DEPENDENCE OF R-AFF PROCESS
ON RHEOLOGICAL CHARACTERISTICS OF SOFT
STYRENE BASED ORGANIC POLYMER
ABRASIVE MEDIUM

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ABSTRACT

Abrasive flow finishing process is an advanced fine finishing process which finishes the work surface using polymer rheological abrasive medium. The medium should possess three basic properties i.e., better flow ability, self deformability and optimum abrading ability to finish the given surface to nano level. Various flow and deformation properties of the medium have been studied by rheological characterization. Rheology is science of flow and deformation of medium. In the present work, different media are made using soft styrene butadiene based polymer, plasticizer, abrasives and rheological additives.

To evaluate static and dynamic rheological properties of these media, experiments are carried out and found that the media are viscoelastic with shear thinning nature. Three different types of media (elastic dominant, viscous dominant, equal elastic and viscous component) are selected to perform finishing operation on Al alloy and its metal matrix composites using rotational AFF process.

Later, the effect of each rheological parameter on the change in average surface roughness (ΔRₐ) is evaluated. As the yield shear stress increases, material removal increases continuously but ΔRₐ increases up to a certain limit, beyond which it starts decreasing.

It is found that the medium with apparently equal viscous and elastic properties gives better surface finish compared to other media.

Keywords: R-AFF, Surface roughness, Metal matrix composites, Rheology, Polymer Medium

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1. INTRODUCTION

Traditional fine finishing processes such as grinding, lapping, honing and super-finishing have many applications but their use is limited in the production of flat and cylindrical workpieces. Finishing of complex shaped components needs advanced finishing processes to produce nano level surface finish. Abrasive flow finishing (AFF) is an advanced finishing process in which a small quantity of workpiece material is removed by flowing polymer rheological abrasive medium over the surface to be finished (Rhoades, 1988, 1991, Loveless, 1994, Rajeshwar, 1994, Williams, 1989). This process is capable of producing 50 nm surface finish and can deburr the holes as small as 0.2 mm in diameter. But the finishing rate of the AFF process is low hence to improve its finishing rate, a modified version of the process is developed, and it is named ‘Rotational Abrasive Flow Finishing’ (R-AFF) process.

In R-AFF process, medium is the most important element. Medium is a complex rheological material in which different compositions exhibit different viscous and elastic properties under varying conditions of shear rate, stress, strain and temperature. It is indigenously developed by homogeneously mixing using soft styrene butadiene polymer, plasticizer, abrasives and rheological additives with the help of a two rolls mill. The rheological properties of the medium determine the pattern and aggressiveness of the abrasive action. Abrasion is high where medium experiences high restriction and travels with high velocity (Williams, 1992, 1992, Jain, 2002, 2010).

This viscoelastic medium when left at rest, it flows slowly like a fluid due to natural gravitational forces. When rolled into a ball and bounce, it behaves like an elastic solid ball. Lastly, when stretched rapidly, it breaks as if it is a solid plastic piece. These unique properties demonstrate the importance of measuring the rheological properties to understand how does it perform during finishing process. Static and dynamic rheological tests are carried out on a large spectrum of medium. From the creep compliance test, three media with different properties are selected for finishing experiments using R-AFF process.

2. EXPERIMENTATION

Media are prepared using base soft styrene butadiene co-polymer, plasticizer (hydrocarbon oil), abrasives (SiC #220) and rheological additives (softeners etc). Base polymer consists of two monomers (styrene and butadiene), in which butadiene is only single chain and styrene is branched to provide both flexibility and low density to the medium. Linear polymers are flexible because, repeating units are joined together in single chain that possesses extensive van der Waals bonding between the chains. Branched polymers are those in which side-branch chains are part of the main-chain molecules. The chain packing efficiency is reduced with the formation of side branches, which results in a lowering of the polymer density. Uncured polymers are used so as to avoid covalent bonds, thus the base polymer is soft in nature.

Plasticizers are used for gelling of the polymers by diffusing between the polymer chains. Plasticizers are low molecular weight fluids which easily diffuse in between the high molecular weight base polymer chains. So, the inter polymer molecular forces reduce and free volume in the medium increases. This creates the polymer chain flexibility, better flow ability and self deformability. Since the plasticizers play major role in rheological properties of the
medium, in the present work, a spectrum of rheological media with variety of rheological properties are made by varying the weight percentage (%) plasticizer (Ravi Sankar, 2010(a)).

