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A comparative study of precision finishing of rebuild engine valve faces using micro-grinding and ECH

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Abstract

This paper presents a comparative analysis of process performance of micro-grinding and electrochemical honing, with the aim to achieve higher precision and surface quality of rebuild surfaces of the engine valve face. The discarded engine valve face was rebuilt using plasma transferred arc cladding technique and its surface finish was evaluated in terms of average roughness and maximum roughness value. The improvement in profile error and total run-out were used to evaluate the optimum processing time of micro-grinding and ECH. The sets of experiments for micro-grinding and ECH were conducted. The results reveal that the ECH process is one of the ideal choice for finishing of recovered surfaces. The surface morphology of the processed part is significantly improved resulting in glazed and uniform texture. Results show that the ECH can produce the workpiece surface 75 % efficient than the micro-grinding. A significant improvement of 23.37 % in the average surface roughness value was found after ECH as compared with the micro-grinding.

Keywords: PTA; X40CrSiMo10-2 alloy steel; Micro-grinding; ECH; Product recovery; Engine valve; Surface quality

Background

The engine valve is one of the important parts in the combustion chamber and its functions is to maintain the combustion chamber pressure tight. They are subjected to high frequency impact at 1400 times/s at a high temperature. Therefore, these valves are functioning over a long period of time under the combined effects of mechanical stress, thermal stress and chemical corrosive stress [1]. Schlager presented that the engine valve faces will get eroded and wear-out during working, even resulting in cracking of the valve face [2]. From the last two decades, it was noticed that the fuel oil quality deteriorated, whereas engine power ratings increased significantly, which has resulted in high thermal loads and a more corrosive environment for a valve and valve seat surfaces [3].

Today's scenario, the first preventing method in industrial application is to deposit a special coating on the valve face. This coating has to offer a proper wear resistance, thermal resistance and corrosive resistance on the valve face. In addition, it would be useful to upgrade the used valve faces [4]. Therefore, functional properties of engineering components can be, however, recovered and upgraded by using a suitable metal deposition technique on the worn or waste mechanical parts. In general, thermal spray, plasma transformed arc (PTA), laser cladding (LC), bead welding, etc. are used as a material deposition techniques. All these techniques have advantages and disadvantages connected with quality and production cost. Out of them PTA cladding and laser cladding, are extensively used to deposit materials due to its key ability to bond many materials together, it becomes a famous technology for recovering parts [5]. A common feature to these processes is that both use powdered hardfacing material. The hardfacing materials such as cobalt based alloys (strengthened by carbides), nickel-chrome based alloys, etc. are used in petroleum refinery and automobile equipments are heat resistant materials not much has been done to evaluate the surface topography after deposition [6]. Therefore, for this phase good machinabilty is an important aspect of deposit coating.

Traditionally, grinding process is applied to finish the top-surface of the deposited layer specially required for mating surfaces, i.e., valve face, crankshafts, etc. The major disadvantages associated with the conventional surface finishing processes are (i) it suffers from low finishing rate, high tool wear, and high probability of surface damage due to existence of point forces on the workpiece surface [7, 8], (ii) the hardness of the workpiece surface act as a determining factor and even sometimes such materials are very difficult-to-machine using conventional methods [9], (iii) it suffers from low geometrical accuracy, which is almost impossible to attain up to the desire level for such advance materials by conventional methods [10, 11]. Therefore, there is a need for an alternate process which has the capability of nano-level finishing at higher finishing rate. The process is expected to be effective for finishing intricate external profiles and advanced materials. In the recent years, electrochemical honing (ECH) is emerging as a prominent finishing technique for both internal and external surfaces [12, 13].

Till date no work has been reported on finishing of PTA clad layers using ECH process. This paper presented a comparison study of recovered part working surface using micro-grinding and ECH process, to better summarize the process capabilities of these processes over deposited material. The aim of this work was to upgrade and recover the discarded engine valves to like-new performance. The surface properties, such as microstructure, surface roughness and the design properties such as geometrical accuracy and profile dimensions have been investigated.

