Experimental determination of viscosity of abrasive flow machining media

A. Agrawal, V.K. Jain and K. Muralidhar*

Department of Mechanical Engineering, Indian Institute of Technology, Kanpur, Kanpur 208016 UP, India
E-mail: Kmurli@iitk.ac.in E-mail: vkjain@iitk.ac.in
*Corresponding author

Abstract: Abrasive flow machining (AFM) is a non-traditional process used to de-burr, radius, polish and remove recast layers of the components in a wide range of applications. The material removal in abrasive flow machining takes place by flowing the media, mixed with abrasives, across the surface to be machined. The media is the key element in the process because of its ability to precisely abrade the selected areas along its flow path. From the review of literature, it was found that there is a need to know the viscosity of the media, since it has a significant effect on the process performance parameters. In the present work, a viscometer set-up has been fabricated based on the principle of visco-elasticity. The creep compliance and the bulk modulus have been determined and the viscosity of the abrasive media has been subsequently calculated. Measurements have been conducted for obtaining viscosity along with an assessment of specimen length and initial load, the influence of reduced data points and the repeatability of the experiments. Besides this, experiments have been conducted at varying concentration and temperature of the abrasive media. Experiments show that the viscosity of the media increases with the percentage concentration of abrasives and decreases with temperature. Viscosities at different concentration of the abrasives were compared with the values obtained from a capillary viscometer and the comparison was found to be good.

Keywords: AFM media; bulk modulus; creep compliance; Kelvin's solid; viscosity.

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Biographical notes: Amreesh Agarwal has done his MTech in Mechanical Engineering from I.I.T.Kanpur.

In recognition of his research work, Vijay Kumar Jain has been opted as a member of the editorial board of six international journals. He has also worked as a guest editor for three special issues on TQM, CAPP and advanced machining. Professor Jain has also worked as an editor of the Proceedings of the 5th Conference of Indian Society of Mechanical Engineers (1982), DST sponsored 6th SERC school held at IIT Kanpur in 1999 and the 3rd SERC School on Precision Engineering in 2002. He has guided 10 PhD theses, and 70 MTech theses and has some 200 publications including four books. Dr Jain has various research areas of interest, including advanced machining techniques,

machining of advanced engineering materials, shear strain acceleration phenomenon in metal cutting, computer aided manufacturing, CAPP and other areas related to manufacturing science and engineering.

Dr K. Muralidhar has been on the Faculty of the Mechanical Engineering Department, Indian Institute of Technology, Kanpur, since 1987. He received a doctorate in Applied Science from the University of Delaware, USA in 1985 and was subsequently a post-doctoral fellow at Lawrence Berkeley Laboratory, Berkeley until June 1987. He joined IIT Kanpur as an Assistant Professor, was promoted to the post of Associate Professor in 1993 and became a full Professor in 1995. His areas of interest are primarily in fluid mechanics and thermal sciences. Dr Muralidhar conducts experiments and numerical simulation, and his research involves resolving fundamental issues as well as engineering applications. His experiments utilise a variety of laser measurement techniques, some of which have been developed in his laboratory. His current interests are in growth of optical crystals, vorticity dynamics, drag reduction, interfacial phenomena and inverse determination of thermophysical properties. He is the author of a text book entitled *Advanced Engineering Fluid Mechanics* and has an edited volume on *Computational Fluid Flow and Heat Transfer*. He has over 60 publications in international journals, 15 in Indian journals, and over 70 conference publications.

1 Introduction

Abrasive flow machining is a finishing process in which a small quantity of material is removed by flowing semi-solid, abrasive-laden putty (called *media*) over the machined surface. The media is a rubber-like material of a high viscosity and can be deformed by applying a little pressure. Two vertically opposed cylinders extrude abrasive media back and forth through the passage formed either by the workpiece and tooling, or by the workpiece alone. The semi-solid abrasive media is forced through the workpiece or through the restricted passage formed by the workpiece. Abrasive particles act as cutting tools, resulting in a multi-point cutting process. The material removal rate is quite low. The process is employed for both metals and non-metals. Abrasive flow machining is suitable to automate finish operations that ask for high cost and are labour intensive. It is also employed for finishing operations in aerospace, automotive, semiconductor and medical component industries. Specifically, it is very useful for finishing the surfaces of extrusion dies, nozzles of a flame cutting torch and airfoil surface of an impeller, deburring of aircraft valves bodies and removing of recast layer after electric discharge machining.