![Figure 1. Schematic diagram of parallel plate rheometer.](image)

**Table 1. Wt% of various ingredients in medium composition**

<table>
<thead>
<tr>
<th>Ingredient name</th>
<th>Medium-1</th>
<th>Medium-2</th>
<th>Medium-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt% of Plasticizer (%)</td>
<td>7.5</td>
<td>10.0</td>
<td>12.5</td>
</tr>
<tr>
<td>Wt% of base polymer (%)</td>
<td>26.0</td>
<td>23.5</td>
<td>21.0</td>
</tr>
<tr>
<td>Wt% of SiC (%)</td>
<td>66.5</td>
<td>66.5</td>
<td>66.5</td>
</tr>
</tbody>
</table>

In the present work, experiments were designed using one variable at a time approach. Three different media compositions were prepared by varying weight percentage of medium ingredients. The details of the same are given in Table.1. Static and dynamic rheological characterization of these three medium compositions are carried out to find viscoelastic characteristics.

The static (flow, creep compliance, stress relaxation) and dynamic (frequency sweep) rheological properties of each medium samples are tested using parallel plate rheometer (Anton Paar MCR301) whose schematic diagram is given in the figure.1. From creep compliance test of viscoelastic medium, the quantities of viscous and elastic components are known (discussed later).
Three characteristics of different media (elastic dominant, viscous dominant and approximate equal viscous and elastic properties) are selected for carrying out the finishing experiments using R-AFF process so as to finding relationship with finishing capability of the process (Ravi Sankar, 2009 (a), 2009(b), 2009(c), 2010(b)).

Finishing experiments are carried out using R-AFF setup (Figure 2) on Al alloy, Al alloy/SiC MMC with 10% SiC and 15 % SiC volume. The input conditions of R-AFF process for finishing experiments are number of cycles = 650, extrusion pressure = 6.25 MPa, workpiece rotational Speed = 10 rpm. All the workpieces are ground to the initial $R_a$ of 0.30±0.05 μm. The change in average surface roughness ($\Delta R_a$) and material removal are
measured after finishing using R-AFF process. The difference between initial and final $R_a$ value is named as $\Delta R_a$. Change in initial and final weight is considered as material removal (MR). Since the metal matrix composites are heterogeneous materials, to have consistency, the finishing experiments are conducted twice and average values of $\Delta R_a$ as well as MR are reported. Then the effect of each rheological parameter on $\Delta R_a$ and MR are studied to show the importance of the rheology on finishing in R-AFF process.

3. RESULTS AND DISCUSSION

Effect of process parameters on $\Delta R_a$ and Material removal

3.1. Yield Shear Stress

At low shear rate, the movement of the polymer molecular chains is slow and gradually climb up one over other leading to higher density of polymer molecular chains entanglement. Thus, shear stress gradually increases up to yield point where the polymer molecular chains entanglement density is maximum. The molecular chains cannot resist any further increase in shear rate and start breaking. As a result polymer molecular entanglement density starts decreasing and shear stress decreases. Low molecular weight plasticizer easily diffuses in between polymer chains and increases distance between the polymer chains. Hence, intermolecular forces between polymer molecules decreases and thus shear stress reduces with increase in plasticizer content (Figure 3). This property of the media is used to explain the results related to the material removal and $\Delta R_a$ during R-AFF process.

Figure 3. Effect of shear rate on shear stress (Logarithmic scale on both X and Y axes).
Low yield shear stress (high plasticizer content) medium possesses better flow properties but poor abrasion properties. In such cases, when an abrasive strikes the work surface peak, it can partially shear the sharp edges but may not shear complete surface peak. So, the material removal is low. As the shear strength increases with better flow properties, the medium shears the surface peaks completely, resulting in increased material removal. By increasing the shear strength beyond this limit (maxima in Figure 3), the self deformability and, flow property of the medium become poor. Hence, it starts creating deep scratches on the finished surface and also leads to reinforcement pullout in MMCs. Thus, material removal increases (Figure 4(a)).

Figure 4. Effect of yield shear stress on (a) material removal, and (b) $\Delta R_s$. 
At low shear stress, since medium can shear sharp surface peak edges and leaves partial surface peak, the $\Delta R_a$ is low. As the shear strength of the medium increases, the shearing capability of the medium gradually improves and shears surface peaks across its full width. So, $\Delta R_a$ increases. Further increase beyond optimum $\Delta R_a$ (Figure 4(b)) causes severe abrasion phenomenon which not only shears the surface peaks but also creates its own deeper scratches on the finished surface. Thus, $\Delta R_a$ starts decreasing (Figure 4(b)).