Methods

For the present study, discarded engine valves were collected and prepared for PTA cladding as shown in Fig. 1a. After cladding, it is observed that the average thickness of

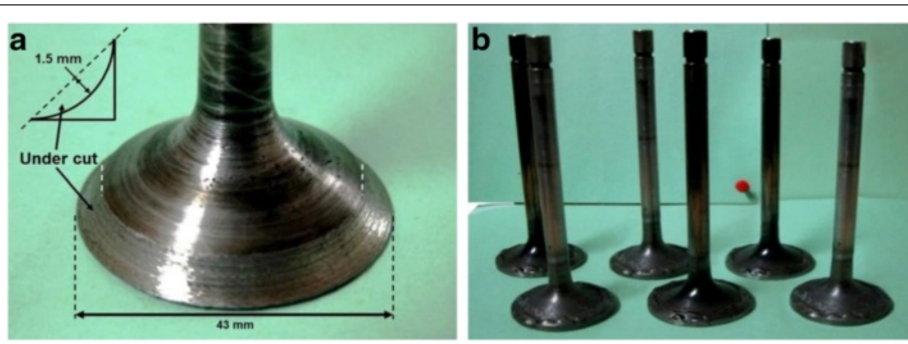

Fig. 1 **a** A view of the faying faces of valve head prepared for PTA cladding; **b** A view of PTA clad engine valves prior to finishing

Table 1 Chemical composition of the engine valve face

Element	C	Cr	Mn	Mo	Si	S	P	Fe
Weight (%)	0.36	12	0.78	1.05	1.95	0.03	0.043	balanced

the deposited cladding was around 2 mm. Therefore, to meet the original dimensions and geometry of the processed part a post machining process is required. Figure 1b describes a photographic view of engine valves prior to finishing. Table 1 present the chemical composition of working surface of valve after PTA cladding that were observed through a BAIRD made atomic absorption spectroscopy instrument. The average surface roughness of PTA cladding before grinding was lying between 30 and 40 μm.

Before starting the experimental study to investigate the optimum input process parameters in respect of the monitored outputs, the workpieces were required a rough machining process (grinding). It is observed from the Fig. 1b that deposited material using PTA process gives a rough and irregular shape which cannot be fitted directly in the precision process such as micro-grinding and ECH process due to the constraints of the high processing time and tooling cost. Therefore, recovered workpieces are first passed through a rough grinding process to generate a layout of the valve face geometry. Figure 2 shows the photographic view of the engine valve face after rough grinding.

Study on ECH of rebuild valve face

A study on the ECH of the working surface of the valves head face made of X40CrSiMo10-2 alloy steel using PTA cladding had been carried out. The process principle of the ECH of engine valves, experimental detail and results have been presented below:

The working principle of ECH process

The process principle of ECH is based on the Faraday's laws of electrolysis and mechanical scrubbing. Figure 3 describes the proposed working principle of ECH process of engine valves. In this process, most of the metal is removed at the atomic scale by anodic dissolution. Moreover, the honing action acts as a performance multiplier.

In ECH process, the workpiece is connected with the positive terminal and the tool is connected with the negative terminal of the power supply system and a small DC electric potential across them is applied. The inter-electrode gap (IEG) between the workpiece and tool around the ECM zone is filled with the full streams of electrolyte and an

