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Development and Rheological Characterisation of Abrasive Flow Finishing Medium for Finishing Macro to Micro Features

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ABSTRACT

Technological advancement demands the manufacturing of components with a fine surface finish at a minimal cost. This scenario acts as the driving force for the research communities to develop economic finishing processes. Abrasive flow finishing (AFF) is one of the advanced finishing processes employed for finishing, deburring, radiusing and recast layer removal from the workpiece surfaces. AFF process uses a finishing medium that acts as a deformable tool during the finishing process. It is the rheological properties of the medium that profoundly influences the end surface finish obtained on the workpiece after the AFF process. In the current work, an attempt is made to develop an economic AFF medium by using viscoelastic polymers i.e., soft styrene and soft silicone polymer. Detailed static and dynamic characterisation of the medium is carried out. Later, to study the finishing performance of the developed medium, AFF experiments are performed for the finishing of macro and micro feature components. The experimental study showed that the nano surface finish could be achieved by varying the viscosity of the developed medium. Developed medium achieved 89.06 per cent improvement in surface roughness during finishing of tubes (macro feature component), while 92.13 per cent and 88.11 per cent surface roughness improvement is achieved during finishing of microslots and microholes (micro feature component), respectively.

Keywords: Abrasive flow finishing; Surface roughness; Medium; Rheology

1. INTRODUCTION

The surface finish of the components determines its functionality and life span. High surface roughness on the flow passages of the components not only change the flow rate but can also cause contamination of the fluid carried by them. Dimensions of the passageway can vary from macro to few micron ranges. Some of the examples include stents in medical, fuel injector nozzle in automobile, turbine blades in aerospace, microfluidic channels, pipes in chemical and food processing industry. Change in the intended flow rate or contamination of the flowing liquid not only affects the functionality of the components but are also harmful to the patient's health in medical industries. Several advanced finishing processes and their variants are developed over the last few decades. Abrasive flow finishing (AFF) process is one of the advanced finishing processes successfully employed for finishing macro to micro featured components[1].

Experimental study of the AFF process is done by several researchers during finishing of macro features. Their study demonstrated the effect of AFF input parameters viz. pressure, AFF cycles, wt. % and mesh size of the abrasive particles on the output responses[2-4]. In addition to the above input parameters, medium is one of the most critical constituents of AFF process that decides its finishing performance. However, few authors reported the medium rheological study. Medium employed by AFF process is a viscoelastic non-Newtonian fluid. The study of the rheological properties of the non-Newtonian fluids is necessary to understand and maximize their performance[5-6]. It is the rheology of the medium that decides the properties and hence functionality of non-Newtonian fluids. Hull[7], *et al.* studied the dynamic nature of the commercially used medium i.e., polyborosiloxane medium. Authors reported that depending on the magnitude of shear rate medium shows shear thinning and shear thickening behaviour. Davies and Fletcher[8] did rheological study on polyborosiloxane (PBS) medium with varying viscosities. One of the major outcomes of the study was the role of temperature in deciding medium viscosity which in turn influences its finishing performance. Tzeng[9], *et al.* proposed a medium for finishing micro channels with self-modulating nature. It was reported that the medium viscosity changes with the finishing time.

Sankar[10], *et al.* carried out the experimental study of the developed medium and reported the influence of medium rheological properties in determining the material removal and workpiece surface roughness. Lunn[11] added thermoplastic polymer in the medium to enhance its elastomer properties, which helped in achieving uniform surface roughness in passageways having a large length/diameter ratio. Kar[12-13], *et al.* experimented with various types of base polymers. It was concluded from the study that medium containing styrene butadiene rubber gives the maximum surface roughness

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improvement of 88 %. Few authors also developed a low viscous medium to finish micro features. Perry[14] developed slurry by adding abrasive particles into the fluid medium (cutting fluid or honing fluids) for finishing microhole. While, Yin[15], *et al.* developed water based abrasive slurry for finishing of microholes machined on the ceramic material using the AFF process. Uhlmann[16], *et al.* developed a material model to simulate the flow behaviour of the medium. Sarkar[17], *et al.* developed viscoelastic fluid by mixing hydrocarbon oil with the polyborosiloxane to be used as a medium for finishing workpieces with freeform surfaces using AFF process. To achieve uniform surface finish on complex holes abrasive gels are prepared in-house by Wang[18], et al. Few authors[19-20] attempted to develop an accurate model of the AFF process by using the experimentally measured rheological properties as its input data. Various variants of silicone base medium were prepared and their rheological study was carried out by Sankar[21] *et al.*, authors showed that wt. % of the abrasive particles significantly affect the workpiece surface finish.

