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Metal particulate production by modulation-assisted machining

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Continuous production of Al 6061-T6 particulate using modulation-assisted machining (MAM) is demonstrated. Superimposition of a controlled, low-frequency modulation in conventional machining causes chips to form as discrete particles. By adjusting the conditions, equiaxed, platelet and fiber-shaped particles having narrow size distributions can be produced. Large-strain deformation leads to microstructure refinement and enhanced hardness. The process is applicable to a wide range of alloys and appears to be intrinsically scalable for large-volume production.

Keywords: Powder processing; Machining; Severe plastic deformation (SPD); Ultrafine grained microstructure

Metal and alloy powders are produced by a wide range of physical, chemical and mechanical routes, each of which imparts characteristic morphology and microstructure to the particles [1]. These processes typically yield broad particle size distributions, requiring subsequent classification. Although particle shape (e.g. spherical, flake, dendritic, irregular) is process specific, there is generally little control of shape within a given process. Particle internal structure is also process dependent. High-energy milling, for example, imparts severe plastic deformation (SPD), which enables mechanical alloying, dispersion of fine oxide particles and extreme grain-substructure refinement (nanocrystalline structure) within the particles [2]. But the process is often limited by contamination associated with high surface area exposure during repetitive comminution and agglomeration steps, and there is limited control of particle (agglomerate) size.

Recently, a new machining process – modulation-assisted machining (MAM) – that superimposes a low-frequency modulation on to the tool has demonstrated unique control of chip formation [3,4]. The MAM process causes the chip to form as small discrete segments. The present study describes a variant of MAM wherein the discrete chip formation is scaled down to produce chips of powder particle size. The particle shape and size are determined by the modulation and machining conditions, and the process offers the possibility of realizing narrow particle size distributions. Furthermore, since chip formation involves SPD, particulate produced by MAM are likely to be ultrafine grained (UFG) or nanocrystalline, with enhanced hardness and strength [5,6].

Figure 1 shows a schematic of plane-strain machining. Chip formation occurs by a process of concentrated shear in a narrow deformation zone, which is often idealized as a shear plane [7]. If a low-frequency (<1000 Hz) modulation is superimposed onto the motion of the tool or the workpiece, then continuous chip formation is replaced by a series of discrete cutting or chip formation events. The MAM process is also shown in Figure 1, wherein a sinusoidal modulation, $\Delta z(t) = A\sin(2\pi f_m t)$, with peak-to-peak amplitude, $2A$, and frequency, f_m, is superimposed onto the continuous linear motion of the tool in a direction parallel to the undeformed chip thickness. Unlike conventional machining, the instantaneous undeformed chip thickness, $s(t)$, in MAM is not constant, but varies with time (i.e. along the length of a machining pass) between some maximum, s_{max}, and minimum value as, $s(t) = s_0 + A\sin(2\pi f_m t)$. If A is sufficiently large, then $s(t)$ becomes zero at some time in each cycle of modulation, resulting in a 'discrete' chip or particle [3,4,8]. The number of particles created per second is equal to f_m.

Continuous production of particulate may be achieved by carrying out MAM at sufficiently small $s(t)$ in a sequence of machining passes on the workpiece. In this case, the profile of the workpiece surface prior to a machining pass will be different than the flat surface

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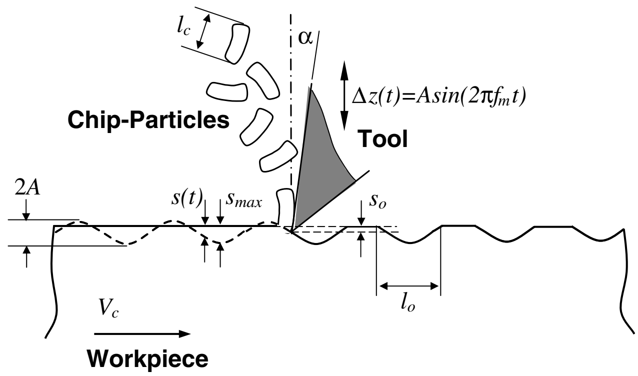

