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Manufacture of nanocrystalline metals by machining processes

M.J. Jackson [a,*], G.M. Robinson [b], M.D. Whitfield [b]
[a] Birck Nanotechnology Centre, College of Technology, Purdue University, West Lafayette, Indiana, USA
[b] Center for Advanced Manufacturing, College of Technology, Purdue University, West Lafayette, Indiana, USA
* Corresponding author: E-mail address: jacksomj@purdue.edu

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ABSTRACT

Purpose: The paper shows how extremely high-speed micromachining can be used as a method for manufacturing nanocrystalline feedstock from machining chips. The feedstock can be used in processes such as cold spraying that improve the surface characteristics of engineering components.

Design/methodology/approach: The design and methodology relies on the construction and the correct operation of a micromachining operation that produces functional feedstock material that is produced from machining chips at spindle speeds in excess of half-a-million revolutions per minute. The approach provides an economical way of producing metal nanocrystals.

Findings: The findings of the research show that intense plastic shearing of metals produces nanosized crystals in the range 30nm to 150nm. The crystals produced can be used to create superior functional coatings on engineering components.

Research limitations/implications: The research conducted implies that a cost effective and environmentally-benign process can produce metal nanocrystals. The limitations of the research are currently restricted to cold spraying of functional surfaces.

Practical implications: The practical implications of the research show that high-speed micromachining can be used as a method of producing nanocrystalline feedstock that can be used in a variety of secondary manufacturing processes in addition to cold spraying.

Originality/value: The paper demonstrates the originality of using well-established machining processes for producing nanocrystalline metals. The paper describes how machining at extremely high speeds can be achieved to produce material that can be used to strengthen and harden engineering components.

Keywords: Machining; Nanocrystalline metals; Cold spraying

1. Introduction

A growing area of development is spraying of metals to substrates in order to provide protection of surfaces and the formation of three-dimensional micro structures. There have been may studies conducted on the effects of thermal spraying such as bonding mechanisms [1], high strain rate deformation [2] optimization [3], modeling [4], selection of materials [5], particle-substrate interactions [6], evaluation of coatings [7], effects of spraying angle [8], spraying equipment [9], and cost comparison between different spraying techniques [10]. Few studies have been made on the ability to spray microparts. However, a recent study by Sandia National Laboratory has compared the use of thermal and cold spray techniques for the manufacture of molds for use in the LiGA process. Thermal spray processes offer significant advantages over electroplating that is restricted to depositing materials such as gold, copper, nickel, and permalloy (80% nickel and 20% iron). Thermal spray processes also produce a denser layer of metal, but tends to have significant disadvantages when compared to cold spraying. Cold spraying appears to have some distinct advantages over thermal spraying, the most important being:

1. The amount of heat delivered to the part is very small;
2. Oxidation of the impacting particles is minimal;
3. Nanophase, intermetallic, and amorphous materials can be sprayed;
4. Grain growth is avoided;
5. Segregation of phases is avoided; and
6. Peening effects produce compressive residual effects in the surface of the component.

The spraying of nanostructured metals is a new area of research recently started by the authors at Purdue University. In this process, metal nanoparticles are created by machining metals at extremely high speed using a specially designed high-speed machine tool.

The process of machining has always been a strong contender for playing a role in the future of micromanufacturing. The ability to machine any material guarantees that micromachining will continue to be a micromanufacturing process of choice. In recent years, the size of the cutting tool has become smaller and smaller, and as such very small tools are now being fabricated by laser micromachining and ion beam milling processes. Figure 1 shows a collection of cutting tools fabricated by ion beam milling. Laser micromachining shows promise in being able to remove very small areas of material using extremely high fluences. This can be achieved using femtosecond pulsed lasers and future applications of this type of laser may include sharpening very small diamonds that can be attached to tips such as AFM probes. The AFM may be developed as a nanomachining tool that can cleave the bonds between atoms. Diamond and titanium based cutting tools are required to machine a wide variety of engineering materials. Developments in PVD and CVD coating technologies will also be fundamental to the future development of micromachining cutting tools [11-15]. The future development of very stiff machine tools will also figure significantly in the future too. Developments in this area have already begun by various research institutions in the United States of America and are described as 'meso machine tools' (mMTs).