Fig. 2 A photographic view of the few workpieces after rough grinding

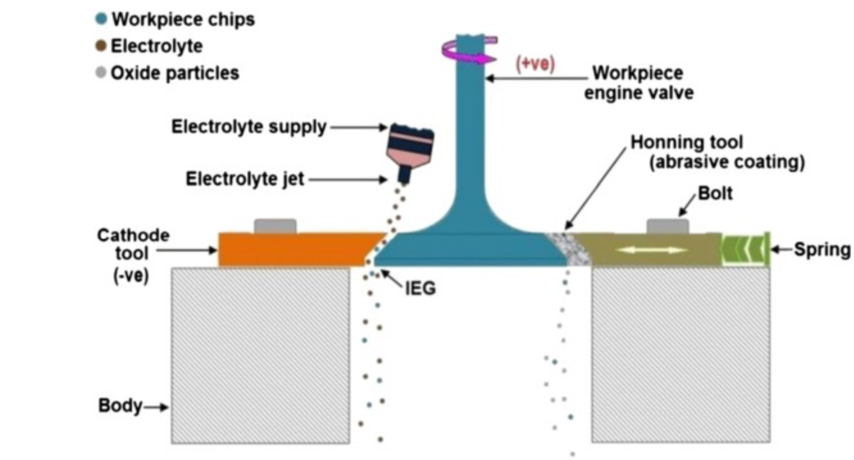

Fig. 3 Proposed working principle of ECH of rebuild engine valve face

applied current is passed through them. During the process of material removal from the workpiece, oxygen is evolved out at cathode after dissolution of aqua solution and this oxygen reacts with anodic workpiece to form a thin metal oxide micro-film on workpiece. This micro-film is insulating in nature and protects the workpiece surface from being further removed and it minimizes the ECM action. This oxide layer on the surface of the workpiece gear is scraped by the honing action when it comes in contact with honing tool. The honing tool was spring loaded and help to complete scrubbing of the workpiece surface. This scrubbed surface, when returning to the ECM zone, is removed electrochemically once again. The surface quality and geometric accuracy of the workpiece surface is rapidly improved as the process continue.

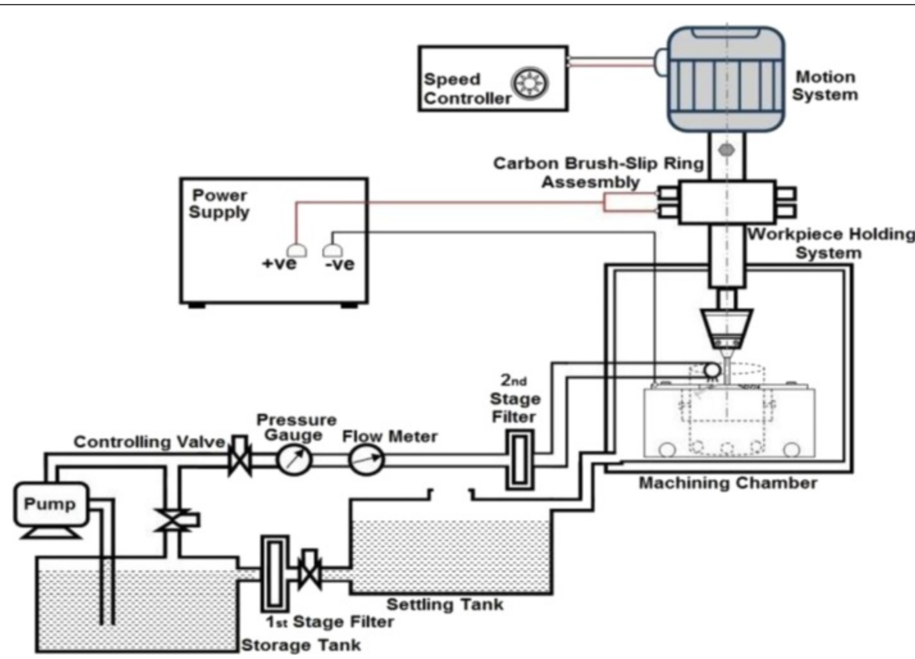

Fig. 4 Schematic view of the ECH setup used for finishing of engine valve face

Table 2 List of fixed parameters of ECH [14, 15]

Power based parameters	
Voltage	30 V
IEG	0.5 mm
Cathode material	Copper
Electrolyte based parameters	
Composition	75 % NaCl + 25 % $NaNO_3$
Concentration	10 % (by Volume)
Temperature	34 °C
Flow	15 lpm
Honing based parameters	
Honing material	NiCr
Rotary speed	80 rpm
Abrasive size	800 mesh size
Pressure	0.03 MPa

Experimentation details

Figure 4 depicts the schematic diagram of the experimental setup of ECH of engine valves. This setup has four subsystems namely (i) finishing chamber housing workpiece, cathode and honing tools; (ii) electrolyte supply system; (iii) power supply system; and (iv) rotation system to the tooling system. The input process parameters are fixed based on the literature review and the machine constraints as described in Table 2 [14, 15]. For the present study, processing time and continuous DC current used as an input process variable to investigate the effect of ECH on the clad surfaces by analysing the surface roughness, morphology finished surface and geometrical accuracy before and after the process. The range of input variables for ECH process have been presented in Table 3. The processing time is increased at the interval of 20 s for each value of current and fixed where profile error is minimum. The profile dimensions are checked and compared with the original engine valve profile. The profile error is calculated based on the difference in the profile area between the original (designed) part and finished workpiece (remanufactured). The negative sign shows the finished workpiece to have a large profile area than original profile area and vice-versa. For the investigation, the experimental setup has been designed and fabricated for ECH of rebuild surfaces of engine valves as shown in Fig. 5.