The characteristics of the media, including its viscosity, abrasive concentration and temperature determine the aggressiveness of action of the abrasives during the abrasive flow machining process. The media used in abrasive flow machining is a pliable material and is resilient enough to act as a self-forming grinding stone when forced through a passageway (Rhoades, 1989). It consists of a base and abrasive grits of two or three sizes. The base material is visco-elastic and made up of an organic polymer and hydrocarbon gel. The composition of the base material determines its degree of stiffness. The stiffest medium is used for small holes. High stiffness of the media results in pure extrusion, while soft media leads to a faster flow in the centre instead of along walls. It is reported that media with a greater stiffness finishes a passageway more uniformly, while a less stiff

media results in a greater radius of the passage opening (Williams and Rajurkar, 1989, 1992). Experience with various types of media and abrasives have been reported in the literature (Inasaki et al., 1993; Loveless et al., 1994; Perry, 1989). There is clear evidence that the viscosity of the media plays a very important role in abrasive flow machining. While limited attempts have been reported in the literature (Davies and Fletcher, 1995; Fletcher et al., 1990; Hall et al., 1992), a systematic approach towards the evaluation of the viscosity of media has not been addressed.

In an earlier study (Jain et al., 2001), the authors reported the development of a capillary viscometer for viscosity measurement of the AFM media. The advantage of the design was its simplicity, specifically the possibility of making measurements at steady state. However, it had two drawbacks: Firstly, the instrument was bulky, requiring a large amount of material. Secondly, the static load required to maintain flow was quite large, being in the range of 100–150 kg. Thirdly, traces of oil in the media sample led to considerable scatter in the measured data. The apparatus developed in the present work requires smaller samples and smaller loads, but the technique relies on the temporal response of the media, and hence requires measurements as a function of time. The compactness of the apparatus has an inherent advantage when the viscosity is to be obtained as a function of bulk temperature.

The main objectives of the present work can now be summarised as follows:

- design and fabrication of a set-up for viscosity measurement of the abrasive media
- study changes in viscosity with abrasive concentration and temperature
- compare the results obtained with those from a capillary viscometer.

2 Viscoelastic model

The AFM media has been modelled in the present study as a Kelvin solid (Flugge, 1967). It can be visualised as a combination of a spring and a dashpot, connected in parallel. At all times, the strain ε of the two elements are equal and the total stress σ is split into σ' (spring) and σ'' (dashpot) in such a way that they experience equal strain ε. This condition is expressed as

$$\sigma' = E\varepsilon \tag{1}$$

$$\sigma'' = \eta\dot{\varepsilon} \tag{2}$$

Here, E is the elasticity modulus and η is the viscosity. The total stress will be the sum of both the stresses supported by the spring and the dashpot, namely:

$$\sigma = \sigma' + \sigma'' \tag{3}$$

Hence
$$\sigma = E\varepsilon + \eta\dot{\varepsilon}. \quad \text{Or,} \quad \dot{\varepsilon} + \frac{\varepsilon}{T} = \frac{\sigma}{\eta} \tag{4}$$

where $T=\frac{\eta}{E}$. Equations (4) defines the behaviour of a Kelvin solid. For a unit applied stress

$$\sigma=H(t). \tag{5}$$

Equation 4 can be integrated to yield

$$\varepsilon(t) = \frac{1}{E}(1-\exp(\frac{-t}{T})) \tag{6}$$

To study the behaviour of viscoelastic materials, a standard creep test is often utilised. Here, a stress $\sigma=\sigma_0\Delta(t)$ is applied, and the time-dependent strain ϵ is measured. For linear materials the strain is proportional to stress and may be written as

$$\varepsilon(t) = \sigma_0 J(t) \tag{7}$$

The function $J(t)$ is the strain per unit applied stress, and is a material property; for $t>0$, it is a monotonically increasing function and is called the creep compliance. For a Kelvin solid, Equation (6) shows that the creep compliance is given as

$$J(t) = \frac{1}{E}(1-\exp(\frac{-t}{T})) \tag{8}$$

The creep compliance given by Equation (8) can be found experimentally. With the help of the creep compliance function, the viscosity of the AFM media can be calculated. The modulus of elasticity can be equivalently found in terms of the bulk modulus (Agrawal, 1999; Drozdov, 1996; Flugge, 1967).

The experimental determination of the bulk modulus and creep compliance of the AFM media, and the calculation of viscosity from creep compliance are discussed below. The following assumptions have been enforced:

- inertia forces are neglected
- the body forces are assumed to be negligible
- the stress and strain fields are assumed to be axi-symmetric
- plane stress condition is assumed to hold (stress component in the z direction is zero).

The loading condition for obtaining the bulk modulus is the following. Consider a cylindrical piece of radius r and length L. Pressure P_0 is applied radially up to angle α ($=\pi$) from both sides. It is assumed that there will be no change in the shape of the workpiece during loading, i.e. the condition of pure dilatation holds. Using the correspondence principle, the expression for volume change as a function of time for a Kelvin solid can be shown to be (Drozdov, 1996; Flugge, 1967):

$$\Delta V(t) = \frac{-2}{3} r^2 \pi L P_0 B(t) \tag{9}$$

Here *B(t)* is the bulk modulus of the viscoelastic material and is a function of time. The loading conditions for the measurement of creep compliance are as follows. There is a cylinder of radius r and length L of viscoelastic material. Radial pressure is applied throughout the periphery of cylinder. The quantity Δ is the distance between the rigid plane and the upper surface of the cylinder. In time t^* the cylinder will touch the rigid plane. As discussed in Davies and Fletcher (1995), the expression for the creep compliance function can be derived as

