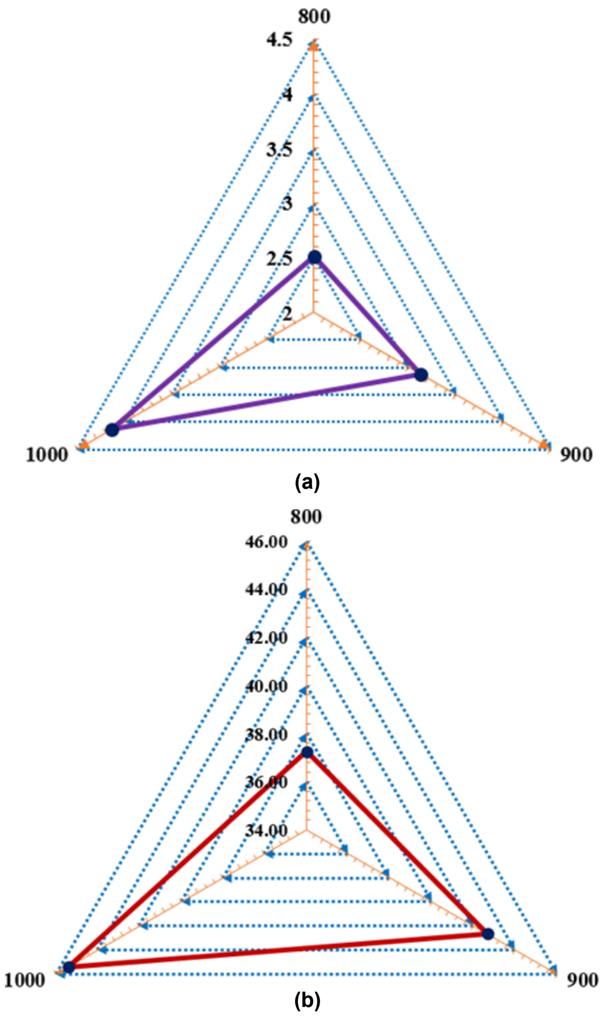


Figure7. Variation in machinability measures with feed: (a) maximum roughness depth and (b) material removal rate.

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.*

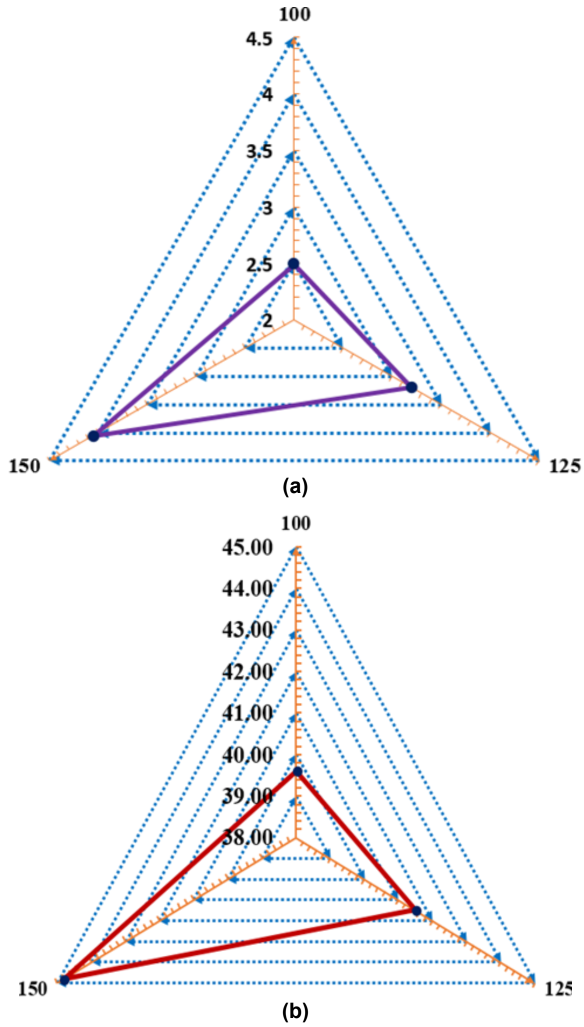


Figure8. Variation in machinability measures with plunge feed: (a) maximum roughness depth and (b) material removal rate.

