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Rheological characterization of styrene-butadiene based medium and its finishing performance using rotational abrasive flow finishing process

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ABSTRACT

Finishing of complex shaped components needs advanced finishing processes to produce nano level surface finish. Abrasive flow finishing (AFF) process uses abrasive mixed polymer as a medium to finish complex shapes. The medium should possess three basic properties i.e., better flow ability, self deformability and abrading ability to finish the given surface to nano scale. Various flow and deformation properties of the medium can be investigated by rheological characterization. In the present work, different media are made using specially co-polymered soft styrene butadiene based polymer, plasticizer and abrasives. Static and dynamic rheological properties of these in-house prepared media are evaluated, and it is found that these media follow viscoelastic behavior with shear thinning nature. For a small rise in temperature, the medium starts losing its original properties.

In the present work, static (flow test, creep compliance test, stress relaxation test) and dynamic (amplitude sweep and frequency sweep) rheological properties are measured. Finishing experiments are carried out on Al alloy as well as its metal matrix composites using rotational abrasive flow finishing (R-AFF) process. Later, the effect of each rheological parameter such as shear stress, % viscous component, stress relaxation modulus and storage modulus on the change in average surface roughness (ΔR_a) and material removal rate during R-AFF is found.

1. Introduction

Traditional fine finishing processes such as grinding, lapping, honing and super-finishing have many applications but their use is limited to the production of flat and cylindrical workpieces. Finishing of complex shaped components needs advanced fine finishing processes to produce nano level surface finish. Abrasive flow finishing (AFF) is one of such processes, which can finish the complex shaped surfaces to nano scales. In AFF process, a small quantity of workpiece material is removed by flowing medium over the surface to be finished [1–4]. This process is capable of producing 50 nm surface finish and can deburr the holes as small as 0.2 mm diameter [5]. Three major elements of AFF process are AFF machine, tooling and medium.

In commercial AFF machines, the process parameters (extrusion pressure, number of cycles, relative speed) can be varied. Along with these process parameters, medium parameters (rheological parameters) also play a major role in finishing operation to achieve the desired nano level surface finish. Having knowledge of both the classes of parameters (process parameters and rheological parameters), the operator has a wider choice of variables through which the process performance can be appropriately controlled.

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 [6,7]. Since most of the polymers are amorphous in nature, their rheological characterization is a challenge. Polymer rheological properties depend on polymer molecular shape, structures and interactions. Polymer consists of a large number of molecular chains and these chains can bend, coil and twist, leading to extensive entanglement and intertwining with neighboring chains. These complex molecular entanglements of chains contribute to a large extent in determining important mechanical and thermal properties of polymers. Normally, AFF medium is a complex viscoelastic material in which different constituents exhibit different viscous and elastic properties under varying conditions of shear rate, stress, strain, time and temperature. This viscoelastic medium when left at rest, with the effect of natural gravitational forces, slowly flows like a fluid. When rolled into a ball and bounce, it behaves like an elastic solid ball as well as when stretched rapidly, it breaks as a solid plastic piece. These unique properties demonstrate the importance of measuring the rheological properties to understand its behavior during the finishing process.

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The basic problem with AFF process is low finishing rate (rate of change of surface roughness value, μm/s). Due to continuous shearing of surface peaks and friction in finishing zone, the medium temperature rises. The base carrier in the medium is polymer and it is sensitive to temperature (medium shear viscosity decreases as the temperature increases at different plasticizer content (Fig. 1)). Hence, change in shear viscosity due to a change in medium temperature is studied. As the temperature increases, the long chains disintegrate into small segments as well as the polymer molecules gain energy and try to move apart. So, with rise in temperature, the shear viscosity gradually decreases (Fig. 1). As the shear viscosity decreases, the medium also losses its finishing capabilities. At lower shear viscosity, the magnitude of maximum force that can be sustained by the medium before breakdown of polymer chains decreases hence the height of the peak that can be sheared in one pass reduces or in other words the finishing rate decreases.

To characterize the various media prepared in-house, static and dynamic rheological properties were evaluated using a standard rheometer (Anton Paar MCR-301). It also helped in understanding the pattern and aggressiveness of the abrasive action. In this study, stress, strain, time and frequency are controlled to measure various properties such as shear viscosity, stress relaxation (long chain branching on linear viscoelastic properties), creep/recovery (molecular architecture) amplitude and frequency sweep (viscoelasticity). It is found that all the studied abrasive media follow viscoelastic behavior with shear thinning nature. Specifically, viscoelasticity is a molecular rearrangement (i.e., change of long polymer chain position with applied stress). Polymers remain as a semisolid material even though the polymer chains rearrange (viscous nature) within the medium in order to resist the applied stress, and this polymer rearrangement creates a back stress (elastic nature) in the abrasive medium as a whole.