$$J(t) = \frac{1}{3}\left[\frac{9\Delta}{L\sigma_0} + 2B(t)\right] \tag{10}$$

Creep compliance for any viscoelastic material can be experimentally found by the Equation (10). From the data of creep compliance as a function of time, a curve of the form

$$J(t) = a + b \times \exp(-c \times t) \tag{11}$$

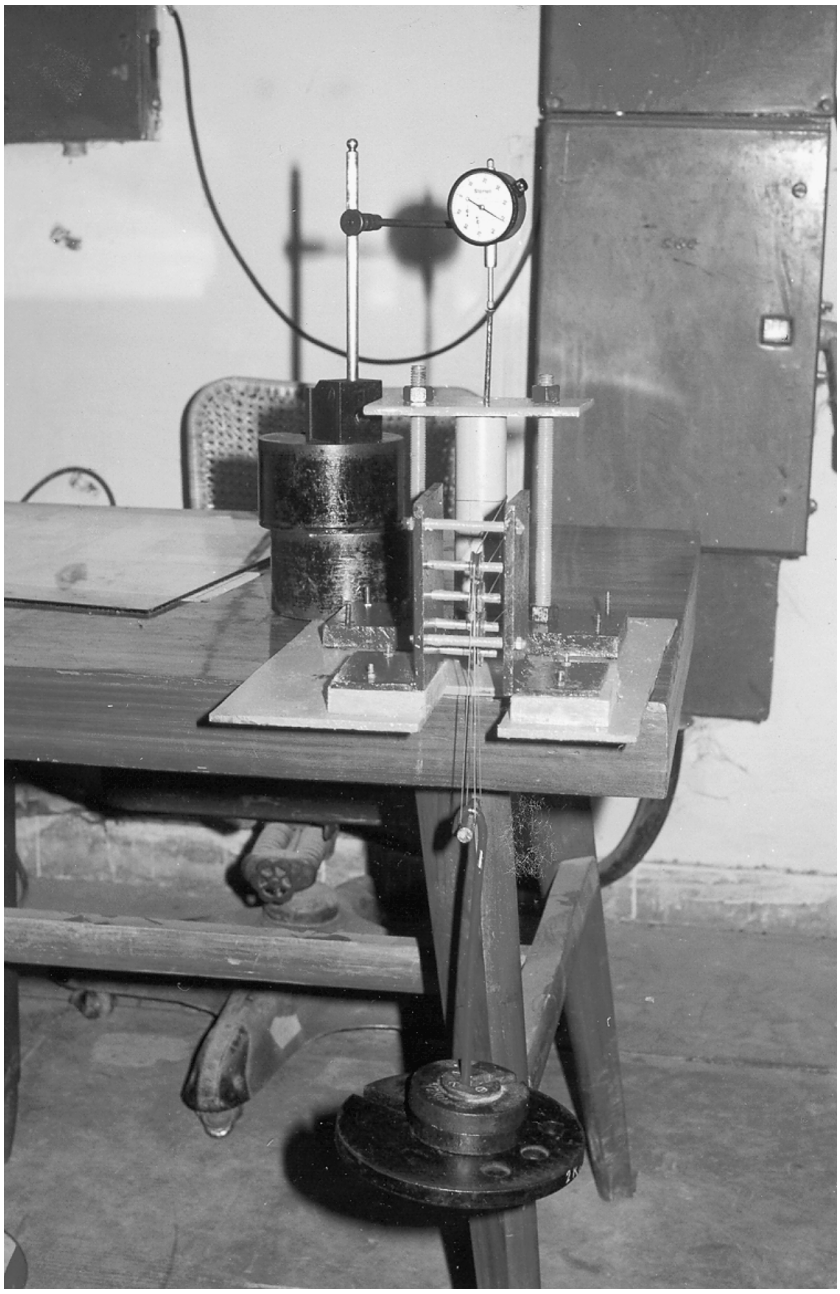
can be fitted with *a, b*, and *c* as regression coefficients. On comparing the above equation (11) with Equation (8), the material viscosity η can be obtained as $1/(a \times c)$.