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

$$d_{FW_j} = \left(\frac{R_{t_{\max}} - R_{t_j}}{R_{t_{\max}} - R_{t_{\min}}} \right)^{0.5} \tag{2}$$

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

$$d_{FW_j} = \left(\frac{MRR_j - MRR_{\max}}{MRR_{\max} - MRR_{\min}} \right)^{0.5} \tag{3}$$

where Rt_{max}, MRR_{max}, Rt_{min}, and MRR_{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 mm^3/min, respectively. At the same time, the corresponding lowest values are 1.26 µm and 30.92 mm^3/min, res–pectively.

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.

$$D_J = \left[\left\{ \left(d_{R_t} \right)_j \right\}^{0.5} \left\{ \left(d_{MRR} \right)_j \right\}^{0.5} \right]^{\frac{1}{0.5+0.5}} \tag{4}$$

$$D_J = \left[\left(d_{R_t} \right)_j \left(d_{MRR} \right)_j \right]^{0.5} \tag{5}$$

The optimum results (i.e., 2.82 µm $R_t$and 41.36mm^3/min *MRR*) predicted from the best desira–bility (i.e., 0.761) were validated by conducting two confirmation experiments (CEs) at optimal variables combination (i.e., 6496 mm/minas S_R; 898 mm/min as *f*; and 100 mm/min asP_f:) 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 = 2.95µm)and *MRR* (43.1+43.8 = 43.45 mm^3/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.

Machining details		Optimal results (DFA)	Confirmation results		
			CE$_1$	CE$_2$	Avg.
Machine variables	Rotational speed 'S_R' (rpm)	6496	6496		
	Feed '*f*' (mm/min)	898	898		
	Plunge feed 'P_f' (mm/min)	100	100		
Machinabi-lity measures	Maximum roughness depth 'R_t' (µm)	2.82	2.70	3.20	2.95
	Material removal rate '*MRR*'(mm^3/min)	41.36	43.1	43.8	43.45

3.2 Analysis of rotor wheel manufactured at opti–mum variables combination

A total of two small-sized rotor wheels were manu–factured 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 CE$_1$ 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_t- 2.95 µm; average roughness R_a- 0.28 µm; mean roughness R_z- 1.6 µm; Skewness- 0.25; andKurtosis- 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 kur–tosis greater than 3 indicates good bearing strength of the machined surface rotor blade.

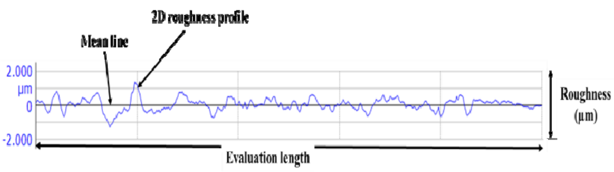
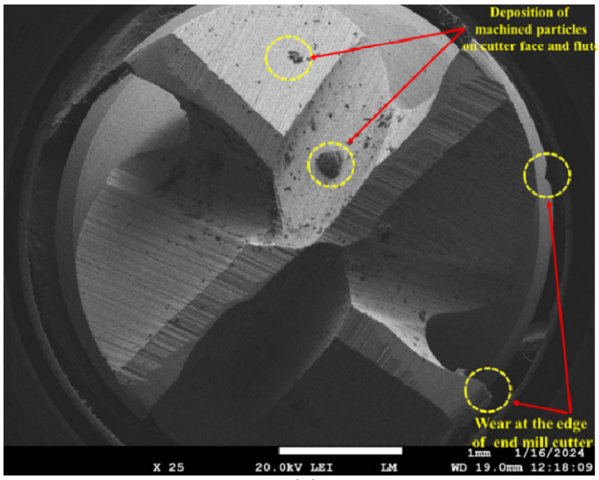
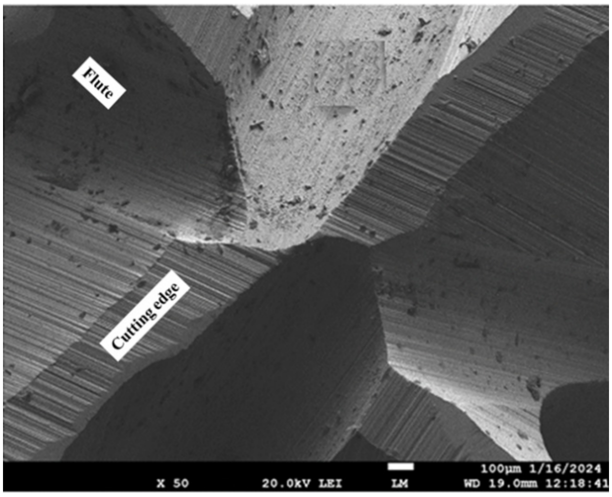


Figure 9. 2D profile for maximum roughness depth value 2.70 µm on rotor wheel manufactured at optimum combination.

