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Innovative reconsolidation of carbon steel machining swarf by laser metal deposition

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ABSTRACT

The concept of widespread recycling of metals in order to save cost, energy and ecological damage is gaining importance and this necessitates not simply disposing of machining waste. In this work a new way of reconstituting chips/swarf into a usable solid structure is explored by using them in place of metal powder in laser direct metal deposition. Samples of carbon steel machining swarf in three size ranges are reconstituted and the final structural characteristics like clad dimension, microstructure and physical properties are analysed. The results show that it is possible to reproduce a material that has full density, fine microstructure and no significant contamination from an unprecedented size and shape of particles. As general trends, individual deposition tracks become lower, wider and less hard as particle size increases. This work shows that the laser deposition process can be used with a larger range of particle geometries than previously considered and this could be the point leading to a new 'local' recycling method.

1. Introduction

Machining of metals to manufacture components of all types leads to wastage of the materials and energy that is required to bring them from initial raw material shape to the desired geometrical shape. A large quantity of raw material ends up as machining swarf or chips. For instance, manufacturing of aerospace fan blade from solid forged titanium can produce 90% of waste machining chips [1]. Natural resources are becoming more precious and the need to reduce power usage for economic and environmental reasons is increasing; these trends are likely to continue because the current estimate of world population growth brings it to 10 billion in 2050 [2]. Thus there is an ever-increasing need for efficient manufacturing and recycling methods. Laser direct metal deposition (LDMD) and laser direct melting have been proposed as addressing the former [3]; being additive methods they can e.g. increase material usage efficiency for organic like geometries . However, the high cost of new powders means that they are unlikely to become serious competitors to conventional machining for large parts, so a way of recycling machine swarf is still needed [4].

This paper also examines recycling via LDMD, in which metallic material in a carrier gas stream is injected into a laser melt pool on a metallic substrate. The pool quickly solidifies as the laser traverses, leaving a bead fused to the surface. Layer by layer deposition can be used to obtain a desired geometrical shape [5]. The clad geometry so obtained depends on time, material properties and other process parameters [6]. Gas-atomised metal powder particles with size up to 150 μm and spherical morphology are usually used in laser cladding, although quite rarely particles of sizes in the range 200–250 μm have also been used [7,8]. Grujicic et al. [9] established that even coarser particles (400–595 μm) can be melted by maximizing laser power and particle interaction time under laser beam so that sufficient specific energy is absorbed by the in flight particles.

Little work has been done on the effect of particle geometry, but evidence of depositing water-atomised particles with irregular geometrical shape is available [10]. The irregular water-atomised particles produced a hotter melt pool and smaller but smoother final clads than their spherical counterparts, attributed to a combination of different shadowing and melt pool flow effects.

The size and the morphology of machining chips are determined by cutting conditions [11], tool geometry [12] and work piece material [13] . Machining of brittle materials using very low or very high cutting speeds along with high feed rate, large depth of cut or using tool with low rake angle generally produces discontinuous chips. It is established that use of cutting fluids to ward off effects of high temperature oxidizes and contaminates the chips. Various measures to avoid contamination are being looked into and followed. These include dry machining [14], use of self-lubricated

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tools [15] and cryogenic cooling [16]. Decontamination efforts include gravity drainage of fluids, drying, chemical treatment and heat pasteurization [17].

In this paper, the use of machining swarf as the build material in LDMD is investigated and reported. Samples of chips in different size ranges were obtained by dry machining medium carbon steel in the first instance. These samples were deposited as thin walls onto material of the same type. Chips that did not form a part of clad were collected and reused a second time to form additional 'recycled chips' walls. The walls were analysed and the results and a simple model to help explain the findings is presented.

2. Experimental procedure

A FERRARI CNC milling machine was used to mill a medium carbon steel circular bar (0.48% C, 0.8% Mn, balance Fe). Before the start of operation, the machine was thoroughly cleaned and dried to avoid mixing of previously deposited cutting fluid contaminants. The rust layer initially present on the exterior of the steel rod was removed by turning on a lathe immediately before the machining. The material was then subjected to dry face milling with a 22 mm diameter carbide tip milling cutter with 3 flutes. Chips of different sizes were produced by setting the feed rate at 100 mm/min, spindle speed at 1000 rpm and depth of cut between 0.1 and 0.9 mm. The chips were collected by a special arrangement using thick transparent plastic sheet and magnets/demagnetizers after each change in cutting conditions. The complete setup of chips production and collection is shown in Fig. 1.

Chips were then combined and passed through sieves of different mesh sizes to categorise them into three particle size ranges of <150, 151–295 and 296–425 μm, which were termed samples O1, O2 and O3, respectively, the 'O' representing the fact that these were original chips. A Malvern Mastersizer laser diffractometer was used to find the particle size distribution of each category. A representative from each sample was tested for elemental composition and morphology by energy dispersive spectroscopy (EDS) and scanning electron microscopy (SEM), respectively, using ZEISS EVO60 equipment.