3 Experimental apparatus

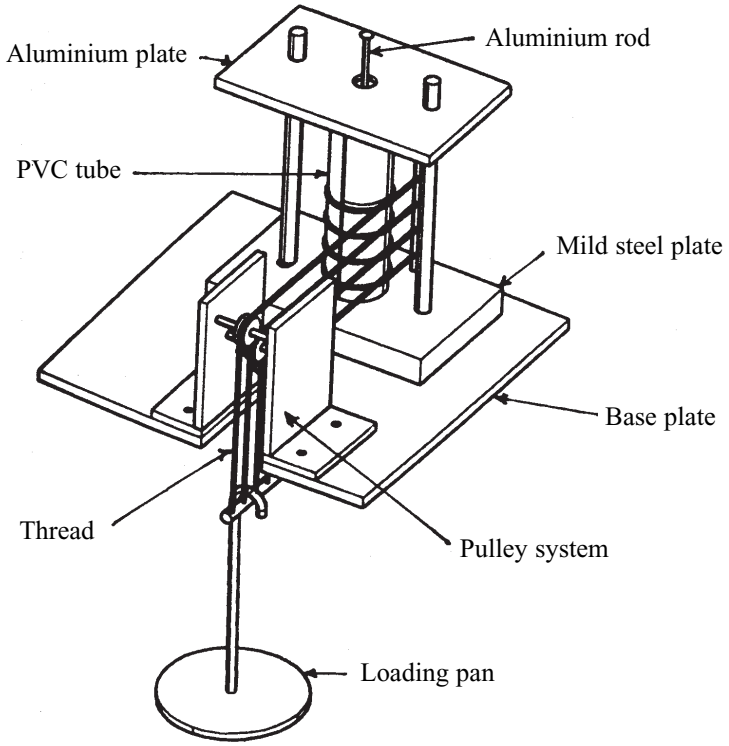
The media used in the present work is Polyborosilixane (supplied by Extrude Hone, USA), with silicon carbide particles as abrasives.

The loading of the specimen comprises applying a uniform radial pressure distribution along the length of a cylindrical piece of AFM media. For this purpose, a polyvinyl chloride (PVC) tube of length 160 mm, outside diameter 40 mm and thickness of 1 mm is used. This tube is cut along its length in such a way that one free longitudinal end of the tube can roll on top of the other and radial pressure is transmitted to the cylindrical piece. Radial pressure is applied on the PVC tube with the help of a nylon rope. The rope is fixed at one end of the steel rod, that is tightened on a mild steel plate. The apparatus is designed in such a way that the pressure applied through the tube on the abrasive media is purely radial and uniformly distributed over the length of the cylindrical piece. The friction between the medium and the inner surface of the tube is taken to be negligible. Friction between the nylon thread and the outer surface of the tube is also negligible in comparison with the loads employed in the experiment. The design, fabrication and testing of the apparatus has been discussed in Agrawal (1999). A photograph of the apparatus as well as the schematic drawing are shown in Figure 1. A drawing of the capillary viscometer is shown in Figure 2.

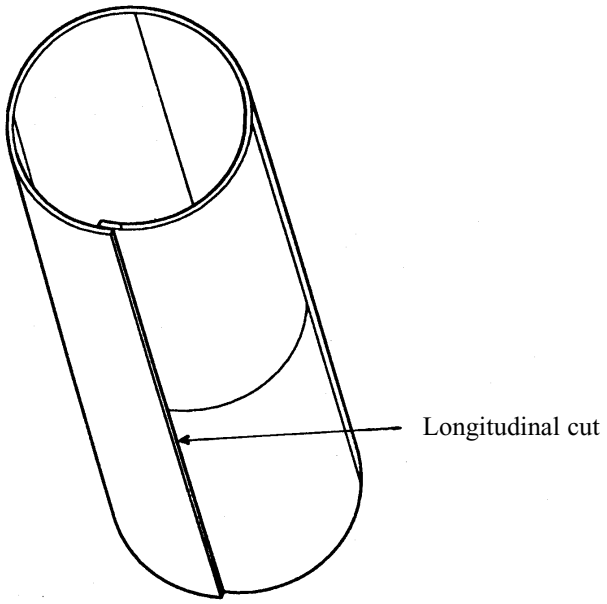
Figure 1 (a) Photograph of the viscosity measuring apparatus based on principles of viscoelasticity; (b) Schematic drawing of the experimental apparatus; (c) Drawing of the PVC tube holding the media, with the longitudinal cut shown



(a)

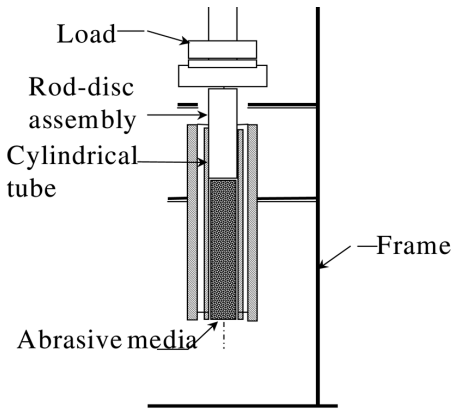


(b)



(c)

Figure 2 Schematic drawing of the capillary viscometer, from Jain et al. (2001)



