Materials and Design 109 (2016) 580–589

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

On the machinability and surface finish of cutting nanoparticle and elastomer modified epoxy

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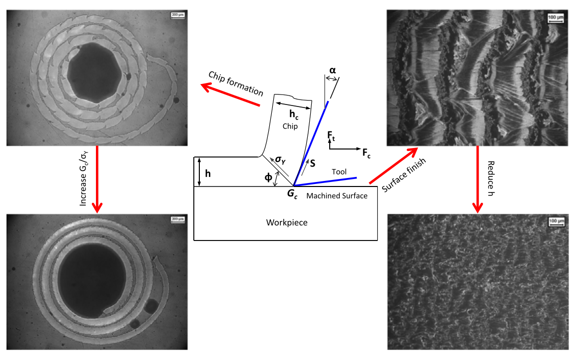
HIGHLIGHTS

- Incorporating fillers changes the tensile behaviour and hence the cutting force behaviour of an epoxy.
- Rigid silica results in higher cutting forces than soft rubber due to the stiffened and strengthened material properties.
- Fracture toughness plays a key role in surface finish, though its effect on the cutting forces is much less significant.
- Higher toughness to yield stress ratio and lower cut depth favour the controllability of the material removal process.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 15 May 2016
Received in revised form 18 July 2016
Accepted 21 July 2016
Available online 22 July 2016

Keywords:
Cutting
Material removal
Nanosilica and CTBN reinforced epoxy
Fracture
Surface finish

ABSTRACT

In the present paper, we investigate the material removal behaviour of epoxy-based composites in an orthogonal cutting process, and its dependence on two different fillers: a rigid nanosilica (SiO_2) and a soft carboxyl-terminated butadiene-acrylonitrile (CTBN) elastomer. The results obtained show that fracture plays a key role in the formation of the newly cut surface as the chip is separated from the workpiece by the cutting tool. The surface finish after cutting is dependent on the cutting depth, h, and the ratio between fracture toughness and yield strength, G_c/σ_y. The latter can be determined by a cutting theory. In general, a smaller value of h and/or a higher value of G_c/σ_y favour the controllability of the surface finish, i.e., a stable material removal process with enhanced surface integrity. This work highlights the important role of the fillers in determining not only the mechanical properties of epoxy composites but also their machinability. It provides useful guidance for better design and processing of epoxy-based materials for different engineering applications.

1. Introduction

With its strong mechanical properties and excellent thermal and chemical resistances, epoxy has a wide range of industrial applications. In practice, reinforcements, such as nanoparticles and elastomeric modifiers, either singly or conjointly, are often used to

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http://dx.doi.org/10.1016/j.matdes.2016.07.112
0264-1275/© 2016 Published by Elsevier Ltd.

Nomenclature

Greek alphabet

α	rake angle
γ	shear strain
η	clearance angle
μ	friction coefficient
σ_y	yield stress in cutting test
σ_Y	yield stress in tensile test
τ	friction angle
φ	shear angle

English alphabet

b	width of cut, width of workpiece
E	Young's modulus
F_c	cutting force
F_n	normal force on the shear plane
F_r	resultant force of F_c and F_t
F_s	shear force on the shear plane
F_t	transverse force
G_{Ic}	fracture toughness in CT test
G_c	fracture toughness in cutting test
h	cutting depth
h_c	chip thickness
N	normal force on the tool chip interface
R^2	coefficient of determination
R_a	roughness
S	friction force on the tool/chip interface
V	cutting speed

further enhance the fracture, electrical and tribological properties of the epoxy, thereby broadening its applications in more specific fields. For instance, rubber-toughened epoxy is widely used as a structural adhesive in the automobile and aerospace industries, where it can offer many advantages over traditional methods of joining [1]. In the electronics industry, nanoceramic or nanoclay modified epoxy can be made into heat sinks, die attachment and encapsulation, etc. to facilitate heat dissipation and alleviate thermal fatigue problems [2].