Figure 1. Plane-strain machining with and without modulation. A workpiece moving at a velocity V_c is traversed by the sharp cutting edge of a wedge-shaped tool inclined at rake angle, α. In conventional machining, the tool is engaged at a preset depth, s_0 (undeformed chip thickness). In modulation-assisted machining (MAM), a sinusoidal motion $\Delta z(t)$ is superimposed on to the tool in the direction of undeformed chip thickness. When the modulation amplitude, A, is sufficiently high, the chips form as discrete particles with undeformed length, l_0, and undeformed thickness, s_{max}, with one particle being created in every cycle of the modulation.

depicted in Figure 1, as a consequence of the surface generated by the previous machining passes. The undeformed chip thickness is the difference between the position of the tool edge and workpiece surface in each cycle of modulation. Numerical simulation shows that after a few passes the workpiece surface profile reaches a steady state and the maximum undeformed chip thickness, s_{max}, is a constant. The undeformed chip length, l_0, in MAM is the total distance that the tool is engaged with the workpiece in each cycle of modulation (Fig. 1). This length is determined as the path integral of the tool position over the duration of the cutting portion of each modulation cycle. The third dimension of the chip (into the plane of paper in Fig. 1) is the chip width, which is the same prior to and after the deformation in plane-strain machining.

Production of particulate employing a sequence of MAM passes is best implemented in a cylinder machining configuration on a lathe. A tool is fed axially along the length of a cylindrical workpiece of diameter D (mm), rotating at f_w rotations per second (rps), and producing a chip at a cutting velocity, $V_c = \pi D f_w$ (mm s^{-1}). This machining configuration has a one-to-one correspondence with Figure 1, albeit the tool path is a helix on the surface of the cylindrical workpiece. Particle formation is realized by modulating the tool axially, in the direction of tool feed or undeformed chip thickness. Particle formation will occur as long as the modulation amplitude is sufficiently large for $s(t)$ to reach zero during each cycle of the modulation and f_m is not an integer multiple of f_w. The minimum value of the amplitude required for particle formation is $2A = s_0$, and occurs when $f_m/f_w = (\text{integer} + 1/2)$ [3]. In practice, the amplitude $2A$ is set slightly greater than s_0, so as to compensate for any elastic compliance in the machining system. This is the modulation condition implemented in the present study.

Particles with different sizes and aspect ratios are created by varying the modulation and machining conditions. An estimate of undeformed particle (i.e. prior to its detachment) dimensions is obtained as follows. The time taken for each revolution of the workpiece is $1/f_w$ (s), during which about f_m/f_w particle formation events occur. Since the tool traverses a distance of $\sim\pi D$ in this time, each particle has undeformed length $l_0 \approx 1/2(\pi D f_w/f_m)$ and $l_c = r l_0$, where l_c is the particle length after detachment and $r = l_c/l_0$ is the cutting ratio [7] (see Fig. 1). Alternatively, l_0 can be obtained from a numerical simulation of the tool motion. When MAM is carried out under plane-strain conditions, the maximum particle thickness is $r s_{max}$, controlled primarily by the axial feed-rate, s_0 (mm rev^{-1}). The third dimension of the particle, the particle width, is unchanged from its value prior to detachment from the workpiece because of the plane-strain constraint. In cylinder machining, this width is equal to the radial depth of cut. It should be noted that particles of high-aspect ratio (e.g. platelet, needle, fiber) are created under plane-strain conditions; in the case of needles or fibers, the long axis is the particle width as defined above. Equiaxed particles (aspect ratio ∼1) are formed under non-plane strain conditions.

A series of experiments was carried out to demonstrate particulate production using MAM. A tungsten carbide tool (zero-degree rake angle) installed on a computer numerically controlled (CNC) lathe was used to machine an Al 6061-T6 cylinder with controlled sinusoidal modulation applied to the tool in the direction of tool feed (undeformed chip thickness). In this configuration the axial feed-rate of the cutting tool per workpiece revolution is the analog of s_0 in Figure 1. The modulation was effected by a piezo electric actuator built into the tool-holder [9], the actuator being controlled via an external power supply (model E-505.00, Physik Instrumente) and a digital waveform generator (model 33220A, Agilent Technologies).

