A new method of laser beam induced surface modification

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Surfi-Sculpt® is a power beam process, invented at and patented by TWI, which enables controlled surface features to be developed on a range of substrates, including but not limited to metals, polymers and ceramics. Such surface features were first demonstrated using electron beams, employing electromagnetic coils to first focus the beam and then deflect this focused beam over the material surface in a rapid and controlled manner. This article will describe more recent work, which has involved the use of focused laser beams to develop similar features.

The process

Fibre delivered laser beams and galvanometer driven scanning mirrors were used in this work to produce the rapidly moving spot of laser energy required for the process. After generation of a molten pool in the substrate material, the beam is then rapidly moved relative to the workpiece. As a result of vapour pressure and surface tension effects, the laser beam movement results in material being moved from within the pool to regions at the extreme end of the beam movement. By repeating this process, it is possible to build up protrusions of several millimeters in height above the surface of the material. By combining and sequencing these protrusions together, a variety of shapes or features can be formed.

The laser experiments have been performed in air and in various gaseous environments and, for comparison purposes, with electron beam work, in vacuum. The technique is not limited to the production of protruding surface features; it can also be used to modify the structure deeper within the work-piece, so as to effect modification in the bulk substrate, for example, by the creation of deep holes in the material.

The types of surfaces produced are being investigated for many applications, including orthopaedic implants, with improved fixation due to promotion of bone in-growth, preparations for metals to be joined to composite, and for making surface features that enhance thermal transfer for high performance heat exchangers.

Investigations

In the results reported here, both disc and fibre lasers have been used at relatively modest laser powers of less than 2kW, in conjunction with two different laser beam scanning systems, both developed primarily with laser welding applications for the automotive industry in mind. The disc laser was manufactured by Trumpf and the fibre laser by IPG Photonics. The scanning systems were manufactured by Trumpf and Arges.

Trials were conducted on both metal alloys (Ti-6Al-4V) and plastics (polypropylene and polyethylene). For all materials, initial work consisted of producing simple linear shapes, using a repeated 'swipe' of the focused beam across the surface of the material. The main process variables were laser power, swipe speed, swipe length and the dwell time between swipes. Subsequently, more complex shapes were attempted, by combining several single swipes together to form a pre-determined pattern. For both the Trumpf and IPG laser systems, the minimum focused spot size was estimated to be between 0.3 and 0.34 mm in diameter

Metals

Figure 1 shows typical preliminary results of using a laser beam to generate a conical type Surfi-Sculpt feature in titanium plate, using a 'star' form for the swipe pattern. The sequence consists of repeats of eight radially sequential single swipes. These results were obtained in air and did not use the vacuum normally required for electron beam work.

The processing conditions, as given in the figure caption, were determined from optimisation trials on single swipes. Initially the star shaped pattern was generated with no 'gap' in its centre. This condition resulted in a protrusion which was not particularly conical. The improved shape seen in Figure 1, was

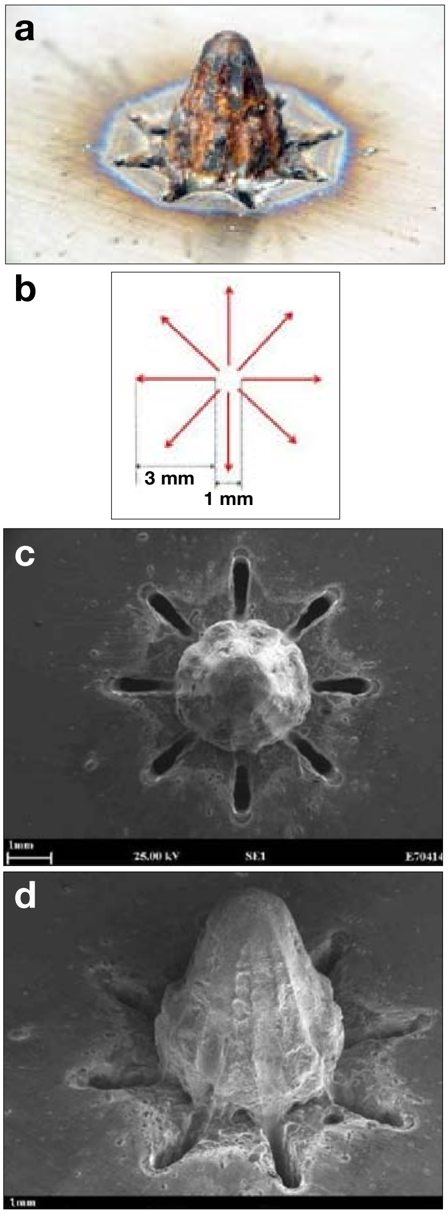

Figure 1: Conical Surfi-Sculpt feature created in air on a titanium alloy plate.

