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CIRP-1803; No. of Pages 4
ARTICLE IN PRESS
CIRP Annals - Manufacturing Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Direct laser assisted machining with a sapphire tool for bulk metallic glass

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ARTICLE INFO

Keywords:
Laser
Surface modification
Sapphire
Bulk metallic glass

ABSTRACT

Bulk metallic glasses (BMGs) are amorphous metallic alloys with high strength and hardness. This paper discusses the machining process of Zr-BMG using a transparent sapphire tool with direct laser assistance. The laser beam passes through the tool and directly heats the workpiece material to improve its machinability. Micro textures were generated on the tool rake face to facilitate chip formation. Reduced cutting forces and improved surface finish were observed with direct laser assistance. The effects of machining speed and laser power on the material deformation mechanism were investigated. A finite element model was developed to investigate the cutting forces.

1. Introduction

Amorphous metals such as bulk metallic glasses (BMGs) received attention due to their unique amorphous atomic structures, which result in high strengths and high corrosion resistance. These difficult-to-cut materials require high cutting forces, causing fast tool wear and low surface finish. Improving the machinability of BMG materials is important in various industries.

Several researchers have investigated methods of improving BMG machinability. These methods include thermally assisted machining and surface texturing of tools. In thermally assisted machining, high-energy heat sources are used to preheat the workpiece to soften the materials. Laser assisted machining (LAM) is commonly used for its highly efficient power density compared to other heat sources such as gas flames or electricity [1]. Fig. 1a illustrates the principle behind the LAM process.

Challenges are associated with LAM. It is inevitable that there is a time delay between heating and chip removal. High-power lasers are used to increase the workpiece's temperature in a process which uses a high volume of electricity and may cause thermal cracking, local buckling, or phase changes when the workpiece materials go through high temperature [2].

It is proposed that micro-laser assisted machining (μ-LAM), which allows an IR diode laser beam to pass through a diamond tool directly during the cutting process [3]. However, the diamond tool has low durability under high temperatures and is therefore not suitable for the machining of ferrous metals such as steel.

Another approach to minimizing cutting forces is to texture the tools' rake faces to reduce friction at the tool–chip interface. The textured rake face can reduce the overall contact area at the tool–chip interface to minimize the frictional forces [4].

In this study, a direct laser assisted machining (DLAM) technique with a sapphire cutting tool is used to machine a Zr-BMG workpiece. The low-powered laser beam passes through the transparent sapphire tool, which has good optical transmission, chemical stability, and hardness [5]. By minimizing the delay of heat that is typical in conventional LAM, the overall heating efficiency can be improved. Power consumption and localized laser effects such as the heat-affected zone, thermal cracking, and phase change can be minimized. The micro textured surface is fabricated on the rake face of the sapphire tool by abrasive blasting since it is very difficult to fabricate textures on a diamond surface.

The effects of the laser's output power, the cutting speed, and the tool surface texture on the chip formation, cutting forces and surface finish of DLAM-machined BMGs were examined. To further elucidate the process, finite element (FE) analysis was performed to simulate DLAM and the effects of tool surface textures.

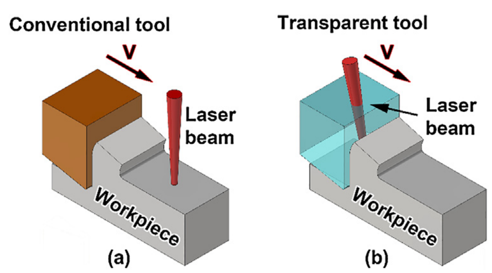

Fig. 1. Schematics of the (a) conventional LAM and (b) direct LAM.

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https://doi.org/10.1016/j.cirp.2018.04.070
0007-8506/© 2018 Published by Elsevier Ltd on behalf of CIRP.

2. Experimental setup

Orthogonal cutting tests were performed to investigate the performance of the DLAM technique on BMG cutting. The workpiece material is Zr-BMG (LiquidMetal, Vit-105 — $Zr_{52.5}Ti_{5}Cu_{17.9}Ni_{14.6}Al_{10}$, by atomic percentage). The hardness, ultimate tensile, and yield strengths of the Vit-105 are 80 HRC, 2133 MPa, and 1524 MPa, respectively at room temperature. The glass transition (T_g) and crystallization temperatures of BMG are 399 °C and 468 °C, respectively.

Sapphire is used as an affordable material for cutting tools with a high hardness [6,7]. In this study, sapphire was chosen as the cutting tool due to its good optical and thermal properties and its heat resistance [8]. A half-sphere sapphire tool with a diameter (D) of 6.35 mm was mounted on a custom-built clamp. Orthogonal tests were performed at a rake angle of 0° with a cutting edge radii (r) of approximately 10 μm (see Fig. 2).

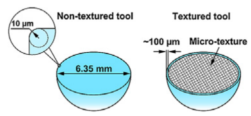

Fig. 2. A schematic of the half-ball sapphire employed in the tests.