4 Experimental procedure

AFM media with the required concentration of abrasives and the appropriate temperature, is taken in the form of a cylindrical piece. This piece is placed inside the PVC tube (Figure 1(c)). The diameter of the media cylinder to be called the *test cylinder* is equal to the inner diameter of the tube. The tube is placed vertically over the mild steel plate such that the cylindrical piece touches the mild steel plate at the bottom. The other end of test cylinder is free to move vertically. The nylon rope is coiled over the tube. An aluminium rod is placed on top of the test cylinder. This end of the tube is covered with an aluminium plate. To measure the movement of the test cylinder, a dial gauge (not shown in Figure 1b) is placed over the top surface of the aluminium rod such that its plunger just touches the aluminium rod. Radial pressure is applied to the tube by placing known weights in the loading pan. In the experiments, weights of the order of 5–10 kg have been used. Owing to the radial pressure, the longitudinal ends of the tube tend to slide on one another, but are restricted by the material inside the tube. The radial pressure that is applied to the tube is completely transmitted to the media. Due to this pressure the diameter of test cylinder decreases and at the same time the length increases. The increment in the length of the test cylinder leads to the movement of the aluminium rod located at the top surface of the cylinder. The upward movement of the aluminium rod can be measured by the dial gauge. The least count of the dial gauge is 0.01 mm. The reduction in diameter is measured with the help of a digital Vernier caliper, that has a lowest count of 0.01 mm. The measurements of length and diameter are performed at pre-defined time instants. A typical duration of the experiment is of the order of 200–300 seconds. To establish the quality of the set-up, experiments have been conducted for different initial lengths of the cylinder and at different loads. For ascertaining repeatability, experiments have been conducted five times for a given length and load of the cylindrical test piece. The effect of abrasive concentration on viscosity has been studied via experiments conducted at different concentrations. To study the effect of temperature, experiments have been conducted at different temperatures for a particular concentration of abrasives. The results of the present study have been compared with those from a capillary viscometer (Figure 2) developed by the authors in an earlier work (Jain et al., 2001).

5 Results and discussion

Viscosity data along with a discussion on their sensitivity to the specimen length and initial load, reduced data points and repeatability of the experimental set-up are reported in the present section. In addition, experiments on viscosity of the media at different abrasive concentrations and temperatures are also reported. The results of the experiments for the viscosity determination at different concentrations of the abrasives from the present viscometer are compared with those obtained by the capillary viscometer of (Jain et al., 2001).

5.1 Effect of specimen length and initial load

Figures 3–4 show the bulk modulus and the creep compliance as a function of time for a typical value of the initial length of the specimen and initial load respectively. It is observed from the graphs that the bulk modulus and the creep compliance both increase exponentially with time. The graphs are quite similar to those for a Kelvin's solid, and in fact validate this assumption. In principle, viscosity calculated from the creep compliance function should not be affected by change in initial length of the specimen and initial load applied. These data are given in Table 1, where the information about load has been equivalently expressed in terms of the radial stress. The best-fit exponential function (Equation 11) for $B(t)$ as well as $J(t)$ have been reported in Table 1. The correlation coefficient of curve fitting is better that 95% in all the experiments. The exponential functions are shown by dashed lines in Figures 3 and 4. It is to be noted from Table 1 that the viscosity obtained at various initial lengths (except at 120 mm) and initial loads are quite close. The mismatch at a length of 120 mm could be classified as a case of isolated scatter since it was not realised in other experiments.

Figure 3 Bulk modulus (mm^2/N) as a function of time at a load of 5 kg and an initial specimen length of 110 mm. Specimen temperature is 30°C

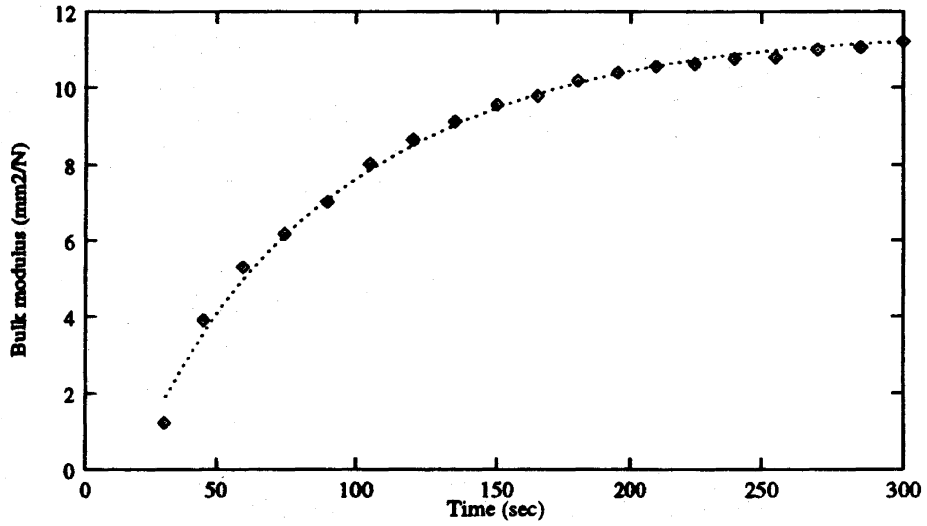
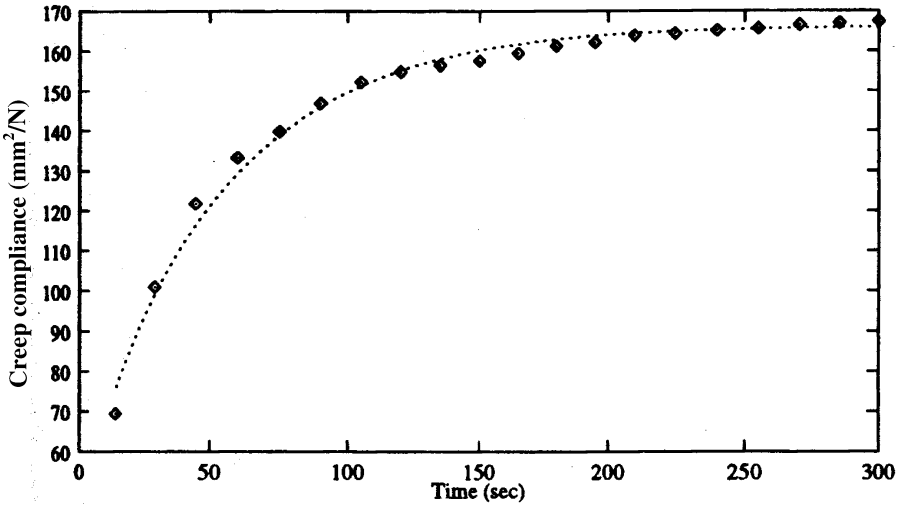