As found from the literature review, minimal work is carried out for developing the medium that is not only economical but with tailored properties for finishing both macro and micro features. In the current work, an in-house economic medium with a blended mixture of soft styrene and soft silicone polymer is developed for finishing macro to micro passageway of the components. High viscous (HV), moderate viscous (MV) and low viscous (LV) medium compositions are prepared by varying the wt. % of the various constituents of the medium and are used for the finishing of tubes, microslots and microholes, respectively. Detailed rheological study of various medium proposed in the current work is performed by using parallel plate rheometer. Experiments are carried out to observe the finishing capability of the developed medium.

2. ABRASIVE FLOW FINISHING PROCESS

Figure 1 shows the AFF process set-up with its major components designed and developed in house. Pairs of hydraulic cylinder, medium cylinder, supporting rod and piston are the major parts of the AFF set-up. Dimensions of the various components are decided based on fundamental design theories for a maximum operating pressure of 12 MPa. Medium is contained in the lower and upper medium cylinder. During the AFF experiments, hydraulic cylinder piston pushes the medium from the medium cylinder through the passageway in the workpiece. As the medium containing abrasive particles passes through the passageway, shearing of the roughness peaks on the workpiece surface takes place.

3. MEDIUM

Medium is one of the essential constituents of the AFF process[21]. It mainly comprises of the viscoelastic base polymer, additives (plasticizers, softeners) and abrasive particles. Figure 1 shows that as extrusion pressure (P) is applied to the medium, the elastic component of medium results in the generation of radial forces (F_R) which are responsible for indenting the abrasive particles into the workpiece surface, while the viscous component generates axial forces (F_A) that moves the indent abrasive particles in the axial direction[10]. In the current paper, by changing the wt.% of medium ingredients, the viscosity of the medium is varied from high to low viscous. High viscous medium is used for finishing macro features (i.e., tubes) while the low viscous medium is used for finishing micro features (i.e., microslot, microhole).

3.1 Development of Viscoelastic Abrasive Medium

In the present work, economic HV, MV and LV medium is developed. Medium is prepared using the two-roll mill set-up. Initially, proper mixing of the styrene polymer and silicone polymer is carried out. Later, abrasive particles are added to the mixture of base polymer. Once the mixture of polymer and abrasives is ready, softeners and plasticizers are added in a varying amount to produce the medium with different viscosities.

Influence of time, shear rate, temperature on the rheological properties of various in-house developed medium is studied by using rheometer (make: Anton Paar-MCR-101 series). Rheometer, shown in Fig. 2 has a parallel plate arrangement consisting of rotating top plate (tool master) and stationary bottom plate (base plate). For properly holding the medium samples ends of both the plates are provided with diamond cone pattern.

3.1.1 Base Polymer

The base polymer consists of the styrene-butadiene polymer (SBP) and soft silicone polymer (SP). The main reason for using SBP as a constituent of the medium is due

