International Journal of Machine Tools & Manufacture 51 (2011) 383–394

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

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

Identification of factors that dominate size effect in micro-machining

A.J Mian*, N. Driver, P.T. Mativenga

Manufacturing and Laser Processing Group, School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, M13 9PL, Manchester, United Kingdom

ARTICLE INFO

Article history:
Received 29 September 2010
Received in revised form
10 January 2011
Accepted 14 January 2011
Available online 2 February 2011

Keywords:
Micro-milling
Size effect
Inconel 718 alloy
Taguchi methods

ABSTRACT

In micro-machining the so called "size effect" is identified as critical in defining process performance. Size effects refers to the phenomenon whereby the reduction of the undeformed chip thickness to levels below the cutting edge radius, or gain size of the workpiece material begins to influence workpiece material deformation mechanisms, chip formation and flow. However, there is no clear agreement on factors that drive this size effect phenomenon. To explore the significance of cutting variables on the size effect, micro-milling tests were conducted on Inconel 718 nickel alloy using 500 μm diameter carbide end mill. The experimental design was based on an L9 Taguchi orthogonal array. Fast Fourier transform (FFT) and wavelet transform (WT) were applied to acoustic emission (AE) signals to identify frequency/energy bands and hence size effect specific process mechanism. The dominant cutting parameters for size effect characteristics were determined by analysis of variance (ANOVA). These findings show that despite most literature focussing on chip thickness as the dominant parameter on size effect, the cutting velocity is also a dominant factor. This suggests that manipulating the cutting speed is also an effective strategy in reducing burr thickness, optimising surface finish and in breaking the lower limit of micro-machining.

1. Introduction

1.1. Size effect in micro-machining

In micro-machining the "size effect" modifies the mechanism of material removal compared to conventional (macro-scale) machining [1–4]. This can arise because the thickness of material to be removed is of the same order of magnitude as the tool edge radius or grain size of the workpiece material. The size effect is typically characterised in machining by a non-linear increase in the energy consumed per unit volume of material removed as the undeformed chip thickness decreases. Experimental observation of this unbounded increase in specific energy in machining of ferrous and non-ferrous materials has been reported. With respect to investigated workpiece materials, difficult to cut materials (Ni, Ti based alloys) have not been reported. Most of the reported research work was undertaken over a limited cutting velocity range and the material thickness removed was in the sub-micron length scale. For a selected cutting speed, the size effect was attributed to tool edge radius effect [5–8], material micro-structure effect i.e. dislocation density/availability [9,10], material strengthening effect due to strain, strain rate, strain gradient [11–16], subsurface plastic deformation [17] and material separation effect [18].

1.2. Machinability of nickel alloys

Nickel-based alloys are extensively used in aerospace components because of their high specific strength (strength to weight ratio) which is maintained over a wide temperature range. Approximately, half of the total materials used for a gas turbine engine are nickel alloys [19]. The most widely used nickel alloy, Inconel 718 accounts for as much as 45% of wrought nickel based alloy production and 25% of cast nickel based products [20]. However, nickel based alloys pose a serious machinability challenge to the industry due to their work hardening, high temperature strength, low thermal conductivity and hard abrasive particles [19]. Moreover, a high adhesion tendency with the tool material, leads to galling and welding of chips on the workpiece surface and short tool life.

Most recently, Klocke et al. [21] presented an assessment of feasibility of micro-milling process on single crystal nickel based super-alloy (René N5). All cutting tests were performed at fixed cutting velocity (50 m/min) and chip load (15 μm/tooth) using 800 μm diameter micro-end mills. In another study, Weinert and Petzoldt [22] demonstrated micro-milling as an alternative production process for NiTi shape memory alloy micro-parts. This was done for a narrow cutting range using 400 μm diameter

* Corresponding author. Tel.: +44 7505957491.
E-mail address: Aamer.Mian@postgrad.manchester.ac.uk (A. Mian).

0890-6955/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmachtools.2011.01.004

micro-tool. The selected cutting velocity was 33 m/min while chip load was varied from 12 to 20 μm/tooth.

1.3. Acoustic emission (AE) signal in micro-milling process

Acoustic emission (AE) refers to the elastic stress waves emitted as a result of the rapid release of strain energy within a material due to rearrangement of its internal structure [23]. In machining, deformation can be considered as the main AE producing source [24]. This implies that AE from machining processes such as turning, grinding and milling represent the unique characteristics of the mechanics of each process. A milling operation is a discontinuous cutting process with varying chip load performed by multiple cutting teeth. AE associated with this process consists of continuous and transient signals. The continuous AE signals stem from plastic deformation of workpiece material in the primary shear zone, at the chip/tool interface (secondary shear zone) and at the tool flank/workpiece surface interface (tertiary shear zone). While the transient signals are associated with pulse shock loading, such as initiation or breakage of chips or by tool fracture. However, in micro-scale milling for chip thickness at or below few microns in length, AE generation is attributed to the interaction of the tool edge radius with the micro-structural features of the workpiece material [25].

Uehara and Kanda [26] reported that the amplitude of an AE signal from the cutting tool is reduced during AE transfer from the tool to the workpiece possibly by damping or reflection at the primary interface. As a result, by monitoring the AE signal from the workpiece side, the primary and tertiary deformation zones can be regarded as most accessible sources of AE generation in micro-milling. In ultra-precision cutting, Carpenter et al. [27] demonstrated that the tertiary deformation zone becomes a more significant source of AE due to the increased energy spent on sliding friction between the tool flank face and newly machined surface.