2. Experimental method

The creation of nanocrystalline materials from single chip turnings was performed using a specially constructed machine tool. The machine tool was constructed using a tetrahedral space frame design that attenuates vibrations generated during high-speed machining. The micro cutting tool is held in an air turbine spindle capable of rotating the grinding tool in excess of speeds of 500,000 revolutions per minute. Figure 2 shows the machine tool complete with three axes of motion in the x, y, and z-directions. A fourth axis capable of rotary motion can also be used on the machine tool. The machine tool was used to create microscale chips at shear strains in the range between 1 and 10. The initial grain size of the chips was 20μm, and the undeformed chip thickness was typically 100μm. Chip width was 3mm and the shear strains were calculated from specially devised quick stop experiments. Microstructure was characterized using optical and transmission electron microscopy to obtain bright and dark field images and selected area electron diffraction patterns. The machine tool creates metal chips with nanosized crystals that possess high hardness and strength properties. Figure 3 shows a micrograph of a machined chip of brass showing the variation in hardness values in Vickers' hardness.

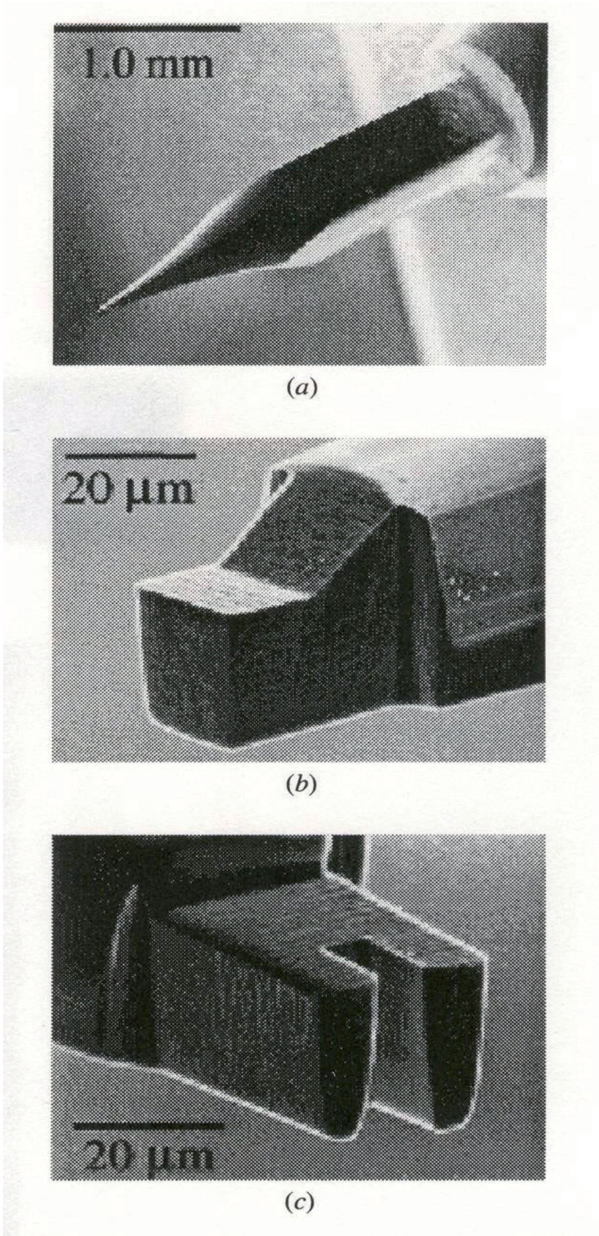

Fig. 1. Focused ion beam milled diamond coated cutting tools

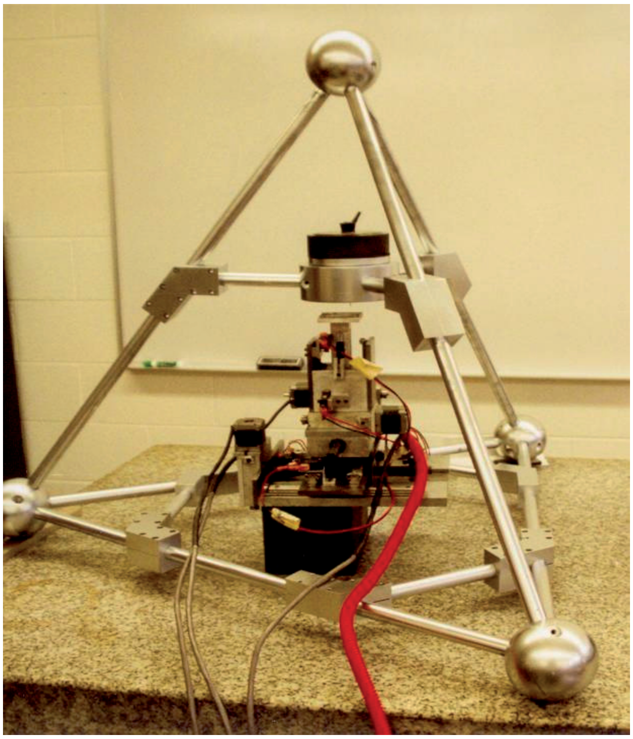