Given the increasing use of epoxy composites, the stiffening, strengthening and toughening mechanisms of the fillers have been widely reported in research papers and reviews [3–7]. In general, the fillers are categorised into rigid and soft, and the degree of property enhancement depends on their size, loading, and interfacial adhesion with the matrix. For instance, the stiffness of a neat epoxy matrix can be readily improved by adding rigid fillers, which have a much higher stiffness than the matrix. However, strength relies on the potential for stress transfer at the filler/matrix interface. The interfacial area and adhesion play critical roles in strengthening. In terms of fracture toughness, either rigid or soft fillers can improve the material performance against crack initiation and propagation. Cavitation, debonding, crack pinning and matrix shear yielding are commonly believed to be the main toughening mechanisms [7]. However, it is our understanding that although the roles of different types of filler in the mechanical performance of an epoxy have been well recognised, their effects on the machining behaviour of the material are as yet unclarified. This may be ascribed to the fact that epoxy materials are more often used in adhesives, coatings and structural matrix materials where their machinability has a less significant role in those traditional applications. Even so, understanding the machining behaviour of an epoxy system is important because: (a) machining is the most ready and straightforward method to remove moulding defects for epoxy encapsulated/potted electronic components that can be used to improve the overall geometrical quality of the components in electronic packaging; (b) it is helpful in precision manufacturing of small-scale parts which cannot be produced by common moulding techniques, and (c) it provides critical evaluation of the epoxy paint/coating removal process.

Although machining has long been used for processing engineered products, the seemingly simple process requires interdisciplinary studies comprising solid mechanics, tribology and heat/mass transfer. To obtain fundamental understanding of the machining process, several mechanistic models have been developed to characterise the material removal mechanism [8–13]. Most models have been based on simple two-dimensional orthogonal cutting (Fig.1) and have focused mainly on metal cutting problems. More recently, in situ techniques have been employed [14] which offer a more direct way for quantitative analysis of the material removal process. Apart from metals, a number of researchers have been active in machining polymers. For instance, Kabayashi and Saito [15] demonstrated the characteristics of cutting polymethylmethacrylate (PMMA), polystyrene (PS) and polytetrafluoroethylene (PTFE). Chip formation, material deformation and the behaviour of cutting forces were investigated using different tool geometries, cutting speeds and ambient temperatures. Further work carried out by Saito [16] revealed the fracture phenomenon that occurred in the cutting of the aforementioned polymers. Davim et al. [17] studied the machinability and surface finish of polyamide (PA) 66 and its glass fibre reinforced composite, in which different micro-cutting tools were compared for precision manufacturing purpose. Ericson and Lindberg [18] employed an instrumented ultramicrotome to cut PMMA and epoxy, thereby working out the relevant fracture energies. Patel et al. [19] reconstructed Merchant's single shear plane orthogonal cutting model [8,9] by considering fracture in the work material. They developed a testing method which could simultaneously measure the yield strength and fracture toughness of a ductile polymer. Subsequent work performed by Blackman et al. [20] also clarified the tool sharpness effect. Thus, the published work of [18–20] has somewhat consolidated our understanding of the presence of fracture in cutting polymers since Saito [16]. Such a notion has provided useful guidance for the machining study of fibre reinforced polymer composites [21,22] and rocks [23]. Nevertheless, till now, most researchers have focused on the basic mechanics with cutting single phase polymers. Little attention has been focused on the effects of the fracture phenomenon on the cutting force

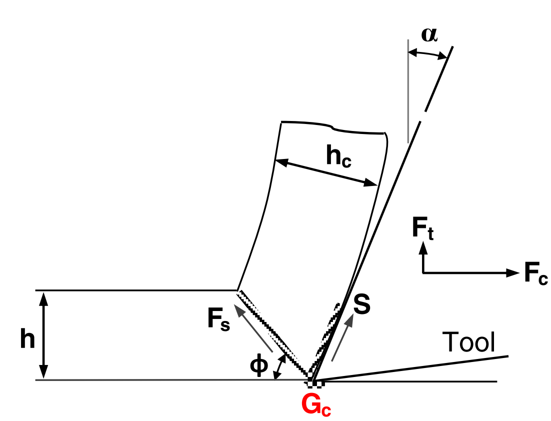

Fig. 1. Schematic of Merchant's single shear plane orthogonal cutting model. There is growing literature [24–26] supporting the concept that fracture energy (G_c) is required to form a newly cut surface as the chip is separated from the work material by the tool cutting edge.