In view of the above, in the present work, medium composition is varied to study the changes in the rheological properties and then to understand their effects on the finishing performance. Additional process parameter (workpiece rotational speed) is introduced in R-AFF process to enhance the process performance. Combination of the process parameters along with the medium rheological parameters would give a better control of the process. To understand the effect of these rheological parameters on AFF process, experiments were conducted on the R-AFF setup and relationship of the process parameters with change in surface roughness (ΔR_a) and material removal (MR) have been discussed in the following sections.

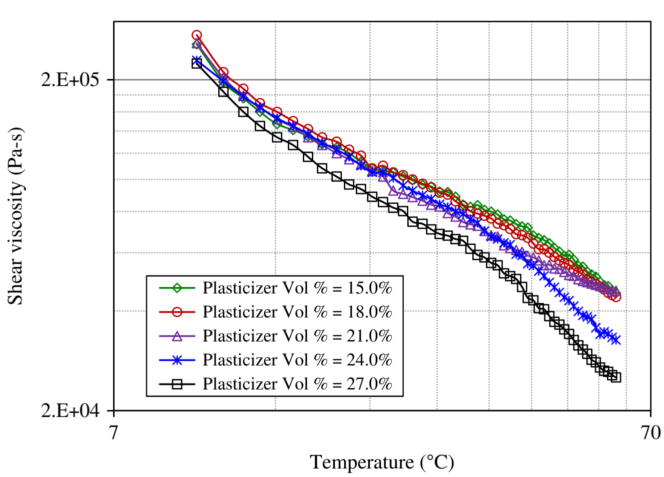

Fig. 1. Effect of temperature on shear viscosity for different volume percentage of plasticizer in the medium.

2. Experimentation

2.1. Materials

2.1.1. Base polymers

Polymer is a long chain compound, which is formed from individual monomers (Fig. 2(a)). These long polymer chains start entangling with one another when shear force is applied. Intermolecular forces and polymer chain entanglement mainly decide the basic physical properties of these polymers. In the present work, mixture of approximately 25% styrene and 75% butadiene repeating monomer units are arranged in a random manner along the polymer chain by random co-polymerization, (Fig. 2(b)).

Base polymer should be mechanically stable and chemically compatible with plasticizer and abrasive particles. Many researchers tried to make different types of base polymer carriers such as polyboro siloxane [8–12], silly putty [13–15], natural rubber, ethylene propylene-diene monomer (EPDM rubber), butyl rubber, silicone rubber, styrene butadiene rubber (SBR) [16] and silicone and emulsion silicone rubber [17]. Some of the base polymers have been used as matrix material in the AFF medium.

The polymer physical properties (strength and flexibility) depend on length of chain, number of side groups, amount of branching and cross linking. Longer chain and presence of polar side groups make the polymer stronger (polymer chains looses their flexibility). Un-branched and systematic arrangement of polymer chains pack together leading to partial crystalline polymer, which is a symbol of strong polymer compared to branched polymer. In the present work, an amorphous polymer is chosen to get better flexibility. The base polymer consists of two monomers, in which one monomer is only main chain (Butadiene) and the other one is branched (Styrene) in order to provide both flexibility and low density to the medium. Linear butadiene polymer chains are flexible because of their repeating units, which are joined together in a single chain with Van der Waals force bonding between the chains. Branched styrene polymer chains possess side-branch chains as a part of the main-chain. The chain packing efficiency reduces with increase in number of side branches and intern reduces the polymer density. The base polymers selected in the present study are uncured polymers in order to avoid covalent bonds in both monomers so as to provide soft nature. Viscosity of the base polymer is reduced in the present study by breaking the molecular bonds through mechanical and thermal breakdown while passing through two rolls mill. These polymers possess dominant elastic properties, which also help the medium to exert the radial force, during AFF.

2.1.2. Plasticizers

Plasticizers (processing oils or dispersants) are small molecules (low molecular weight) and do not possess long chains. Plasticizer molecules are chemically similar to the polymer and

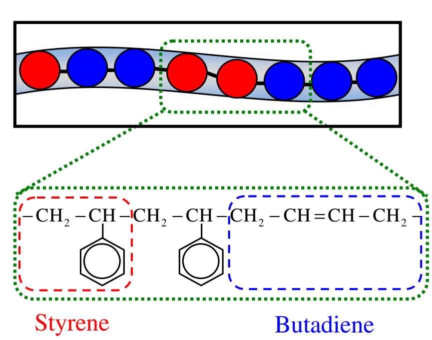

Fig. 2. Polymer chain chemical structure of styrene butadiene co-polymer.