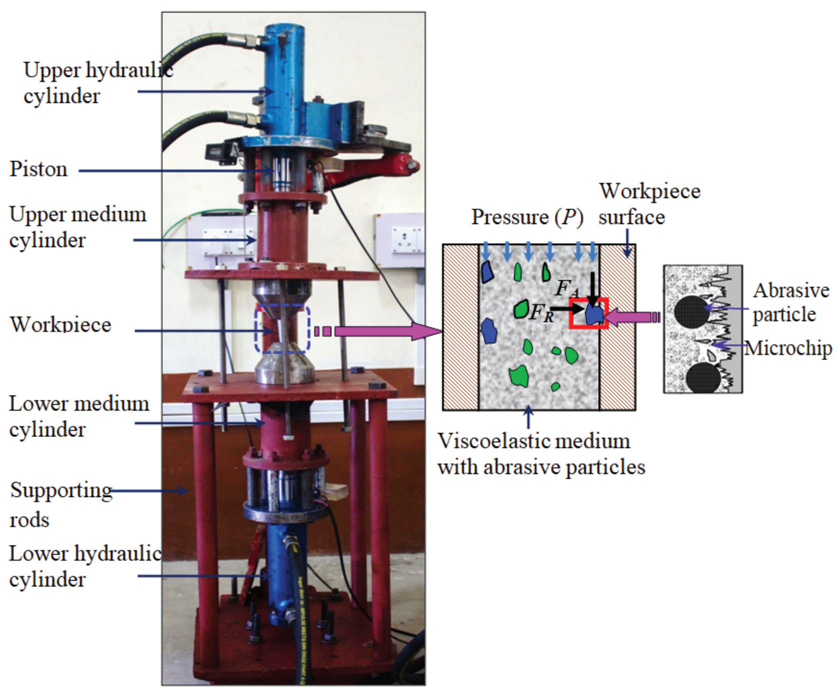


Figure 1. Abrasive flow finishing process set-up with various finishing forces on abrasive particle during the process.

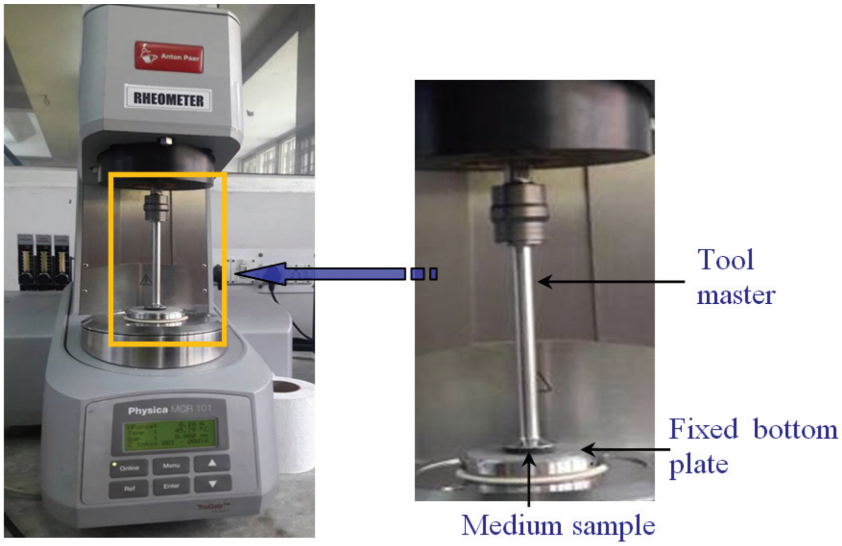


Figure 2. Parallel plate rheometer with sample between top and bottom plate.

to its excellent abrasion resistance and ageing properties. The medium can be used for a more extended period without degrading its properties. In the present work, SBP consists of 75 % butadiene (CH_2=CH-CH=CH_2) and 25% styrene (CH_2=CHC_6H_5) by weight. Styrene monomer possesses a branched structure with phenyl ring acting as the branch, while butadiene has a linear structure. Styrene monomer branches resist the smooth movement of the polymer chains, which enhances the elasticity of SBP, while the butadiene monomer imparts the viscous nature to the medium.

The other base polymer used is a soft silicone polymer. The silicone based polymer is a chain of alternating silicon atoms and oxygen atoms (⋯-Si-O-Si-O-Si-O-⋯). Soft silicone base polymer is non-reactive, stable, and resistant to extreme environments and temperatures. This polymer is very flexible due to the presence of silicon and oxygen bonds with large bond angles and bond lengths. Due to large bond lengths, polymer chains can easily stretch in the direction of applied stress and can easily change their conformation[22].