Results and discussion

The experimental results of ECH of clad valve face have been presented in the following section. During the analysis of the results, main attention was focused on the surface roughness and profile dimensions of the workpiece. Table 4 presents the surface roughness (R_a and R_t) values, profile error and processing time after each run. The

Table 3 List of variable input parameters of ECH of engine valves

Current (A)	20	30	40	50	60
Processing time (min)	Profile dimensions are checked after every 20 s of processing time and fixed where profile error is minimum				

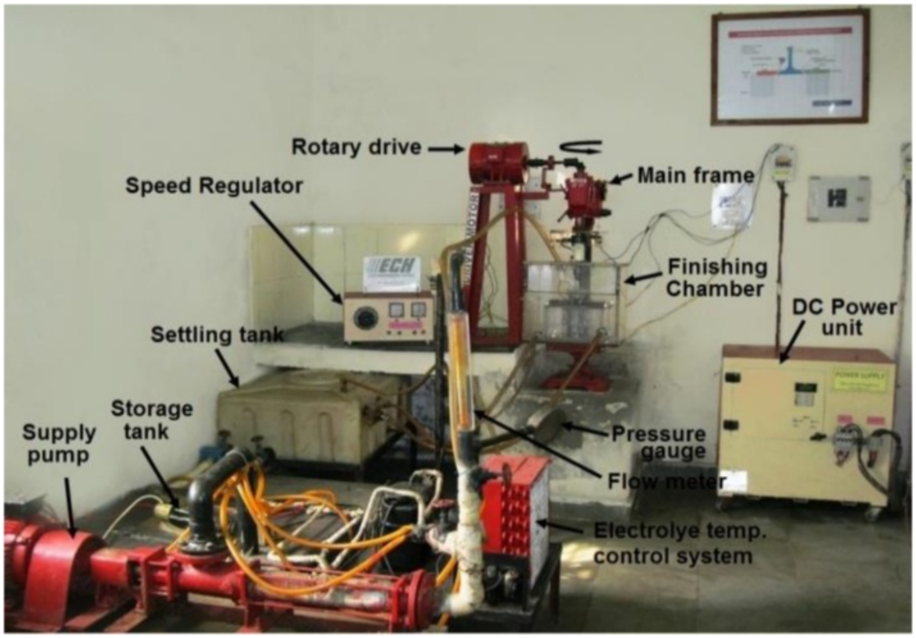

Fig. 5 Photographic view of developed experimental setup for ECH of rebuild surfaces of engine valve face

effect of current on surface roughness is shown in Fig. 6. The optimum value of processing time is selected on the basis of average and maximum workpiece surface roughness. Hence, 120 s was selected as an optimum processing time and 30 A was selected as appropriate amount of input current.

Study on micro-grinding of rebuild valve face

The micro-grinding process is widely used to produce functional surfaces of good dimensional accuracy and precision finish [16]. During processing, the huge part of the produced energy is transferred into thermal energy, which will damage the finished surface in terms of surface deformation, swell, micro-cracks, peeling of surface, etc. [17, 18]. Therefore, a fine grinding input parameters are applied to generate the desired surface. Based on the best experimental conditions for the PTA cladding as reported in the references, fine-grinding of working surface of the engine valve face made of X40CrSiMo10-2 alloy steel has been carried out. The experimental details and results are presented below:

Table 4 Results of surface roughness and processing time of ECH

Current (A)	Processing time (sec)	Profile error (mm^2)	Ra (μm)	Rt (μm)
20	160	+0.19	0.71	6.44
30	120	+0.12	0.59	6.65
40	80	- 0.28	0.84	7.24
50	80	+0.14	1.42	8.47
60	60	+0.08	1.95	9.06