Figure 5. (a) Macro and (b) micro view of severe indentation marks on the soft Al alloy (c) Reinforcement pullouts in reinforcement agglomerated regions in Al alloy/SiC (15%) MMCs.

Al alloy is soft, hence abrasives can easily shear the surface and also can make deep indentations (Figure 5(a). Al alloy/SiC (10%) material is harder and the reinforcements are uniformly distributed. So indentation and shearing of work surface peaks is comparatively difficult. Thus, material removal in Al alloy is higher than MMC (10%) (Figure 4(a)). But in
Al alloy/SiC (15%), the reinforcement agglomeration is dominant and medium can easily shear these agglomerated areas due to poor bonding between reinforcements (Figure 5(b)). Density of this reinforcement is higher so, the material removal in Al alloy/SiC (15%) is higher compared to other two materials. The indentations are severe in Al alloy as compared to reinforcement pullouts in agglomerated regions in Al alloy/SiC (15%). Further, reinforcement pullout is a random phenomenon due to random distribution of agglomeration, and its effect will not be reflected in $\Delta R_a$ unless $R_a$ value is measured under this pull out. The probability of occurrence of this event is comparatively low. So, $\Delta R_a$ is slightly on higher side in case of Al alloy/SiC (15%) compared to soft Al alloy (Figure 4(b)).

### 3.2. Creep Recovery

Creep recovery test of viscoelastic medium gives the quantity of viscous and elastic components in the medium. When extrusion pressure is applied on the medium, the viscous component assists the medium to exert force in axial direction (the direction in which the extrusion pressure is applied ($F_a$)) and elastic component assists to exert the force in radial direction (perpendicular to the applied extrusion pressure direction ($F_r$)) (Figure 6(a)). So, active abrasive grain in viscoelastic medium exert both $F_a$ and $F_r$ on the workpiece when the extrusion pressure ($P$) is applied (Figure 6(b)). $F_a$ and $F_r$ depend on the extrusion pressure and medium viscosity. Depth of indentation depends on the $F_r$ and the corresponding compressive strength of the medium, but the abrasive particle indentation velocity is very low, so the radial velocity is neglected. At higher viscosity and higher extrusion pressure, force ratio ($F_r / F_a$) is more i.e., amount of increase in $F_r$ is more than $F_a$ (Ravi Sankar, 2009).

![Figure 6](image.png)

In Figure 7, AB represents viscoelastic region, BC shows elastic region and remaining AC is viscous region. It is important to know the amount of viscous and elastic components in different media. Thus, the creep recovery test is conducted. For better finishing capabilities,
the medium should possess better deformation as well as flow properties (viscous characteristic) to reach complex nook and corners along with moderate elastic properties to exert gentle radial force on the surface being finished. The soft base polymer possesses elastic properties and addition of plasticizer improves the viscous properties.

As the plasticizer amount increases, more amount of plasticizer diffuses between the polymer chains and spreads them apart forcibly. As a result, with an increase in plasticizer content the inter polymer molecular forces decrease which causes reduced elastic recovery (Figure 7).

At low % of viscous component (at low plasticizer in medium), the medium possesses high % of elastic component, hence the medium exerts more indentation force on the work surface. Since, the medium indents deeper and abrades roughly, the material removal is high. As the amount of viscous component increases, medium’s elastic component (radial force) decreases and the flow property enhances.

Therefore, the material removal gradually decreases compared to low % viscous medium (Figure 8(a)). On further increase in % of viscous component in the medium, it gives better flow properties and substantially decreased radial component of force. Thus, the medium flows over the workpiece surface and shears only the top edges of surface peaks. Hence, the material removal decreases (Figure 8(a)).

Because of aggressive shearing of surface peaks and creation of deep scratches, $\Delta R_a$ is low at low % of viscous component (low % of plasticizer amount in the medium) (Figure 8(b)). On increasing % of viscous component, the medium loses its radial component substantially and thus shearing capability reduces. Thus, the $\Delta R_a$ sharply decreases (Figure 8(b)).

Figure 7. Effect of creep compliance with time (Logarithmic scale on both X and Y axes).
3.3. Stress Relaxation

Stress relaxation describes how fast the medium relieves stress under constant strain in a given time. Since the base polymer possesses dominant elastic properties, low plasticizer medium possesses high relaxation modulus. As the amount of plasticizer increases, the viscous nature increases and relaxation modulus (Eq.1) decreases (Figure 9).