Specific machining and modulation conditions were prescribed to create controlled particle sizes and shapes. The machining conditions spanned workpiece diameters, $D = 2$–12 mm, workpiece rotational frequencies, $f_w = 1$–65 Hz, undeformed chip thickness, $s_0 = 2$–40 μm rev^{-1}, and radial depth of cut = 5–2000 μm. The modulation conditions were $2A = 25$–100 μm and $f_m = 0$–1000 Hz. All of the tests were conducted with $f_m/f_w = (\text{integer} + 1/2)$. This combination of parameters is adequate for producing a wide range of particle sizes (∼20–2000 μm) and shapes (equiaxed, platelet, needle, fiber). The machining velocity, V_c, for these conditions was sufficiently low to minimize temperature influences.

Particle and bulk Al 6061-T6 samples were mounted and polished for Vickers hardness measurement. The load on the hardness indenter was adjusted to maintain the indentation diagonal length at ∼50 μm. The particle size was characterized by direct measurement of ∼100 particles, by laying out particles on a glass slide and measuring their dimensions with an optical microscope.

Figure 2 shows examples of equiaxed-, needle- and platelet-type Al 6061-T6 particles produced by MAM under various process conditions. The extraordinary uniformity in sizes of the particles is apparent from the SEM micrographs (Fig. 2). Other experiments have demonstrated production of particles with sizes ranging

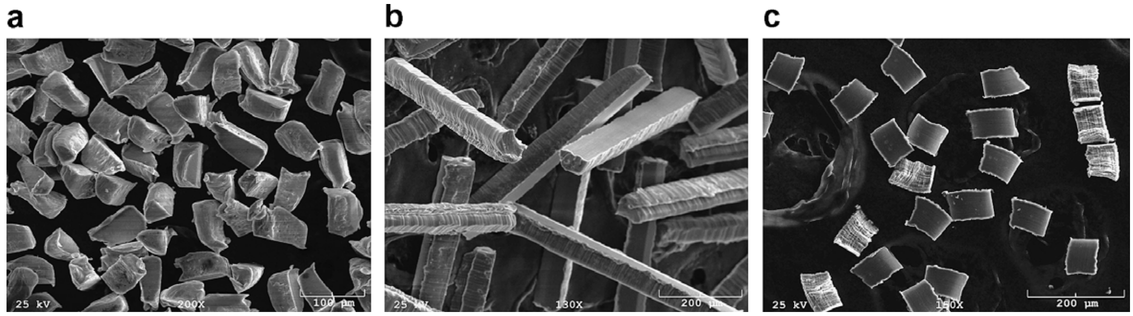

Figure 2. Scanning electron micrographs of Al 6061-T6 particulate produced by MAM: (a) Equiaxed, (b) needle and (c) platelet shapes. Note the uniformity in size and shape of the particles. The corresponding MAM conditions (D, f_w, radial depth of cut, s_0, f_m) were as follows: (a) 6 mm, 3 rps, 150 µm, 50 µm rev^{-1}, 181.5 Hz; (b) 6 mm, 3 rps, 600 µm, 18.75 µm rev^{-1}, 325.5 Hz; (c) 2 mm, 2 rps, 50 µm, 25 µm rev^{-1}, 25 Hz.

from 20 to 2000 µm, with aspect ratios of up to 200. The standard deviations for distributions of particle sizes, l_c, are less than 3% of the mean size. The variability is more a consequence of the limitation of the measurement technique in identifying particle edges than that inherent to the process. This demonstrates the ability of MAM to produce particles of uniform size in each of the basic regular shapes, a consequence of the deterministic nature of the particle formation process.

