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Forces prediction during material deformation in abrasive flow machining

V.K. Gorana [1], V.K. Jain *, G.K. Lal

Department of Mechanical Engineering, Indian Institute of Technology, Kanpur 208016, Uttar Pradesh, India

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Abstract

To study the finishing mechanism of abrasive flow machining (AFM), theoretical model of forces acting on a single grain has been developed. An experimental research has been carried out by measuring the axial force, radial force and active grain density during the AFM process. Results obtained from theoretical model for grain–workpiece interaction during material deformation have been compared with the experimental data of force and active grains obtained during AFM. Scratching experiments have also been carried out to study the mechanism of material removal during the AFM process. The conclusions arrived by the analysis about the presence of rubbing and ploughing is in agreement with the experimental AFM and scratching results.

Keywords: Abrasive flow machining; Axial force; Radial force; Active grain density; Rubbing; Ploughing

1. Introduction

Abrasive flow machining (AFM) was developed by the Extrude Hone Corporation, USA in 1960s as a method to deburr and polish difficult-to-reach surfaces and edges by flowing abrasive laden polymer with special rheological properties. AFM can be applied to an impressive range of finishing operations, providing uniform repeatable and predictable results. In AFM, workpiece is placed in between the two opposite piston cylinder arrangement (Fig. 1). The surfaces and edges of the workpiece are finished by the flowing medium (abrasive laden polymer) across the workpiece.

Rhoades [1–3] studied the basic principle of AFM and reported that the depth of cut primarily depends upon abrasive grain size, relative hardness and sharpness and extrusion pressure. Przylenk [4] described that with small bore diameter of workpiece, more grains come in contact with the wall and material removal increases. Perry [5] reported that abrasion is high where the medium velocity is high. An increase in pressure and medium viscosity increases material removal rate while surface finish value decreases. The type of machining operation used to prepare the specimens prior to AFM is found to significantly affect the improvement in the surface finish [6]. Williams and Rajurkar [7] reported that metal removal and surface finish in AFM are significantly affected by the medium viscosity. Jain [8] evaluated the ‘active grain density’ by counting the number of distinct grains per unit area by viewing over number of randomly selected areas on medium and developed a force model based on abrasion theory. Williams [9] used the acoustic emission technique to analyze the AFM process. The acoustic emission signals were compared with those found in grinding to analyze the mechanism of surface generation involved in abrasive flow machining. Singh and Shan [10] developed a new method of finishing by applying the magnetic field around a component being processed by AFM and an enhanced rate of material removal has been achieved. They considered as the basic mechanism of solid particle erosion for material removal which is proposed by Finne [11] in AFM with some modifications. They concluded that the momentum acquired by the abrasive particles is responsible for microploughing

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* Corresponding author. Tel.: +91 512 2597916; fax: +91 512 2597408.
E-mail address: vkjain@iitk.ac.in (V.K. Jain).

[1] On leave from Department of Mechanical Engineering, Engineering College, Kota 324010, Rajasthan, India.

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and microchipping of the workpiece surface. But this mechanism is proposed for the case when magnetic field has been applied to AFM. The application of magnetic field changes the distribution of abrasive particles across the cross section of slug. Secondly, they have not reported the viscosity of the medium used which plays an important role in fixing the mode of finishing (by chip formation, plastic deformation or rubbing as discussed later) during AFM.

Nomenclature

A	contact area (mm^2)
b	diameter of projected area of grain in contact with workpiece (mm)
C	flow constraint factor
d	undeformed chip thickness from L'vov [15] (mm)
d_g	diameter of abrasive grain (mm)
d_s	undeformed grain depth of cut from Brecker model [20] (mm)
d'	depth of indentation by Hertz theory (mm)
E_m	modulus of elasticity of workpiece material (kg/mm^2)
F	axial force during AFM (kg)
F_ng	radial force during AFM (kg)
F'_ng	total normal load on a single abrasive grain (kg)
F_ap	axial force exerted by putty only (kg)
F_rp	radial force exerted by putty only (kg)
F_r	resultant force during AFM (kg)
F_R	friction force during AFM (kg)
F_rm	measured radial force exerted by the medium when abrasives are mixed (kg)
F_am	measured axial force exerted by the medium when abrasives are mixed (kg)
H_w	surface hardness of workpiece material, (BHN = kg/mm^2)
M_e	grain mesh number
P'	resultant force from Brecker model [20] (kg)
P''	ploughing force during AFM (kg)
r	edge radius of the tool at the onset of chip formation (mm)
R	radius of abrasive grain (mm)

Greek letters

θ	neutral point angle (°)
θ'	conical indenter cone angle (°)
σ	uniaxial flow stress of material (kg/mm^2)
$\bar{\sigma}$	mean stress on the contact area (kg/mm^2)
γ	half cone angle (°)
δ	$\gamma - 90°$ (°)
μ	assumed coefficient of friction between abrasive grain and workpiece material during AFM

It seems from the literature survey that only a little information is available about the basic mechanics of material deformation involved in the abrasive flow machining process under widely varied machining conditions. This paper reports the understanding of mechanics involved in grain–workpiece interaction during AFM. In comparison to the conventional machining operations such as turning, milling, drilling, etc., the study of the basic mechanics of the material deformation process in abrasive flow machining is complicated due to random nature of distribution of abrasive grains into putty, very low depth of indentation of abrasive grains and metal deformation at micro scale. AFM and grinding have some similarities namely, in both the processes, abrasive grains are distributed randomly and depth of penetration by an abrasive is low. The medium gently and uniformly abrades the surfaces and/or edges in AFM. However, in case of grinding, abrasives are held rigidly by hard (solid) bond material whereas in AFM abrasives are mixed and held with semisolid bond (or medium). Therefore, in AFM, medium acts as a "self-deformable stone". The medium used for the present experimentation is silly putty which is generally used for moulding clay toys; the detailed information about the same is available on www.sillyputty.com. The viscosity of this medium is expected to be different as compared to medium used for the industrial purposes. Finished surface characteristics have been studied by Williams and Rajurkar [12].

Three modes of metal deformation so far have been identified in any abrasive machining process which are as follows [13]:

1. elastic deformation associated with rubbing;
2. plastic deformation or ploughing where majority of the material is displaced without being removed;
3. micro-cutting where removal of material takes in the form of miniature chips.

The occurrence of any particular mode of deformation strongly depends on the magnitude of cutting forces acting on an individual grain, and the resulting depth of indentation in the workpiece. In AFM, the mode of metal deformation may change as the grain passes through the workpiece surface. This change in the mode of deformation may take place due to variation in the workpiece material properties, and mainly due to the flexibility of medium holding the grains which are not held so rigidly by the medium as in the case of a grinding wheel. The combined effect may result a change in the depth of indentation during the process which may lead to change in material deformation mode from one to another, say, from plastic deformation to elastic deformation.

2. Theoretical analysis

Many researchers [14–19] proposed the mode of grain–workpiece interaction and developed various theories. As referred in reference [14], L'vov [15] proposed a model to estimate the undeformed chip thickness at the onset of