Fig. 2. Micro machine tool showing tetrahedral spaceframe surrounding the precision x-y-z table and the extremely high-speed air turbine spindle

The chips are then broken down into smaller particulates that can be sprayed to the surface of a substrate, or can be deposited layer-by-layer so that a three-dimensional microscale part can be produced.

3. Experimental results and discussion

The results created by machining at such high shear strains and strain rates (>10^6 s^{-1}), are remarkable. The observation of converting micro sized grains into nanoscale grains is shown in Figure 4 for a particular titanium alloy. There is also a significant number of high angle grain boundaries especially at higher strain rates (~13). This phenomenon coincides with the onset of dynamic recrystallization. Microstructural changes occurring in alloys of moderate strength also have significant improvements in mechanical properties after machining. Figure 4 also shows a bright field TEM image showing a nanoscale grain structure. The inset diffraction pattern shows random orientation of grains, with a misorientation of approximately 20° determined using convergent beam electron diffraction analysis. Misorientations were found to increase with increasing strain. Nanoidentation showed the hardness of the chip to be 585 kg/mm^2 compared to 245 kg/mm^2 for the bulk sample. These observations show that a variety of high-speed machining phenomena can be assessed such as the formation of dislocation substructures, dynamic recrystallization, and strain-induced phase transformations.