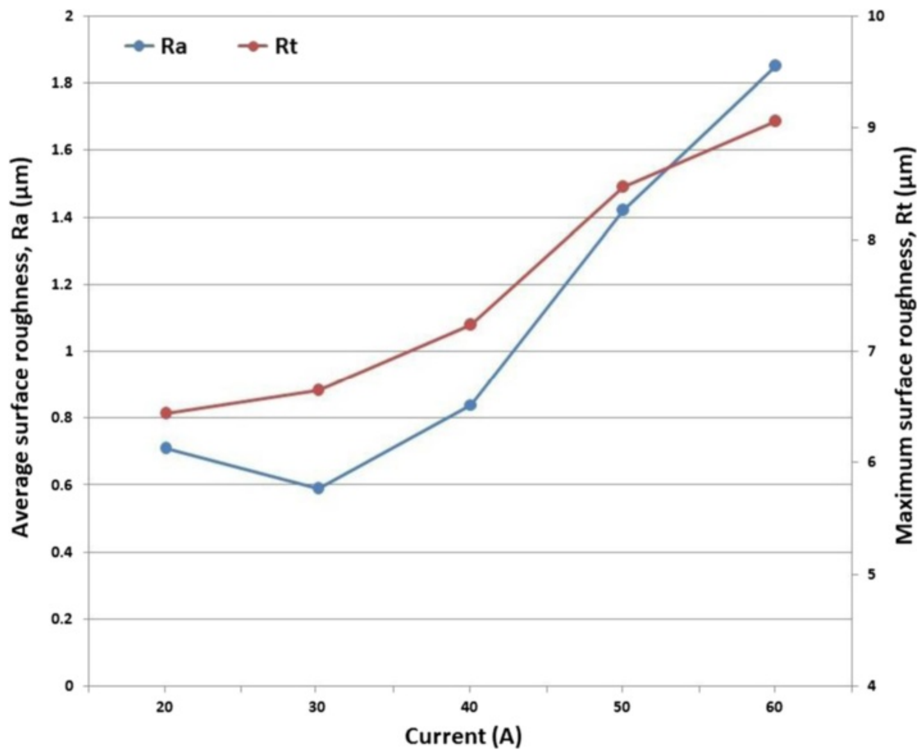

Fig. 6 Variations of surface roughness with different current

Experimentation details

Figure 7 presents the photographic view of micro-grinding of the engine valve face and chips of removed material. The input process parameters are selected based on the literature review and the machine constraints as described in Table 5 and the list of process variable parameters has been presented in Table 6.

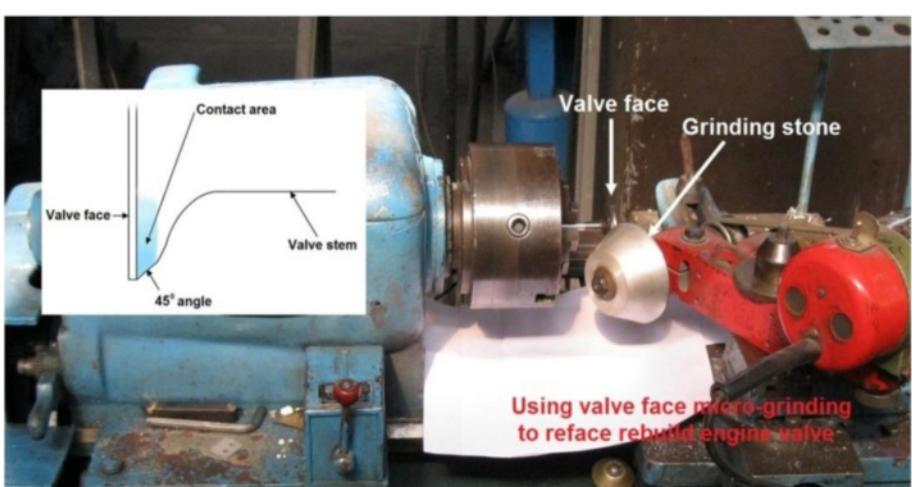

Fig. 7 Photographic view of experimental setup of micro-grinding of recovered surfaces of engine valves

Table 5 List of fixed input parameters of micro-grinding of clad surfaces [18]

Grinding wheel	
Wheel material	Diamond, (SDC, P, B)
Grain size	800
Concentration	100
Grinding based parameters	
Rotational speed	50 rpm
Speed type	Continuous (ACW)

Results and discussion

Table 7 presents the surface roughness (R_a and R_t) values, profile error and processing time after each run. The effect of depth of cut on surface roughness is shown in Fig. 8.