Several methods can be employed to texture the cutting tool surface, including laser, EDM, etc. Sapphires are transparent and non-electrically conductive, so those methods cannot be used. Instead, we used micro abrasive blasting to fabricate non-uniform micro textures on the rake face. Abrasive blasting was performed by a micro-abrasive blaster (COMCO ProCenter^{TM}) using 100 μm micro-abrasive aluminum oxide powders. The textured area was approximately 31.7 mm^2, the nozzle-surface distance was 20 mm, and the air pressure was 0.45 MPa. The textured surface profiles were measured through a 3D optical profiler (Zeta Instrument 20), as shown in Fig. 3. The surface roughness of the non-textured surface's R_a is 0.41 μm and its R_q is 0.52 μm. The textured surface's R_a is 0.78 μm and its R_q is 1.07 μm.

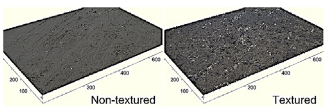

Fig. 3. 3D images of the flat sapphire surface and textured sapphire surface (in μm).

A continuous fiber-coupled diode laser with a wavelength of 808 nm and a maximum output power 10.4 W was employed as the heat source in this study. The laser beam was focused by a collimator. A half-sphere sapphire tool mounted on a customized clamp was used as the cutting tool. The spectral transmittance of sapphire at 808 nm is more than 83% [7], which is sufficient to allow the laser beam to pass through the sapphire with minimal energy loss.

The orthogonal cutting experiments were conducted on a modified vertical CNC machine (KERN Micro 2255), where a custom-made tool holder was installed with the DLAM tool system and mounted on the machine (see Fig. 4). The 20 mm × 15 mm × 1.5 mm BMG plate was placed on top of a three-axis table dynamometer (Kistler 9256C2). The force signals were measured through charge amplifiers and a data acquisition system. A schematic illustration of the experimental setup is shown in Fig. 4.

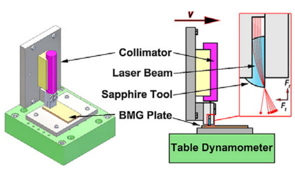

Fig. 4. A schematic of the orthogonal cutting test setup and the focus of the laser beam obtained via optic simulation using COMSOL^{TM} as it passes through the sapphire.

The half-spherical sapphire allows the laser beam to be focused near the cutting edge, while the laser beam's power density at the rake face (flat surface of the sapphire) was increased compared to the original beam. At the rake face, the outcome beam was not perpendicular to that surface, and the shape of the irradiation area was close to a trapezoid. The heating area was approximately 0.053 mm^2 at the rake face base on the simulation result.

Dry orthogonal cutting tests were performed with different laser output power (0, 2.8, & 7.9 W) and different cutting speeds (50, 100, and 150 mm/min) to identify their influences on cutting forces, chip formation, and surface finish.

3. Results and discussions

The effect of laser heating on cutting forces and surface finish were investigated at different cutting speeds. The influences of laser heating on chip morphology and shear banding were examined by a scanning electron microscope (SEM). The micro textured tool rake face was also employed with direct laser heating. Finite element analysis was performed to examine the effects of laser heating and surface texturing.

3.1. Effects of cutting forces due to laser power and cutting speed

Cutting forces were collected and compared for each test with different cutting conditions. The cutting force results with laser output powers of 0, 2.8, and 7.9 W and cutting speed variations of 50, 100, and 150 mm/min is shown in Fig. 5. The tangential force (F_t) and feed force (F_f) decreased about 30% when the 2.8 W laser was used. Whereas 7.9 W power laser has increased the forces at higher cutting speed. Lower cutting speeds yielded greater cutting force reduction for the tangential cutting force with the application of DLAM.

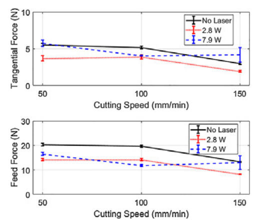

Fig. 5. The cutting force comparison with different laser output power and cutting speeds — no textured case and 15 μm depth.

The deformed chips were collected during the cutting process. The chip morphology of BMG was identified by SEM as shown in Fig. 6. Serrated chip formation with shear localization is commonly observed in BMG machining. Shear localization (adiabatic shear band) in BMG chips is caused by low thermal conductivity (5 W/m-K) and amorphous structure of the BMG material [9].

As shown in Fig. 6a and b, the serrated chip was observed without laser heating. When the laser was 2.8 W (Fig. 6c), the chip formation promoted plastic flow, yielding continuously twisted

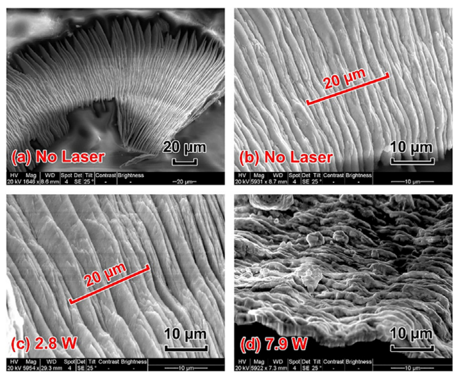

Fig. 6. SEM images of the chips from (a) & (b) no laser cutting, (c) 2.8 W and (d) 7.9 W.

Please cite this article in press as: Park SS, et al. Direct laser assisted machining with a sapphire tool for bulk metallic glass. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.04.070