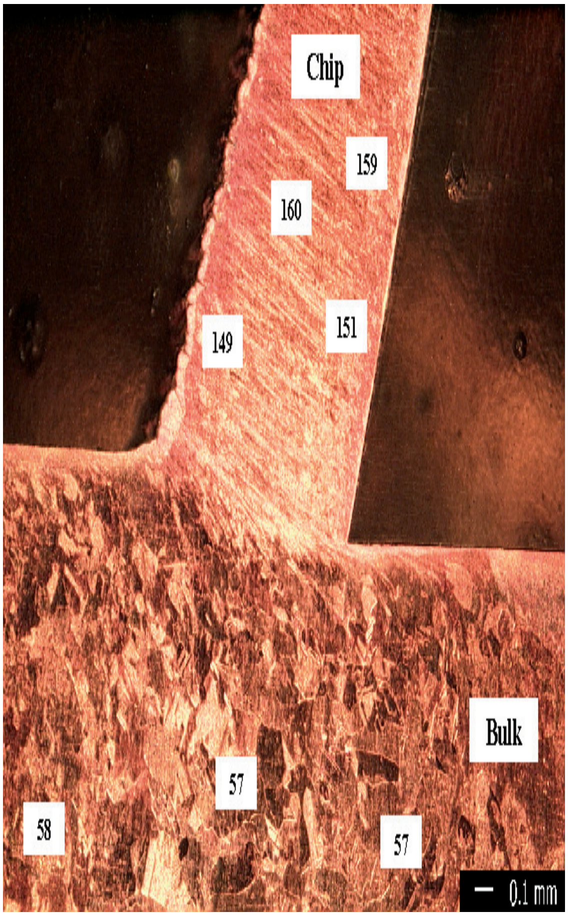

Fig. 3. Hardness variations shown on the machined surface of copper. Hardness values are shown as H_V Kgmm^{-2}

Nanoindentation of chips show the size of grains and variation in hardness. The superposition of hardness values, microstructure, and strain field characteristics, it is possible to understand micro and nanomechanics of large strain deformations. Chips are significantly harder and preliminary findings show that the structure is nanoscale. Although increasing hardness is associated with smaller grain size and the formation of dislocation substructures, much information relating to the interaction of dislocations and the relative contributions of defects is absent at this scale.

4. Conclusions

The application of plane strain machining for studying microstructure associated with very large plastic strains has been demonstrated using titanium alloys. This alloy is used various various aerospace applications and can be applied by cold spraying a component surface with the highly strained machining chips. The technique shows that an economical method has been created that produces nanoscale feedstock especially for cold spraying applications.

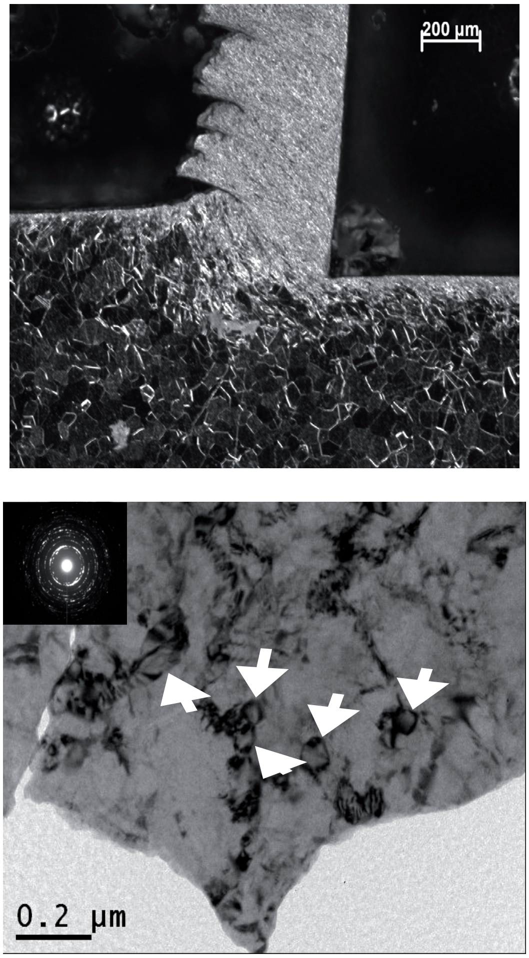

Fig. 4. Micrograph of titanium chip being formed into the nanosized feedstock that is used for cold spraying. Arrows show the grains of size 50-200 nm with a hardness of 535 H_V

The process of machining has always been a strong contender for playing a role in the future of micro and nanomanufacturing. The ability to machine any material guarantees that micromachining will continue to be a micromanufacturing process of choice. In recent years, the size of the cutting tool has become smaller and smaller, and as such very small tools are now being fabricated by laser micromachining and ion beam milling processes. These small tools will enable much smaller machining chips to be produced, and consequently smaller collections of nanocrystals will be produced for use in processes such as cold gas dynamic spraying of functional surfaces and microparts.

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