3.1.2 Abrasive Particles

In the present work, silicon carbide (SiC) abrasive particles with mesh size 180 (mean diameter of 84.67 µm) and 45 wt. % is used in the medium. Abrasive particles with multiple cutting edges act as miniature cutting tools during finishing of the workpieces by the AFF process. It is the randomly oriented sharp cutting edges abrasive particles that help in shearing the surface roughness peaks on the workpiece thus achieving nano surface finish.

3.1.3 Plasticizers and Softeners

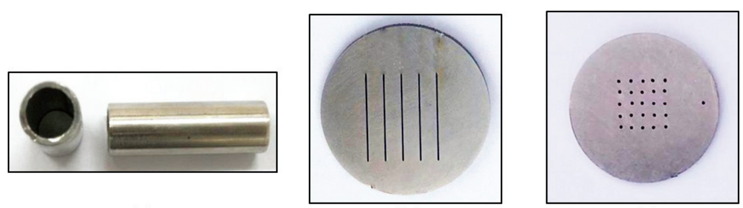
High viscous medium is preferred for finishing of the components with macro features. As the dimensions of the components to be finished decreases, MV to LV medium is preferred. In the current work, the viscosity of the medium is reduced by increasing the plasticizer content. Plasticizer's molecule (small molecular weight materials) diffuse between long polymer chains (high molecular weight materials), thus increasing the gap between the long polymer chains which results in increased mobility and the reduced viscosity of the medium. In the present work, silicone oil is used as the plasticizer.

The addition of plasticizers decreases the medium viscosity. However, above a critical wt. %, it imparts a sticky nature to the medium, resulting reduction in finishing efficiency of the AFF process. Softeners are organic compounds available in micro to nano form, which promotes the flexibility to the polymer chains without imparting stickiness to the medium. Aluminum stearate is the softener employed for developing the medium.

3.1.4 Medium Composition

Finishing capability of the developed medium is demonstrated by finishing tubes, microslots and microholes using the AFF process (Fig. 3). During the finishing of workpieces with macro dimensions, the medium doesn't undergo large deformation while extruding through the workpiece passageway. Therefore, for finishing such workpieces, HV medium with a dominating elastic nature is needed. Considering this reason (dominating elastic component), the wt. % of SBP polymer is kept higher than wt. % of SP in the medium prepared for finishing tubes (Table 1).

The passageway of the microslots through which medium is extruded during the AFF experiments is very narrow due to the micro dimensions of microslots. Thus, the medium needs to undergo substantial deformation during its extrusion through the microslot passageway. So, to assist smooth flow, medium with moderate viscosity and elasticity is prepared. As shown in table 1, higher wt. % of SP than the wt. % of SBP ensures that the MV medium prepared for finishing microslots is less



(a) (b) (c)

Figure 3. Various workpieces finished by the abrasive flow finishing process (a) tubes having inner diameter 12.7 mm, (b) microslots having length 20 mm and width 450 µm, and (c) microhole having radius 425 µm.

Table 1. Percentage contribution of various constituent in high viscous (HV), moderate viscous (MV) and low viscous (LV) medium

Medium	SBP (wt.%)	Silicon polymer (wt.%)	Abrasive particles (wt.%)	Plasticizers (wt.%)	Softeners (wt.%)
HV	26.58	18.33	45.00	4.58	5.50
MV	18.33	22.92	45.00	7.33	6.42
LV	13.59	25.38	45.00	7.66	8.47

viscous as compared to the HV medium prepared for finishing tubes. Viscosity of the LV medium prepared for finishing microholes is further reduced by increasing the wt. % of the plasticizers and softeners.

4. RESULTS AND DISCUSSIONS

Following section includes the detailed rheological study of the various developed medium in the current work. Later, experimental findings obtained after finishing of macro and micro feature components with the developed medium are reported.

4.1 Rheological Characterisation

The type and amount of various ingredients added in the medium preparation had a crucial part in determining the finishing performance of the AFF process. Hence, to understand the flow and deformation of the medium during AFF process, it is necessary to understand the rheological properties of the developed medium. Comparative study is carried out showing the variation in between the rheological properties of the HV, MV and LV medium.