The optimum value of processing time is selected on the basis of average and maximum workpiece surface roughness. Hence, 8 min was selected as an optimum processing time. It is evident from the results, surface roughness of the ground surface increases as the depth of cut increases. It is also cleared from the plot that there is possibility to enhance the surface quality under the 5 μm depth of cut. But is quite difficult to adjust in the present experimental setup and it obviously increases the processing time further.

A comparison on process performance between micro-grinding and ECH

The comparison of process performance of micro-grinding and ECH have been presented in the following sections. Both the results were compared in terms of surface roughness and morphology of the finished surface. Figure 9 shows the photographic view of workpiece surface at different stages.

Surface roughness and material removal

For both the studies, similar conditions of the workpiece were used. Results show that the surface roughness and material removal rate are significantly higher in the ECH process as compared to conventional micro-grinding process. Table 8 presents a comparison of micro-grinding and ECH outcomes, which show that the ECH gives Ra 0.59 μm and Rt 6.65 μm as compared to micro-grinding which gives Ra 0.77 μm and Rt 6.91 μm. It is observed that ECH gives a fine finishing operation at the processing time of 120 s, which is 75 % less than the optimum processing time of micro-grinding process.

Furthermore, ECH process provides the complete profile finish in a single setting of tool and workpiece, but it is quite impossible using the micro-grinding process. This is because of the copying accuracy of the ECH process which primarily depends on the specific geometry of the cathode tool. It can be established that the multi-faces of the engine valve are finished using ECH process, which makes the process further efficient as compared to the micro-grinding process.

Table 6 List of variable input parameters of micro-grinding of engine valves

Depth of cut (μm)	5	10	15	20	25
Processing time (min)	The time taken by every cut is summed up until the workpiece profile dimensions reaches the required dimensions				

Table 7 Results of surface roughness and processing time of fine-grinding

Depth of cut (μm)	Processing time (min)	Profile error (mm^2)	Ra (μm)	Rt (μm)
5	8	+0.16	0.77	6.91
10	6.5	+0.13	0.96	7.03
15	4.25	+0.19	1.61	7.55
20	3	+0.15	1.79	7.69
25	2	+0.19	1.84	7.58

Morphology of finished surfaces

Figure 10a, b and c illustrate the surface topographies of the workpiece surface before finishing, after finishing using micro-grinding and ECH process. It is observed that the surface texture of the finished workpiece by the ECH appears glazed and uniform, indicating significant improvement in the surface finish. It was observed that there was a 97.43 % rate of improvement in the surface of the finished workpiece through micro-grinding, while an improvement rate of 97.63 % was recorded after finishing the part through ECH. The typical profiles presented shows significantly reduced peaks in case of the ECH processed surface.

The SEM analysis was also conducted on workpieces to investigate the morphology of finished surface. Figure 11a clearly show that before finish, the work surface contains voids, spots, porosity, pits etc. The micro-grinding surface of workpiece contains scratches, fused particles etc., but the surface becomes uniform and smooth by removing irregularities as shown in Fig. 11b. The ECH surface presents a glazed appearance and the surface texture had become more uniform and smooth. The asperity heights