In literature it is suggested that, sporadic AE signal collected at the sensor contains many frequencies due to the several AE producing sources being active at the cutting zones [25]. Thus, the frequency of these different frequency bands can be used for identifying the dominant sources of AE in the micro-machining process. Fig. 1 shows identified frequency range according to the material removal length scale and signal source mechanisms. It is also clear from Fig. 1 that AE signals are better suited to characterising machining at very low length scales typically in the nanometre range as encountered close to the minimum chip thickness in micro-machining. Again it can be inferred from Fig. 1 that decomposing the AE signal into the frequency domain will enable identification of cutting mechanisms such as dislocation mechanics, inter-granular micro-fracture, cleavage and shearing material machining modes.

In relation to the cutting zones, it is reported that the primary deformation zone, is the largest AE source and generates in excess of 75% of the total AE signal [28]. Brittle and ductile fracture (as shown in Fig. 2) may occur in the deformation of ductile materials that can emit AE from the primary shear zone depending on the type of material being machined and the operating conditions. It is well known that brittle fracture occur in a transgranular (cleavage) manner while ductile fracture takes place in inter-granular manner where the grain boundaries are the fracture path within the material [29]. Most of the metals undergo a transition from transgranular fracture to inter-granular fracture when deformation occurs at temperatures greater than 0.5–0.7 times that of the melting temperature. Details of these fracture mechanisms are covered elsewhere [30].

In a case of continuous chip formation, Shaw [31] proposed that ductile materials deformed as a result of nucleation, growth and coalescence of microscopic voids (micro-crack initiation) that originated at inclusions and from second phase particle separation. However, due to compressive plastic deformation, the micro-cracks experience closure and this effectively postpones crack propagation until conditions are reached where plastic deformation does not occur. Barry and Byrne [32] observed a lamellae form as a result of cleavage during the non-overlapping cutting of a low alloy steel of 45.6 HRC with cutting speed of 100 m/min and for a depth of cut slightly greater than the minimum chip thickness during continuous chip formation.

With respect to a saw tooth formation, Komanduri and Schroeder noted thermoplastic instability leading to adiabatic shear in the chip formation process of Inconel 718 which was very similar to the mechanisms reported for titanium as well as hardened AISI 4340 steels, when machining at higher cutting speeds [33]. Furthermore, Barry et al. [34] elaborated on this and presented two distinct mechanisms for catastrophic shear failure

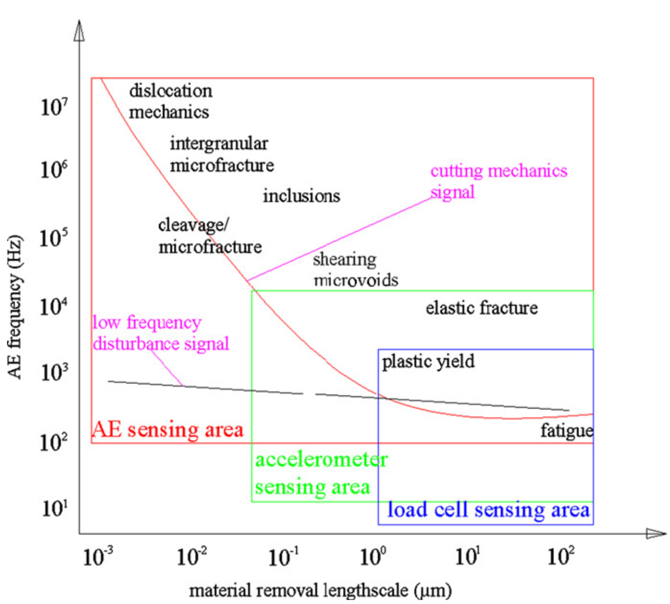

Fig. 1. AE signal source mechanisms (adapted from Lee et al [25]).

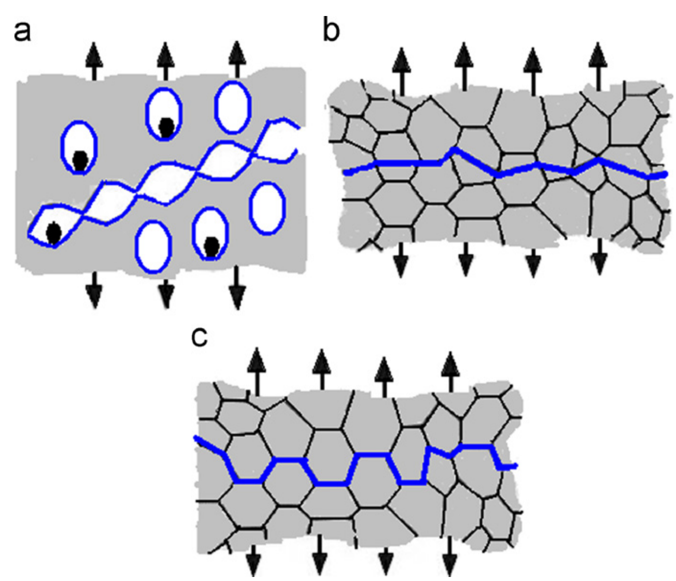

Fig. 2. Micro-mechanisms of fracture in metals [30]. (a) Void coalescence and fracture; (b) Cleavage; (c) Intergranular fracture.