(a) Photograph of the feature

(b) Diagram. The arrows indicate the direction of the movement of the laser beam. The sequence consisted of repeats of eight radially sequential single swipes. (NB Note the 1 mm gap in the centre)

(c) and (d) SEM images

The operating parameters were:
laser power = 1 kW
scanning speed = 16 m/min
number of swipes per arm = 60,
time delay between swipes = 0.5 ms.

The total time required to create this star shape was approximately 5 s.

produced with a gap of about 1mm in diameter in the centre of the pattern. High speed video of the process showed this to be beneficial to the cyclic nature of the build up of the material. It also indicated the possibility of the structure being hollow inside, at its base. Also seen in the SEM images are the swipe terminations and the slots below the surface, from which the material moved to make the protrusion. Clearly, several sets of this particular feature could be put together to form an array on the material surface. In this case the height of the protrusion was about 5mm, and its manufacturing time was about 5 seconds, using a laser power of about 1kW.

Plastics

It is very difficult to process plastic materials using electron beams and another driver for the laser work was to see if the process would work on these materials using laser beams. This has been demonstrated on polypropylene using a CO_2 laser, and on polyethylene using a fibre laser source, although the only results shown here are for polypropylene.

Figure 2. Surfi-Sculpt feature made in polypropylene using a few Watts of CO_2 laser radiation.

Figure 2 shows an attempt to reproduce the star shape shown in Figure 1, in polyethylene, at much reduced laser power. It can be seen that the process appears to work with plastics, notwithstanding the large difference in viscosity between molten plastic and molten metal.

Atmospheric conditions

A small hermetic chamber was used in order to study the effects of atmospheric condition when processing metals. The same programmed laser beam path shown in Figure 1 was used to create features in a 100% argon atmosphere, as well as in air, all on the same titanium plate. The process parameters were kept the same as those shown in the caption to Figure 1, except that only ten swipes per arm of the star shape were employed, instead of sixty.

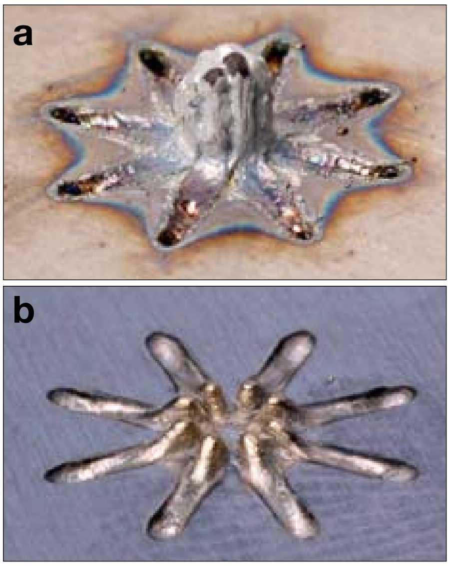

Figure 3. Photographs of Surfi-Sculpt star shapes in titanium alloy made in a) air, b) in argon.

The operating parameters were:
laser power = 1 kW
scanning speed = 16 m/min
number of swipes per arm = 10,
time delay between swipes = 0.5 ms.

The total time required to create each of these star shapes was approximately 1 s.

The results of this experiment can be seen in figure 3. The only change between the two pictures is the atmosphere around the sample. It can be seen that the feature size in air, (figure 3a) is the larger but the feature does not have a smooth surface and there is evidence of spatter and significant oxidation with some heat marking of the substrate surface, whilst in a 100% argon atmosphere (figure 3b) there is practically no evidence of heat marking, oxidation or spatter and the Surfi-Sculpt shape very closely represents the actual programmed path of the laser beam insomuch as the ‘gap’ between the linear swipes is quite obvious, which is not the case for the result in air. These effects are probably associated with differences in the thermal conductivity of the two processing environments and its effect on the viscosity, movement and solidification of the material during the process.

Potential Applications

Orthopaedic implants

The surface of orthopaedic implants can be modified to improve the fixation of metallic implants by encouraging bone in-growth. There are alternative techniques for making these surfaces, but a Surfi-Sculpt process offers the potential benefits of being fast, of allowing close control of the feature shapes and of ensuring surface features are firmly bonded so that they do not detach from the implant.

The general social trend for increased life expectancy and an expectation of people to be mobile and active in old age is reflected in the market for orthopaedic implants worldwide increasing at 7% per annum. In 2005 the total number of hip or knee replacements in US and Europe was 814,000. It is estimated that 10% of these will fail – the overwhelming majority because of aseptic loosening, so the requirement for improvement is immediate and is of significant social benefit.

Composite to metal joining

Composite materials are increasingly being deployed into applications where previously metals were the predominant choice of material. Carbon fibre composite materials account for some 50% of the mass of Boeing’s 787 Dreamliner, for example, and this is a major factor in the claimed 20% improvement in fuel efficiency. Glass fibre composite is being increasingly deployed in ship superstructures and for internal panels – producing a lighter weight structure which improves fuel efficiency, payload and, above the waterline, reduces the tendency to roll.