Figure 4 Creep compliance (mm^2/N) as a function of time at a load of 5 kg and an initial specimen length of 110 mm. Specimen temperature is 30°C



5.2 Reduced data points

It can be seen from Figures 3–4 that the initial rates of increase of the bulk modulus and creep compliance are quite high, but the slopes decrease as time increases. The viscosity of the material is thus expected to be affected strongly by the initial rate. To assess the importance of the data collected at small time, points collected after 120 seconds were ignored. The viscosity re-calculated from the reduced data set was found to be within 1–10% of the values in Table 1, and have been reported in Table 2. This is a confirmation of the result that viscosity depends crucially on the time-varying part of the exponential function and measurements here should be carefully recorded. All subsequent results in the paper have been given in terms of the full data set.

Table 1 Viscosity of AFM media at different initial lengths of the work-piece and loads

Initial length mm	*Radial stress N/m^2*	*Bulk modulus B(t) mm^2/N*	*Creep compliance J(t) mm^2/N*	*Viscosity N-s/mm^2*
90	0.00457	20.01–20.0 exp(−0.014 t)	121.08–108.64 exp(−0.024 t)	0.344
100	0.00575	16.65–16.45 exp(−0.017 t)	115.65–94.075 exp(−0.026 t)	0.332
110	0.00373	11.51–14.27 exp(−0.013 t)	166.23–122.47 exp(−0.02 t)	0.308
115	0.00357	19.19–20.95 exp(−0.011 t)	121.88–110.51 exp(−0.026 t)	0.315
120	0.00205	42.61–45.34 exp(−0.013 t)	193.51–187.23 exp(−0.02 t)	0.258
130	0.0019	19.78–16.58 exp(−0.01 t)	152.65–154.31 exp(−0.021 t)	0.327

Table 2 Viscosity of the AFM media with full and reduced set of data points

Initial length mm	*Radial stress N/m²*	*Creep compliance J(t) mm²/N*	*Viscosity (full data points) N-s/mm²*	*Viscosity (reduced data points) N-s/mm²*	*Percentage change in viscosity (%)*
90	0.00457	119.39–98.91 exp(−0.025 t)	0.344	0.335	2.64
100	0.00575	109.88–78.29 exp(−0.03 t)	0.332	0.303	8.78
110	0.00373	164.01–124.09 exp(−0.022 t)	0.308	0.277	10.07
115	0.00357	119.32–100.85 exp(−0.027 t)	0.315	0.310	1.63
120	0.00205	186.98–184.09 exp(−0.022 t)	0.258	0.243	5.91
130	0.0019	147.79–147.99 exp(−0.0215 t)	0.327	0.314	3.91

5.3 Repeatability of the experiments

An experimental measurement set-up is repeatable if it gives identical results for each set of experiments conducted repeatedly under similar initial length and loading conditions. It was observed in the present work that the viscosity of the media for the experiments conducted under similar initial conditions were quite close. This data is reported in Table 3. The uncertainty band for the viscosity data can be formally specified to be ±4%, with 95% confidence.