4.1.1 Strain Sweep and Creep Recovery

The primary purpose of conducting the strain sweep test is to study the elongation/stretching behaviour of the base polymer of the medium. Polymer chains are stretched by varying % strain and the "range in which the polymer chains are in a stretch without breaking is known as its linear viscoelastic range (LVE range)"[10]. Strain sweep test (Fig. 4(a)) shows that elastically dominant HV medium polymer chains can sustain higher per cent strain ranges without breaking. Creep test is performed to investigate the percentage of the elastic and viscous component in the viscoelastic medium. Creep recovery test is performed by holding the medium at constant stress for a particular duration. As a result of the applied stress, medium deforms which consist of both elastic and viscous deformation. Later, the stress is removed and the medium is allowed to recover from the deformation. Through the creep test it is found that the deformation (elastic + viscous) of LV medium is more than the elastically dominant medium. Due to the dominant viscous nature for the same stress, the strain is high in LV medium, followed by MV medium. In the recovery phase, a large amount of deformation is left in the LV medium as compared to the HV medium (Fig. 4(b)). This is due to the presence of a considerable amount of plasticizers and softeners in MV and LV medium prepared for finishing micro features.

4.1.2 Variation of Viscosity with Temperature

It was reported by several authors that during the AFF experiments, medium temperature increases with the increase in finishing time or flow rate of the medium[8, 10]. Friction acting in between the medium and workpiece surface causes a gain in thermal energy which raises the medium temperature. Therefore, to study the variation in viscosity for HV, MV and LV medium, temperature is studied in the following section. It was found that for the same temperature range, change in viscosity of the HV medium is more as compared to MV medium and LV medium (Fig. 4(c)). The primary reason is that the HV medium mainly consists of SBP. Due to the presence of bulky side groups and double bond between the polymer atoms in SBP, it restricts the free movement of the polymer chains. This results in high viscosity of the HV medium at room temperature. As the SBP enriched medium gains the thermal energy due to the increase in temperature, it starts local agitation and movement of polymer molecules[10]. Therefore, the viscosity of HV medium decreases in a considerable amount compared to the viscosity of MV medium and LV medium.