It is frequently a design requirement to join composite to metal. The production of surface features that allow a metal component to bond to many layers of laminate can potentially improve the bond strength. This technique is currently being assessed for a number of different products.

Heat exchangers

Thermal management of microprocessors and associated systems has become particularly challenging both at chip level and at the system level in data centres. The density of semiconductor devices has continued to increase, as is evident within desktop computers, where the last few years has seen more elaborate solutions to air cooling, and even the introduction of liquid spray cooled devices. A variety of small features produced with power beams, that provide beneficial fluid flow and improved heat transfer are being investigated.

Ultra-thick coatings

Within work at TWI that is focused on the manufacture of the plasma facing components of the ITER fusion vessel, the steel substrate has been treated with electron beam Surfi-Sculpt prior to applying an ultra-thick (e.g. 3mm) tungsten layer using vacuum plasma spray. The process has been shown to be beneficial in preventing ‘peeling’ of the layer, a phenomenon that normally occurs due to the high residual stress built up as a result of the mismatch in expansion coefficient. It is anticipated that this process may have many other applications where it is desirable to apply thick coatings.

Some of these and other potential applications of the Surfi-Sculpt power beam process have already been implemented on a commercial basis using electron beams, but at the moment no applications involving laser beams have reached production.

Conclusions

The objective of this work was to demonstrate the Surfi-Sculpt technique using laser beams. From the results presented it would appear that similar mechanisms and physical processes are involved in the generation of these features, whether laser beams or electron beams are being used. With laser beams, the process lends itself to the use of high brightness fibre delivered laser beams and galvanometer driven scanning systems, although it is possible that some shapes might be produced by using a fixed beam and manipulating the workpiece. The main compromise for the latter will be speed of movement and acceleration available. As well as producing Surfi-Sculpt features in metal, this work has shown that it is also possible to produce similar features in plastic material, notwithstanding the large difference in viscosity of the molten material. When processing titanium alloy, a very significant influence of the atmosphere in the region of the process was noted.

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See Observations p49

Continued from p 55

Micro-Nano processing workshop report

Clive Grafton-Reed of Rolls-Royce provided a brief insight into their laser manufacturing technologies. Applications included laser drilling, cutting of combustors and turbines as well as welding of combustors and fans. Manufacture of compressors includes laser peening of fan blades; lasers are also used for additive manufacture, local heat treatment and cladding, and for cleaning surfaces before repair. Looking to the future, Clive highlighted laser beam pulse shaping and the tuning of energy distribution during the manufacturing process (e.g. during drilling, to reduce recast, micro-cracking, oxide and HAZ and thereby to give better repeatability and hole quality). Rolls-Royce are looking to broaden their use of lasers in production and are keen to acquire more wavelengths and different powers including ultra-short pulse length lasers for “cold” processing at economic rates. Fibre lasers are particularly interesting for welding and when the price matures Clive wants to see them on standard platforms.

Sascha Weiler of Trumpf (DE) discussed industrial micro-machining with high average power picosecond lasers and the ability of these sources to achieve cool or even cold processing and showed impressive results with the new Trumpf TruMicro series of high average power picosecond lasers working at near-IR, green and UV wavelengths with good beam quality ($M^2<1.3$). More on this laser and its applications can be found in an article in this issue, p 41.

Roy McBride of PowerPhotonic spoke about the production of freeform refractive micro-optics by direct laser writing. PowerPhotonic custom micro-optics fabrication is produced on a fused silica substrate using a direct write technique (thereby avoiding tooling costs) and subsequent laser polishing. As a practical example, he showed wavefront mapping the output of high power diode lasers at full operating power where the results were translated into the specification for a wavefront compensating micro-phase plate, producing a high quality output beam.

Heather Booth of Oerlikon reviewed laser applications in photovoltaic (PV) cell manufacture. Heather described the market position, the forecast of technology adoption and the need for capital expenditure per Watt of power to be reduced in order for lasers to be competitive. Drivers for the adoption of new energy sources include the rising cost of energy and environmental concerns. Market demand has produced an exponential growth in PV manufacture and the forecast is for it to continue. Oerlikon Solar are working towards the goal of achieving grid parity by innovating in three areas: (i) Reducing the $/W to make laser technology more competitive; (ii) improving module efficiency; and (iii) improving the economics of scale by using larger fabs. Lasers currently find applications in many areas in the production of PV cells, including patterning, border deletion, edge isolation, ID marking, wrap-through, cutting, doping, defect repair and interconnection. However, most of these applications are only partially adopted or are used only on a pilot line.

Sohaib Khan of NWLEC described the use of CW fibre laser for the production of nanoparticles. The production rate is high and of interest for commercial production as well as for research in-house. Pulsed laser technology is used to make variable sized particles for use in many applications. Applications include: use as an energy converter in solar cells; gas or temperature sensors; solid oxide fuel cell; UV protection; waste water purification; and catalysts and catalyst supports.

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