Two series of experiments were performed. In the first series, LDMD of thin walls using the original chips representing the three particle sizes was carried out. After deposition of each particle size category, O1, O2 and O3, the undeposited chips were collected, and termed as R1, R2 and R3, respectively, the 'R' representing the fact these were recycled chips. These were used for LDMD of thinner walls in a second series of experiments. All experiments were performed using a Laserline LDL160-1500 diode laser with dual wavelength of 808 and 940 nm. The laser beam was focused onto a spot of 1.7 mm diameter on 316 L stainless steel substrates ($50\ mm \times 50\ mm \times 10\ mm$) that had been grit blasted and degreased prior to use. The feed material was conveyed to the melt pool from a disc powder feeder through a nozzle with an annular outlet area of 33 mm^2, coaxial with the laser beam. The standoff distance between nozzle and substrate was constant at 7.5 mm. Argon was used as both central shielding and powder conveyance gas. The walls were built at a single combination of parameters, determined from previous trials: a laser power of 900 W, traverse speed of 4 mm/s, mass feed rate of 0.25 g/s and carrier gas flow rate of 5 L/min.

After deposition, wall dimensions were measured to determine deposit characteristics. Each wall was sectioned in transverse and longitudinal planes, and mounted using acrylic resin (Struers Specifast). These were ground and polished with a diamond paste to 1 μm surface finish, etched using NITAL 2% and images of the upper part of the walls (about 2 mm from the top surface) were taken using a PolyVar-MET optical microscope to determine microstructure. Hardness of the parent material and that of the clad material at different positions were also measured using Buehler Micromet test equipment.

3. Results

3.1. Chips morphology and size distribution

SEM examination of all the chip samples revealed discrete chips with irregular and elongated geometrical shape and uneven, coarse surface texture. The chip size distribution and morphology of each of the original samples are shown in Figs. 2 and 3, respectively.

A lognormal size distribution with wide size range was observed in all the samples, although there are two anomalies visible. Firstly there are small additional concentrations of chips

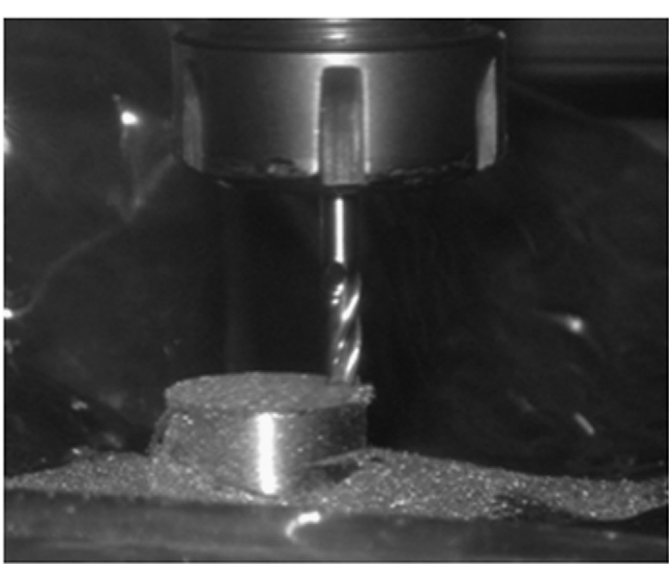

Fig. 1. Chips production and collection arrangement.

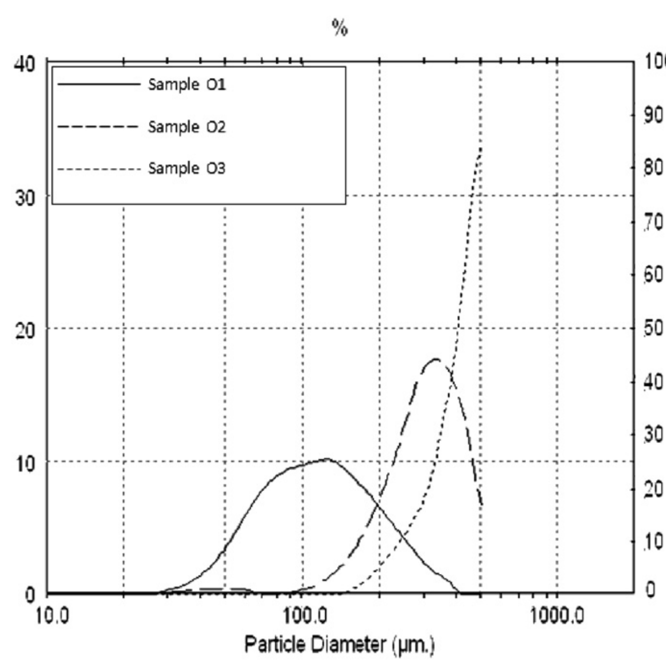

Fig. 2. Size distribution of original chips.