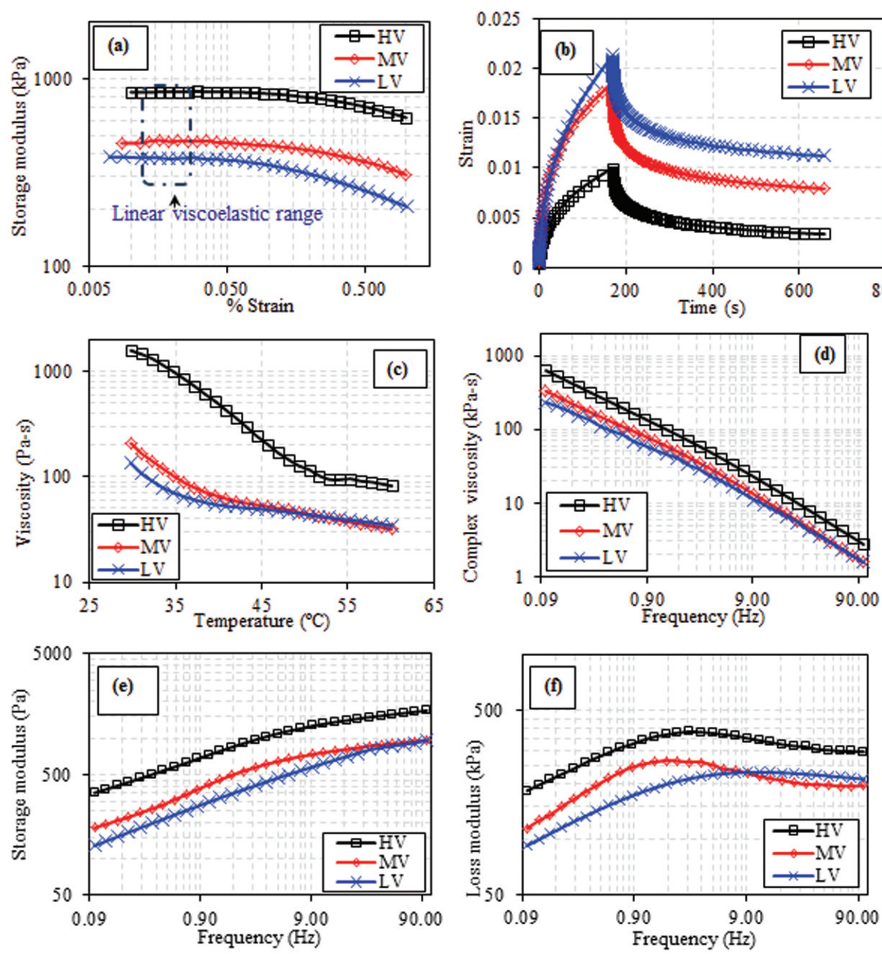


Figure 4. Comparisons of various rheological properties of the high viscous (HV), moderate viscous (MV), low viscous medium (LV) like effect of : (a) % strain on storage modulus (b) time on strain (c) temperature on viscosity (d) frequency on complex viscosity (e) frequency on storage modulus (f) frequency on loss modulus (wt. %. of abrasive particle = 45 %).

4.1.3 Dynamic Rheology

Complex viscosity is an indicator of resistance to deformation of the material under the external forces. With an increase in frequency or shear rate of the medium, complex viscosity of medium decreases, this represents its shear-thinning behaviour (Fig. 4(d)). This is the most desirable medium property required for finishing of micro features by the AFF process. HV medium shows the highest complex viscosity of around 6.33 x 10^5 Pa-s. Elastic nature of the viscoelastic medium is decreased for its smooth flow through the micro features (microslots and microholes). Thus, the maximum value of complex viscosity achieved in MV medium is 3.22 x 10^5 Pa-s which is further lowered to 2.33 x 10^5 Pa-s for the LV medium (Fig. 4(d)). Figure 4(e) shows the comparison between the storage modulus of the various medium. Higher the amount of elastic content in the medium more is the amount of energy it can store[23]. Hence, the storage modulus of the HV medium is very high as compared to the MV and LV medium. The lesser content of elastic nature is shown by the considerable amount of decrease in the storage modulus of MV and LV medium prepared for finishing micro features. Loss modulus for HV medium is considerably higher due to the high friction in medium with more SBP content as compared to the MV and LV medium (Fig. 4(f)).

4.2 AFF Experiments

To demonstrate the finishing efficiency of the developed medium for achieving nano surface finish of macro to micro features, AFF experiments are performed. The initial internal surface of the stainless steel tube contains lathe boring marks with a R_a value of 0.64 µm (Fig. 5(a)). These boring marks are completely removed after finishing the tube by using developed HV medium and achieving a R_a value of 0.07 µm (Fig. 5(b)). The initial workpiece surface doesn't reflect the word "AFF" but after performing finishing operation, workpiece achieves mirror finished surface which is shown by the clear reflection of the word "AFF" from the finished surface.

Wire electric discharge micromachining (WEDµM) process was used for fabricating the microslots in the workpiece. As a result workpiece surface obtained after WEDµM process consists of recast layer with high roughness peaks and deep valleys. As a result, the initial R_a of the workpiece surface is 3.43 µm (Fig. 6(a)). Final R_a value of 0.27 µm is obtained on microslots by AFF process using the MV medium (Fig. 6(b)). This corresponds to an improvement of 92.13 % in the microslot surface roughness.

Microholes are machined by the die sinking electric discharge micromachining (die sinking EDµM) process having an initial R_a value of 1.43 µm. Due to the entrapment of the carbon from oil dielectrics it leads to the formation of carburised recast layer with high hardness and loosely bonded metal debris on the microhole surface. Performing finishing operation by the AFF process with LV developed medium removes the hard recast layer and achieves R_a value of 0.17 µm on the microhole surface (Fig. 7 (b)).