At low relaxation modulus, the medium tries to relax slowly (medium contact time with the finishing surface is high) and it has low elastic component (indentation depth is low). Due to high plasticizer content, a thin layer of the medium sticks on the surface being finished and
rest of the abrasive medium simply slides over it without abrading much. Thus, the material removal is low (Figure 10 (a)).

Figure 9. Effect of stress relaxation modulus with time (Logarithmic scale on both X and Y axis).

\[
\text{Relaxation modulus (Pa)} = \frac{\text{Stress relaxation}}{\text{Strain applied}}
\]  

As the amount of plasticizer in the medium decreases, the relaxation modulus increases and the sticking tendency reduces. This medium also gains sufficient elastic component to impart enough radial force on the surface to shear major surface peaks. It increases material removal. Any further increase in relaxation modulus enhances radial force substantially. Hence, the medium imparts large indentation which shears the surface peaks and creates its own deep scratches. This results in increased material removal (Figure 10(a)).

At low relaxation modulus, the radial force is low hence the medium is able to shear only sharp surface peaks, and fails to shear the surface peaks requiring large force. So, \( \Delta R_a \) is low, and as the radial component increases, the medium tries to shear the larger surface peaks, thus, \( \Delta R_a \) increases (Figure 9(b)). Further increase in relaxation modulus substantially, increases the radial force. As a result apart from shearing the surface peaks, it also creates its own deep scratch marks on the work surface. Hence, the \( \Delta R_a \) deteriorates even though material removal increases (Figure 10(b)).

### 3.4. Complex Viscosity (\( \eta^* \))

Since the medium is viscoelastic, it possess the complex viscosity (\( \eta^* \)) which takes care of viscous and elastic components of the medium (Eq.3).
where $G^1 = \text{Storage modulus}$ $G^{11} = \text{Loss modulus}$

\[
\text{Complex modulus } G = \sqrt{(G^1)^2 + (G^{11})^2}
\]

\[
\text{Complex viscosity } (\eta^*) = \frac{\text{Complex modulus}}{\text{Angular frequency}}
\]
In frequency sweep test, at low frequency, the number of times the shearing takes place is less so the probability of retaining original strength by the polymer chains is high. At high frequency, the medium sample shearing rate increases thus, the polymer chains break and \( \eta^* \) decreases (Figure 11).

Figure 11. Effect of frequency on complex viscosity (Logarithmic scale on both X and Y axis).

Figure 12. (Continued).
At low $\eta^*$, the medium loses its strength due to breaking of polymer chains and more plasticizer content. So, the medium fails in providing sufficient strength to abrasive while finishing. Thus, the abrasive rolls about its own axis when it tries to shear the surface peak. Because of predominant abrasive rolling, it can shear only the sharp edges of surface peaks. Hence, the material removal is low (Figure 12(a)). At higher $\eta^*$, the base polymer chains are not broken, and are at original strength with good flow ability characteristics due to appropriate amount of plasticizer. So, medium can hold the abrasive particles properly and they can shear the workpiece surface peaks. Thus, material removal increases. On further increase in $\eta^*$, medium shear strength is high, so it not only shears the peaks but also tries to shear the finished surface. So, material removal is high at high $\eta^*$ (Figure 12(a)).

Figure 12. Effect of complex viscosity on (a) material removal and (b) $\Delta R_a$.

Figure 13. Atomic force microscopic graphs of (a) initial ground surface, (b) finished surface obtained by R-AFF process.
At low $\eta^*$, $\Delta R_a$ is low because the medium can shear only surface peak edges. As $\eta^*$ increases, the medium can shear more number of surface peaks (Figure 13(a)) because of better abrasive holding ability and flow ability of the medium (Figure 13(b)). But at high $\eta^*$, the medium is tough and flow ability characteristics are so not good. Thus, the abrasive particles not only shears the surface peaks but also indent workpiece surface severely. Hence, $\Delta R_a$ starts decreasing beyond the optimum $\Delta R_a$ (Figure 12(b)).

**CONCLUSION**

The basic aim of present study is to find the effect of rheological properties on nano finishing characteristics in R-AFF process. The different media are developed by varying the weight % of plasticizer. From the creep recovery study, elastic dominant, viscous dominant and equal elastic and viscous dominant media are selected for finishing of Al alloy and its MMCs using R-AFF process. Based on this study, following conclusions have been derived,

- High elastic component medium applies high radial force and indents the surface more deeply.
- The capability of abrasive holding of the high viscous dominant medium is low, hence it gives low $\Delta R_a$.
- Medium with approximately equal elastic and viscous components, possess better flow, self deformable and abrasion properties. Thus, it finishes better compared to other two media and produces better surface finish.

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