Figure 3 shows an enlarged view of a needle shaped particle with an aspect ratio of ~7. One surface of the particle is seen to be smooth; this is the surface that was in contact with the tool rake face. It is interesting to note the resemblance of these particles to fibers created by a chatter-machining process [10–12]. But fiber shape and size can only be controlled to a limited extent in the chatter-machining process.

The shear strain (γ) imposed in particles was estimated from measurement of particle lengths l_c and l_0, using the well-established equation $\gamma = r + (1/r)$ for a zero rake angle tool in plane-strain machining [7]. For this purpose, a specific series of experiments that involved creation of platelet particles was carried out. The modulation frequency f_m was varied between 31.5 and 91.5 Hz in discrete steps such that $f_m = f_w$(integer + 1/2), while keeping $f_w = 3$ rps, $D = 6.0$ mm, radial depth of cut = 150 µm, $s_0 = 18.75$ µm rev^{-1} and $2A =$ 25 µm. The lengths of the platelet particles are inversely proportional to the modulation frequency.

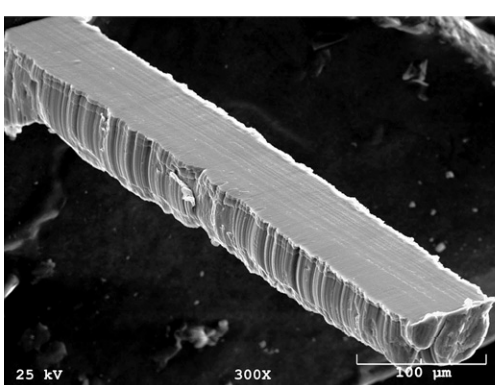

Figure 3. SEM picture of an Al 6061-T6 needle particle (aspect ratio ~7). The geometry and size are controlled by the MAM conditions. The smooth face is the surface that was in contact with the rake face of the tool.

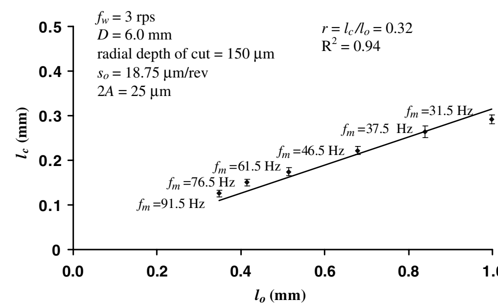

Figure 4. Variation of the measured platelet particle length, l_c, with the undeformed particle length, l_0. The error bars denote one standard deviation for each test condition (f_m). The data fit well to a linear trend ($R^2 = 0.94$) with slope, $r = l_c/l_0 = 0.32$, corresponding to an average shear strain $\gamma = 3.4$.

Figure 4 shows a plot of l_c against l_0 for platelet particles created at different modulation frequencies. The slope of the linear fit to the data gives a cutting ratio, $r = 0.32$. This ratio corresponds to an average shear strain value of $\gamma = 3.4$ in the platelet particles. Furthermore, the excellent linear fit ($R^2 = 0.94$) implies that the average strain is constant over the range of modulation conditions and uniform over the particle volume. Therefore, the deformation process in MAM is self-similar at different particle thicknesses and dependent only on the tool rake angle, as in conventional machining [7]. Additional confirmation of this self-similarity is provided by estimates of strain in continuous chips created under the same machining condition, but without modulation. For this conventional machining condition, $r = 0.31$, giving a strain value of $\gamma = 3.5$, very similar to that for the particles.

The Vickers hardness of the particles was 154 ± 3 HV, a 30% increase over that (110 ± 2 HV) of the bulk Al 6061-T6. A similar high hardness value has been measured in millimeter-sized Al 6061-T6 chips created by machining [13] and Al 6061-T6 bars produced by equal channel angular pressing [14], wherein the high hardness has been attributed to the fine grain size resulting from the SPD. Transmission electron microscope observations of 3 mm size Al 6061-T6 chips created with a shear strain similar to that of the particles have shown the microstructure to consist of equiaxed, nanoscale grains with an average size of 80 nm [13]. Therefore, it is likely that the particles created by the MAM also have an ultrafine grained microstructure. This will be verified in the near future.