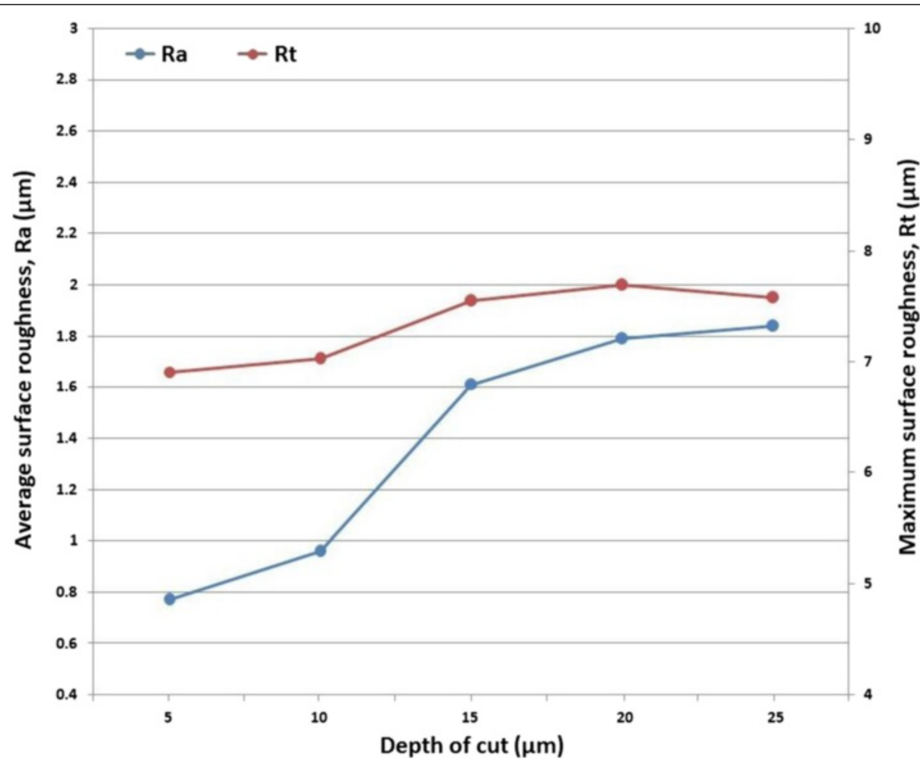

Fig. 8 Variations of surface roughness with different depth of cut

Fig. 9 Photographic view of engine valve faces at different stages

were removed due to the combined action of ECM and honing process. It is observed that the abrasive feed marks are not visible in Fig. 11c due to the existence of low honing pressure in ECH as compared with micro-grinding conditions.

Conclusions

In this study, an alternative machining processes were used, in order to prepare a defect free, smooth, geometrical accurate profile, and high finish of the workpiece surface for a subsequent ECH process and its results are compared with the micro-grinding process. The following conclusions could be drawn based on the comparative analysis.

a) The micro-grinding of PTA clad surfaces gives Ra 0.77 μm/ Rt 6.91 μm, while ECH gives Ra 0.59 μm/ Rt 6.65 μm.
b) ECH process provides stress and thermal damage free finishing operation at higher finishing rate. The ECH of precision finishing of clad surfaces takes 75 % less processing time as compared with micro-grinding.
c) This study shows that a complete profile of the workpiece was finished in case of ECH process depending on the specific geometry of the ECH cathode tool. But, in case of micro-grinding process, only valve head face is finished in a single setting of tooling system which made the ECH process further efficient.
d) It was found from the study that the micro-grinding of rebuild valve face have a high tool wear and abrasive marks on the processed surface.

Table 8 A comparison of micro-grinding and ECH outcomes

Monitored parameters	Micro-grinding	ECH
Processing time (sec)	480	120
Ra (μm)	0.77	0.59
Ra (μm)	6.91	6.65
OOR (μm)	20.16	33.92