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: 'S_R: 6500 rpm; feed: 1000 mm/min; and P_f: 150 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.



(a)

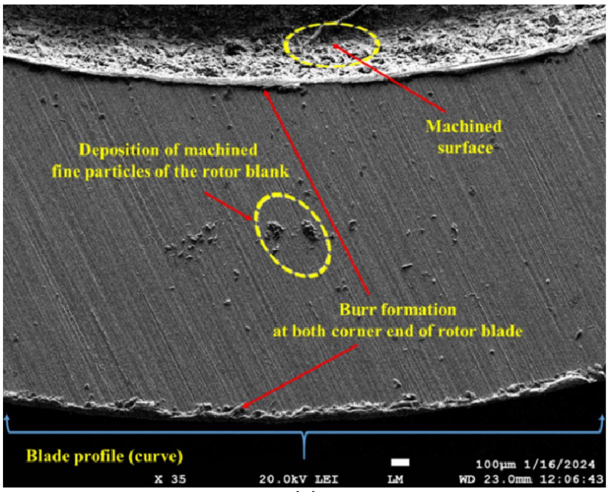


(b)

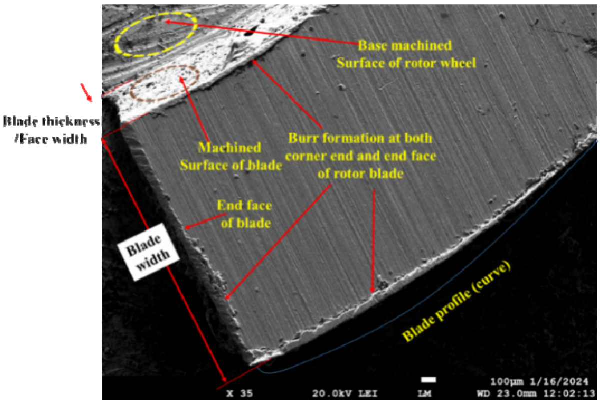
Fig. 10: SEM micrographs of tungsten carbide end mill cutting tool after engraving rotor wheel: (a) after engraving experimental run 14 (i.e., *max. R_t*and *MRR*); and (b) at optimum variables combination.

Tool wear at the edge cutting tool and deposition of fine machined particles of the blank material on the tool face can be observed in Fig. 10(a). Meanwhile, the minimum amount of fine particle deposition on the cutting tool face and negligible tool wear were observed in combination with the optimum variables, as shown in Fig. 10(b).

Figures 11(a) and 11(b) show the geometrical profile and microstructure of the machined surface at 35x magnification of the rotor blade manufactured at expe–rimental run 14 and the optimum variable combination, respectively. Excessive and sharp burr formation on both corner edges of side faces and the end face and 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.



(a)



(b)

Fig. 11: SEM micrographs of CNC engraved rotor blades machined at (a) experimental run 14 (i.e., *max.* R_t 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 investi–gation 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 mm^3/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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ИСТРАЖИВАЊЕ ПРОИЗВОДЊЕ МАЛОГ СТЕПЕНАСТОГ РОТОРСКОГ ТОЧКА ПОСТУПКОМ ГРАВИРАЊА

С.К. Чауби, К. Гупта

Ова студија има за циљ да истражи потенцијал процеса глодања гравирања за производњу 3Д структура и распореда попут точкова ротора. Урађена је експериментална студија за производњу точка са степенастим ротором од ЕН8 челичног бланка коришћењем компјутерске нумеричке контроле (ЦНЦ) алатне машине за гравирање. Утицај варијабилних параметара, а то су брзина ротације (СР), помак (ф) и помак (Пф), на максималну дубину храпавости (Рт) и брзину уклањања материјала (МРР) одређен је кроз укупно четрнаест тестова, сваки са две репликације засноване на Бок-Бехнкеновом дизајну (ББД) методологије површине одговора (РСМ). Најбоља комбинација варијабли пронађена је коришћењем функционалне анализе пожељности (ДФА) са циљевима минимизирања Рт и максимизирања МРР-а. Најбоље вредности постигнуте при оптималној комбинацији варијабилних параметара биле су 2,95 μм као Рт и 43,45 мм3/мин као МРР. Микро–фотографије лопатица роторског точка и алата за сечење подржале су налазе.