The particle shape and dimensions are determined to first order by the tool/workpiece motions, and the level of strain imposed in the particle can be controlled by varying the tool rake angle. Hence, it is feasible to precisely set the modulation and machining conditions to achieve desired particulate characteristics. The ability to control the shape of the particle while simultaneously achieving uniformity in particle sizes is a consequence of the deterministic nature of the particle formation process in MAM. This is to be contrasted with other particle production processes, such as atomization and milling, wherein particle formation is governed at least partially, if not fully, by stochastic mechanisms.

In summary, a process using modulation-assisted machining has been demonstrated for production of metal particulate using Al 6061-T6 as the model material system. In this process, a specially designed tool-holder applies low-frequency modulation to the cutting tool in a conventional cylinder machining process. Particles are created by a discrete, mesoscale chip formation process, where the rate of particulate production is f_m per second and size and shape of the particles are determined precisely by the modulation and machining conditions. Particles with shapes such as equiaxed, needle and platelet have been created with tightly controlled sizes in the range of 20–2000 μm. We are unaware of any commercial process that offers similar wide ranging control of particle shape and size. The modulation and machining conditions needed for producing particulate with specific shape and size characteristics can be determined using a kinematic model of the chip formation, enabling a priori design of process conditions. The hardness of the Al 6061-T6 particles is much higher than that of the bulk material and consistent with the levels of strain imposed in the particles by the MAM. At these strain levels, the particulates are likely to have an UFG or nanocrystalline microstructure. The MAM process is inherently scalable for large-volume production of particulates from a variety of metals and alloys. The uniformity of particulate size offers potential for achieving increased production yields, as well as enhanced consolidation behavior. Current work is exploring the application of the process to a broader range of materials (e.g. Ti alloys and steels) and the characteristics of the particulate microstructure.

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[1] F.V. Lenel, Powder Metallurgy: Principles and Applications, Metal Powder Industries Federation, Princeton, NJ, 1980.
[2] R.M. German, Powder metallurgy science, second ed. Metal Powder Industries Federation, Princeton, NJ, 1994.
[3] J.B. Mann, M.R. Shankar, S. Chandrasekar, W.D. Compton, W. Moscoso, U.S. Patent Application, Ser. No. 11/381,392, Filed May 3, 2006.
[4] H.G. Toews, W.D. Compton, S. Chandrasekar, Precision Engineering 22 (1998) 1.
[5] T.L. Brown, S. Swaminathan, S. Chandrasekar, W.D. Compton, A.H. King, K.P. Trumble, Journal of Materials Research 17 (2002) 2484.
[6] S. Swaminathan, M.R. Shankar, B.C. Rao, A.H. King, S. Chandrasekar, W.D. Compton, K.P. Trumble, Journal of Materials Science 42 (2007) 1529.
[7] M.C. Shaw, Metal Cutting Principles, Oxford University Press, Oxford, 1984.
[8] P.N. Chhabra, B. Ackroyd, W.D. Compton, S. Chandrasekar, Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture 216 (2002) 321.
[9] J.B. Mann, S. Chandrasekar, W.D. Compton, U.S. Patent Application, Ser. No. 11/381,513, Filed May 3, 2006.
[10] S. Doi, S. Kato, Transactions of the American Society of Mechanical Engineers 78 (1956) 1127.
[11] T. Nakagawa, K. Suzuki, US Patent 4,703,898, November 3, 1987.
[12] T. Nakagawa, K. Suzuki, T. Uematsu, H. Koyama, in: Proceedings of the 23rd International Machine Tool Design and Research Conference, 1982, p. 323.
[13] M. Shankar, S. Chandrasekar, A.H. King, W.D. Compton, Acta Materialia 53 (2005) 4781.
[14] S. Ferasse, V.M. Segal, K.T. Hartwig, R.E. Goforth, Journal of Materials Research 12 (1997) 1253.