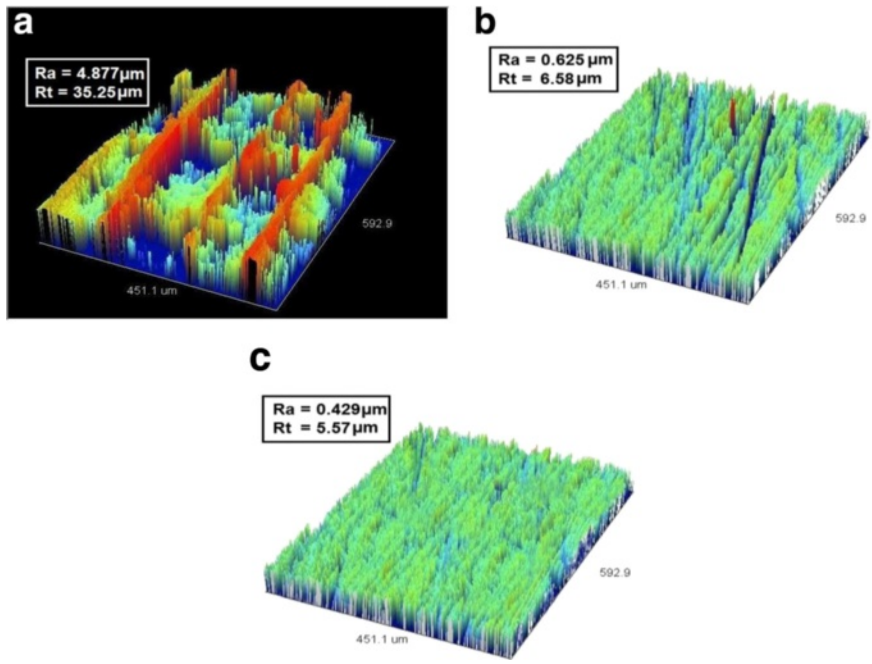

Fig. 10 Topography of the workpiece surfaces obtained through optical profilometer: **a** prefinished; **b** after micro-grinding; **c** after ECH

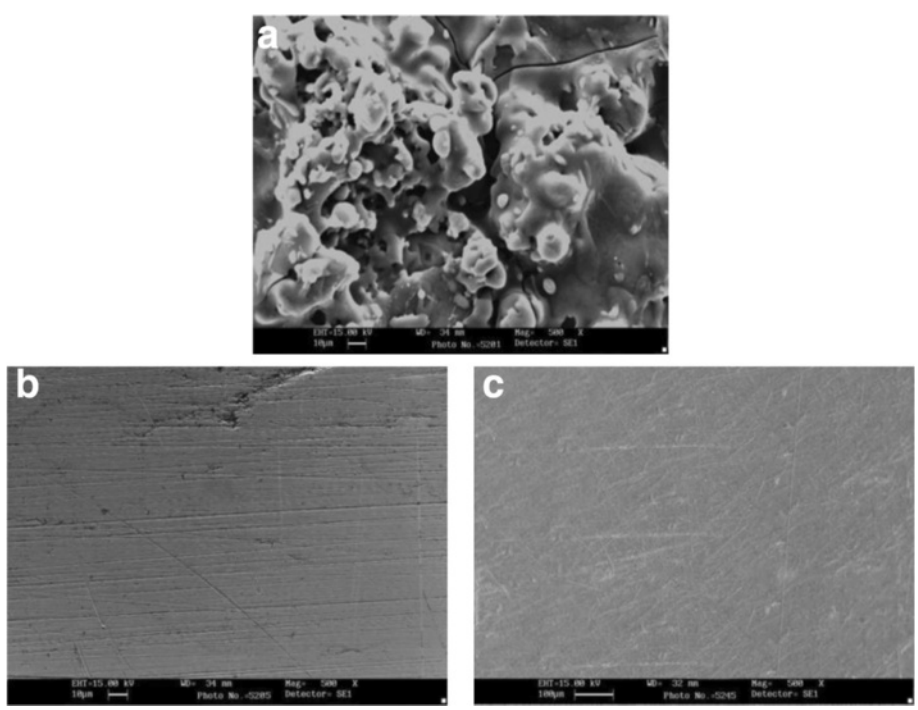

Fig. 11 Typical SEM micrographs: **a** prefinished; **b** after grinding; **c** after ECH process

e) It is reported that the ECH processed surface have no deep feed marks, microstructure is more uniform and smooth as compared with the micro-grinding processed surface.
f) Improvement in surface quality is rapid during the initial phases of ECH, while the material removal rate remains almost unchanged.

Competing interests
The authors declare that they have no competing interests.

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Authors' contributions
The recovery of the engine valve face has been studied and presented in the manuscript using PTA cladding, micro-grinding and ECH process to achieve a high precision and surface finish. Both the authors reviewed critically the manuscript and gave the final approval of the version to be published.

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