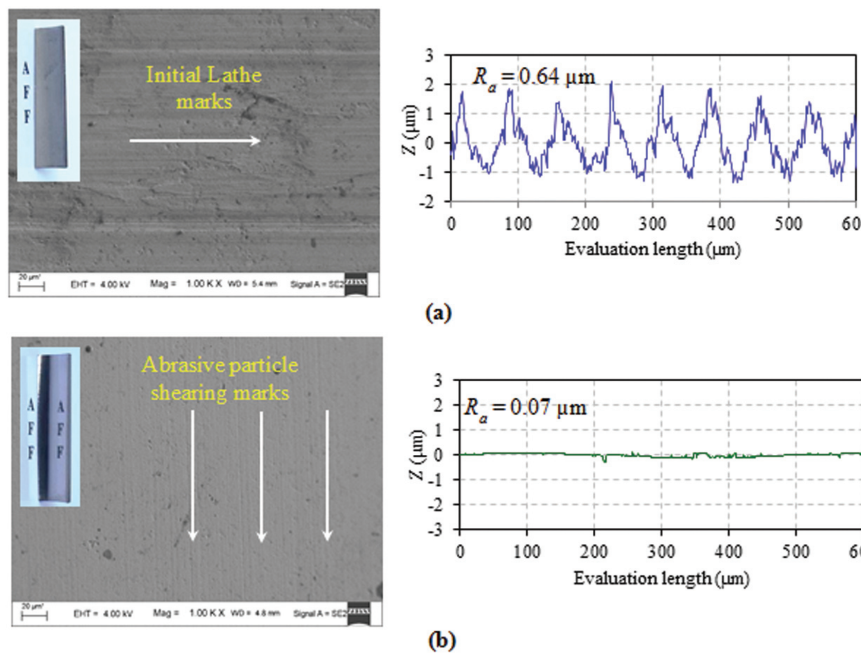


Figure 5. Topography of the tube surface (a) initial (b) after abrasive flow finishing (wt. %. of abrasive particle = 45 %).

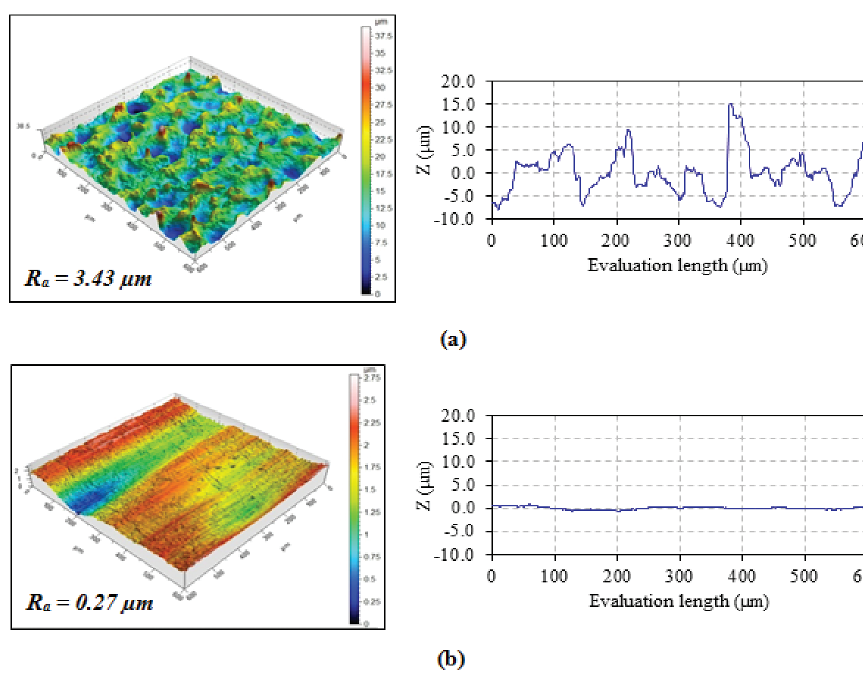
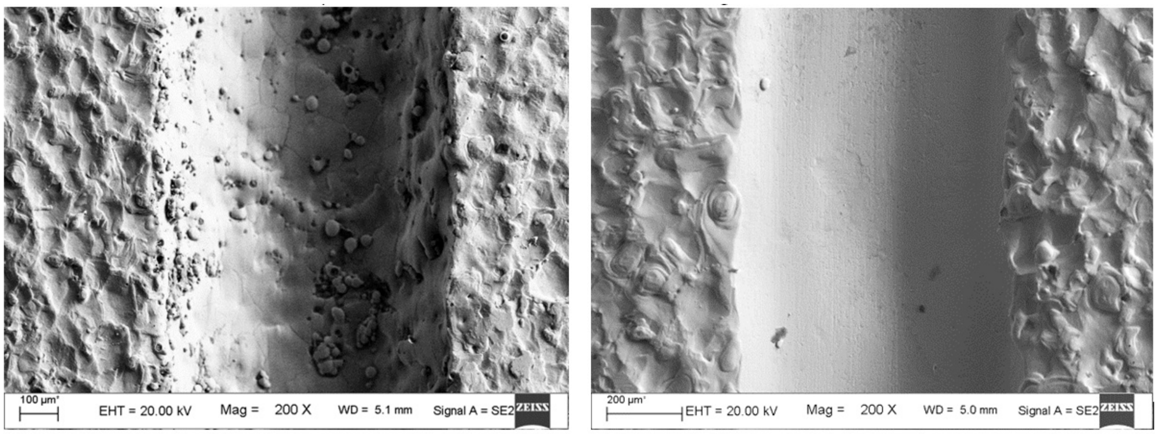