Table 3 Repeatability test for the determination of viscosity of AFM media from five independent experiments

Initial length mm	*Radial stress N/m²*	*Bulk modulus B(t) mm²/N*	*Creep compliance J(t) mm²/N*	*Viscosity N-s/mm²*
110	0.00224	32.57–35.23 exp(−0.008 t)	186.01–185.98 exp(−0.016 t)	0.336
110	0.00224	40.37–46.98 exp(−0.006 t)	176.83–157.17 exp(−0.016 t)	0.345
110	0.00224	29.80–36.55 exp(−0.009 t)	190.81–178.39 exp(−0.015 t)	0.349
110	0.00224	34.35–31.48 exp(−0.007 t)	182.64–153.3 exp (−0.0165 t)	0.332
110	0.00224	25.30–25.01 exp(−0.018 t)	170.86–155.08 exp(−0.017 t)	0.344

5.4 Effect of abrasive concentration

Figure 5 shows the creep compliance as a function of time when the AFM media is loaded with abrasives. The effect of abrasives on the bulk modulus was found to be minimal and has not been reported. This is understandable because the abrasive particles, as well as the basic AFM material, are both practically incompressible. In contrast, it is observed in the present work that as the percentage of concentration of abrasives in the media increases, the viscosity of the media increases. The viscosity at different concentrations of the media is reported in Table 4. As the percentage concentration of the abrasives in the media increases, the mobility of the media particles decreases.

Consequently, the increment in the length of the cylindrical piece in viscometer decreases. This leads ultimately to an increase in the viscosity of the media. An alternative explanation can be provided in terms of the theory of mixtures. The equivalent viscosity of the abrasive particles being practically infinity, the abrasive-media mixture will have a viscosity greater than that of the media alone.

Figure 5 Creep compliance (mm^2/N) as a function of time at a load of 3 kg and an initial specimen length of 110 mm. Specimen temperature is 30°C. Abrasive concentration is 66%

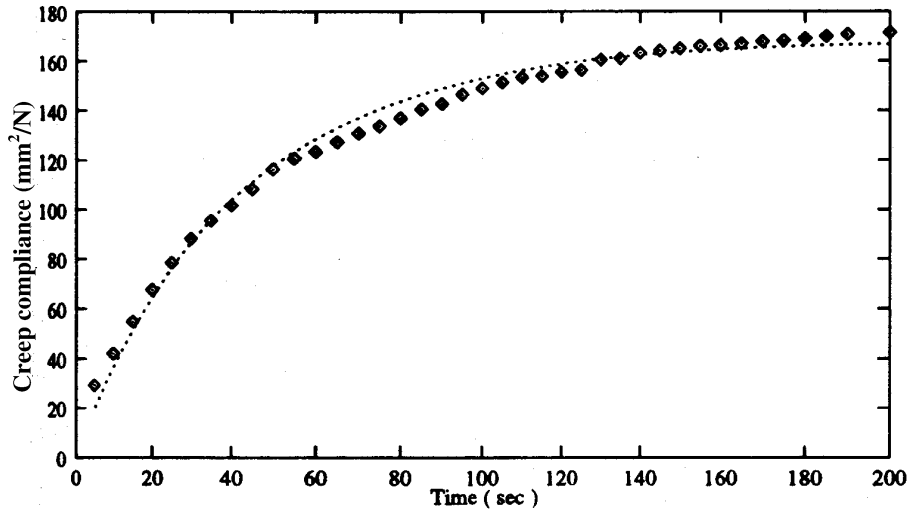


Table 4 Viscosity of AFM media at different concentration of abrasives

Initial length mm	*Radial stress N/m^2*	*Abrasives concentration (%)*	*Creep compliance J(t) mm^2/N*	*Viscosity N-s/mm^2*
110	0.00224	56	190.22–145.408 exp(−0.037 t)	0.142
110	0.00224	61	169.494–140.807 exp(−0.03 t)	0.197
110	0.00224	66	168.228–167.804 exp(−0.024 t)	0.248
110	0.00224	71	140.722–124.352 exp(−0.0254 t)	0.279
110	0.00224	76	169.91–143.23 exp(−0.017 t)	0.346

5.5 Effect of temperature

To study the effect of temperature on viscosity, experiments have been conducted at different temperatures of the media. The specimen was kept in a constant temperature bath for a sufficiently long time to raise its temperature to a desired value. Table 5 presents the viscosity of the media at different average temperatures. It is quite clear that, as

the temperature increases, there is a decrease in the viscosity of the media. As the temperature of the media increases, an increase in the rate of change in the length of the cylindrical piece is observed in the temporal response. This is equivalent to a reduction in viscosity. In this respect, the media behaviour is consistent with that of a classical viscous fluid.

Table 5 Viscosity of AFM media as a function of temperature

Initial length mm	*Radial stress N/m^2*	*Temperature of the media* (°C)	*Creep compliance J(t) mm^2/N*	*Viscosity $N\text{-}s/mm^2$*
110	0.00149	30	150.164–136.35 exp(−0.023 t)	0.289
110	0.00149	36	166.622–145.562 exp(−0.026 t)	0.231
110	0.00149	42	202.86–180.043 exp(−0.027 t)	0.183
110	0.00149	50	217.343–203.432 exp(−0.038 t)	0.121

5.6 Viscosity measurements by the capillary viscometer

To study independently the effect of concentration on viscosity of the media, experiments have been conducted using a capillary viscometer (Jain et al., 2001). Table 6 shows the values of viscosity at different concentration of abrasive particles obtained from the capillary viscometer as well as the present viscometer. It is observed that the results from the capillary viscometer are similar to the results of the present viscometer. It is observed that at 56% abrasive concentration, the difference in viscosity is high. This is because at lower concentrations of the abrasive particles, the rate of change of length of the specimen is high, and inaccuracies in time measurement play a role. At lower concentrations, alternate mixing arrangements are possible for the particles, in addition to a clustering of the abrasives. These factors lead to scatter in the viscosity data. The differences in the measurement from the two viscometers are smaller than at other abrasive concentrations.

Table 6 Viscosity of AFM media at different abrasive concentrations; comparison of the present viscometer with a capillary viscometer of (Jain et al., 2001)

Abrasives concentration %	*Average viscosity (capillary (Jain et al., 2001)) $kN\text{-}s/m^2$*	*Average viscosity (present viscometer) $kN\text{-}s/m^2$*	*Difference %*
56	185.40	142.08	23.36
61	205.60	196.66	4.35
66	231.87	247.69	6.82
71	273.35	279.77	2.35
76	320.07	346.20	8.16

6 Conclusions

Experiments have been conducted for the determination of the viscosity of AFM media, along with a discussion on the sensitivity of the property on the initial length of the specimen, reduced data points and repeatability of the measurements. Good repeatability has been observed and the data are not sensitive to the process parameters such as the load and the specimen dimension. Experiments have also been conducted at different abrasive concentrations and bulk temperature of the AFM media. Viscosity has also been determined at different concentrations using a capillary viscometer, and compared with the present viscometer. The major conclusions drawn from the present work are as follows:

- The AFM media has a well-defined viscosity, and its mechanical behaviour closely approximates a Kelvin solid.
- As the percentage concentration of the abrasive increases, there is a continuous increase in the viscosity.
- A significant effect of temperature on the viscosity of the media is observed. The viscosity of the media decreases with an increase in temperature.
- The viscometer developed in this study is versatile and repeatable. The results of the viscosity of the media at different concentrations of abrasives are close to those of the capillary viscometer. The measurement of the viscosity of the abrasive media using the present approach is, however, simpler to that of the capillary viscometer.

References

Agrawal, A. (1999) 'On the determination of the viscosity of AFM media', *Master's Thesis*, Department of Mechanical Engineering, IIT Kanpur, India.

Davies, P.J. and Fletcher, A.J. (1995) 'The assessment of the rheological characteristics of various polyborosiloxane/grit mixtures as utilised in the abrasive flow machining process', *Journal of Mechanical Engineering Science: Inst. of Mech. Engineers*, Part C, Vol. 209, pp.409–418.

Drozdov, A.D. (1996) *Finite Elasticity and Viscoelasticity*, Singapore: World Scientific, pp.228–300.

Fletcher, A.J., Hull, J.B., Mackie, J. and Trengove, S.A. (1990) 'Computer modelling of the abrasive flow machining process', *Proceedings of the International Conference on Surface Engineering: Current Trends and Future Prospects*, Toronto, Canada, pp.592–601.

Flugge, W. (1967) *Viscoelasticity*, Waltham, Massachusetls. Toronto. London: Blaisdell Pub. Co., pp.3–24.

Hull, J.B., O'Sullivan, D., Fletcher, A.J., Trengove, S.A. and Mackie, J. (1992) 'Rheology of carrier media used in abrasive flow machining', *Key Engineering Materials*, Vol. 72–74, pp.617–626.

Inasaki, I., Tonshoff, H.K. and Howes, T.D. (1993) 'Abrasive flow machining in future', *Annals of CIRP*, Vol. 42, p.723.

Jain, V.K., Ranganath, C. and Muralidhar, K. (2001) 'Evaluation of rheological properties of medium for AFM process', *Machining Science and Technology*, Vol. 5, No. 2, pp.151–170.

Loveless, T.R., Williams, R.E. and Rajurkar, K.P. (1994) 'A study of the effects of abrasive flow machining on various machined surfaces', *Journal of Material Processing Technology*, Vol. 47, pp.133–151.

Perry, W.B. (1989) 'Abrasive flow machining – principles and practices', *Non-traditional Conference Proceedings*, pp.121–127.

Rhoades, L.J. (1989) 'Abrasive flow machining', *Manufacturing Engg.*, pp.75–78.

Williams, R.E. and Rajurkar, K.P. (1989) 'Metal removal and surface finish characteristics in abrasive flow machining', *Trans. ASME, PED*, Vol. 83, pp.93–106.

Williams, R.E. and Rajurkar, K.P. (1992) 'Stochastic modelling and analysis of abrasive flow machining', *Trans ASME, Journal of Engg. For Ind.*, Vol. 14, pp.74–81.