Figure 6. Topography of the microslot surface (a) initial (b) after abrasive flow finishing (wt. %. of abrasive particle = 45 %).



(a) (b)

Figure 7. Topography of the microhole surface (a) R_a = 1.43 µm, initial and (b) R_a = 0.17 µm, after abrasive flow finishing (wt. %. of abrasive particle = 45 %).

5. CONCLUSIONS

In the present work, in-house economic AFF medium is prepared. Various constituents of the medium can be varied to have HV, MV and LV type of medium that successfully finished macro and micro featured components. Developed medium is a viable alternative to commercially used expensive AFF medium. Rheological characterisation of the developed medium is performed and it was observed that time, temperature and shear rate affects rheological properties of the medium. Later, finishing of macro and micro feature components is performed using the developed medium. Some of the significant findings of the present work are:

i. Medium is viscoelastic in nature with shear-thinning property.
ii. From the creep recovery test, it is observed that the elastic component of the medium is highest in the HV medium, while it is least in LV medium.
iii. The viscosity of the medium decreases with an increase in temperature. This is mainly due to the motion of polymer molecules and the breaking of polymer chains because of the addition of thermal energy. In the range of 30º C to 60º C the viscosity of the HV medium decreases from 1.58×10^6 Pa-s to 8.20×10^4 Pa-s. While for MV and LV medium, it decreases from 2.08×10^5 Pa-s to 3.17×10^4 Pa-s and 1.35×10^5 Pa-s to 3.44×10^4 Pa-s respectively.
iv. With an increase in frequency, the storage modulus of medium increases. Higher the external forces acting on the medium, more energy it stores during the deformation process.
v. HV medium with 45 wt. % of abrasive particles show the highest complex viscosity with a value of around 6.33×10^5 Pa-s. The decrease in the elastic component of the viscoelastic medium results in a smooth flow of medium through the micro features (microslots and microholes). The maximum value of complex viscosity of the MV medium used for finishing of the microslot is 3.22×10^5 Pa-s, whereas it is 2.33×10^5 Pa-s for LV medium for the finishing of the microholes.
vi. HV medium successfully finishes internal surfaces of stainless steel tubes with an 89.06 % in the surface roughness. The recast layer on the machined surfaces of the microslot and microholes is completely removed by the AFF process using MV and LV medium, respectively. Thus, highly rough surfaces of the micro features are changed into finely finished surfaces using the developed medium.

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In the current study, he involved in material selection, purchasing of material, analysis of the results and correction of the manuscript.