CHOICE OF LASER SOURCES FOR MICROMACHINING APPLICATIONS

Paper M204

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Abstract

To date majority of the micromachining applications have been addressed with the lamp pumped pulsed Nd: YAG laser. However, the increasing complexity of microelectronics/ engineering devices and the requirement for higher yields and automated production systems place stringent demands on the micromachining techniques. This has led to development of new laser sources fiber and dick lasers etc. These lasers with diffraction limited beam quality offer many advantages such as small spot size, high power density, enhanced processing speeds, reduced heat affected zone for a range of micromachining applications.

In this work, we will provide some processing data achieved with single mode fiber up to 400W average power for a range of materials and compare its processing performance with lamp pumped Nd: YAG laser of up to 300W. The focus of this work is therefore laser microcutting, joining and drilling with both laser sources.

Introduction

A range of industrial lasers are currently available for micromachining applications (Figure 1) and the choice of a laser source for a specific application is no longer straightforward and obvious. Laser users are now faced with additional questions of laser beam quality and brightness etc. For a number of years pulsed Nd: YAG lasers have been the laser of choice when detailed cutting, fine welding and drilling of metals is required. At wavelengths of around 1µm, the focusing optics are smaller and simpler to enable smaller spot sizes than equivalent CO_2 lasers. The need for more efficient, compact and high beam quality lasers for very fine micromachining has fuelled the rapid growth for developing fiber and disk lasers.

Fiber lasers operate at near IR spectral region and offer multitude of advantages over conventional lasers and shows greater promise to open up new micromachining applications. The low power (100-500) fiber lasers are very compact and robust and has an edge over lamp pumped Nd: YAG lasers in terms of beam quality and wall plug efficiency (approx 20%). Current investigations show that the single –mode fiber laser is an efficient, reliable and compact solution for microcutting and micro joining. The diode- pumped technology offers low maintenance cycles and high conversion efficiency. Theoretical pump- light conversions of more than 80% are possible [1] but typical optical conversion efficiencies for Ytterbium double- clad fiber lasers are 60-70% [2]. Average power levels up to 100W are possible with air-cooling. Since the overall efficiency is high, most fiber lasers are powered by standard 110V/230Vsupplies.

In the design of a robust and reliable fibre laser system, a number of other fibre-based components enable the construction of monolithic “all-fibre” laser cavities. The benefits of the all-fibre design have been widely discussed elsewhere [3], with two of the principal advantages being the absence of optical alignment and exposed optical surfaces. Chief amongst these enabling components are the pump combiner and Bragg grating reflector. Figure 2 below shows a schematic of such a fibre laser cavity of our design. The output fibre has a single mode core with a diameter of less than 10 microns which ensures a high beam quality output. This architecture is designed to be capable of producing output powers of up to 500W with a 100,000 hour diode ensemble lifetime in a water-cooled heatsink configuration and up to 120W using forced air-cooling at ambient air temperatures of up to 35C with the same level of diode reliability.

Central to the performance and reliability of the fibre laser system are the pump laser diodes. In the last ten years, multimode diode pump sources emitting many Watts of output power in the 900-980nm wavelength range have become commercially available. Some of these sources have extremely high levels of reliability, with mean time to failure of greater than 500,000 hours under normal operating conditions. By incorporating a suitable level of redundancy, ensembles of such pump sources having a MTBF of greater than 100,000 hours can be used to construct fibre lasers emitting several hundred Watts of output power.

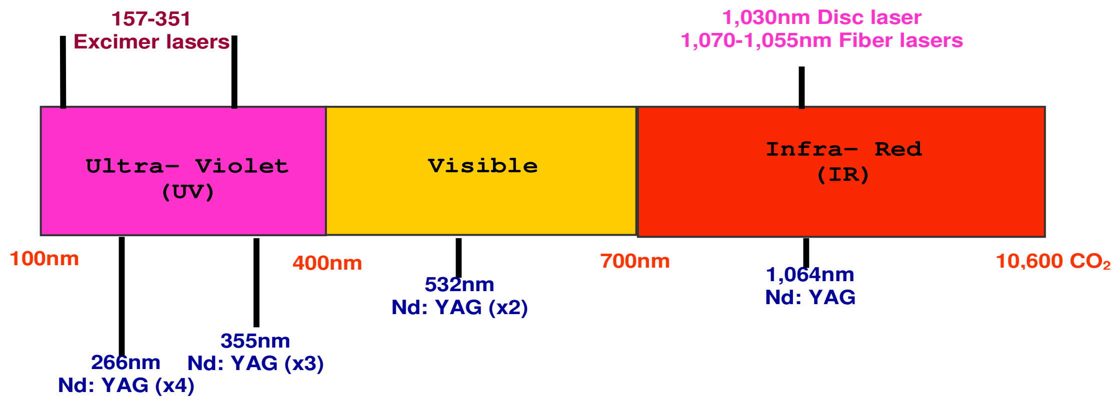


Figure 1: Some of the laser sources for micromachining applications

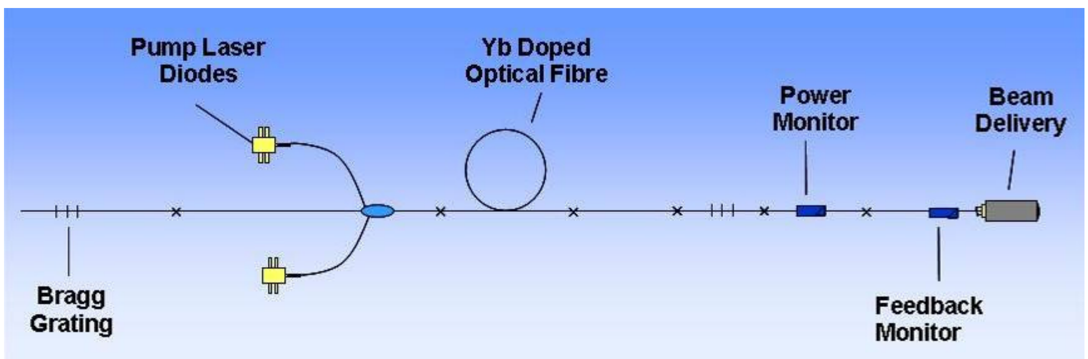


Figure 2: Schematic diagram of single mode fiber laser

Beam Quality / Delivery

When employing such a laser in materials processing applications, delivery of the output beam to the work-piece is an important issue. A fiber laser beam delivery system must protect the fiber end-face from damage due to contamination or back-reflected light from the work-piece. Furthermore, to take advantage of the high beam quality in fine cutting and welding applications, high quality optics and "through-the-lens" viewing are advantageous. We manufacture process and scanning heads. Figure 3 shows a schematic of a PIPA fiber termination designed for high power YAG laser fiber beam delivery of old JK laser products. This patented technology makes use of a fiber mounting scheme and an angled capillary that is robust against back reflection. We are using a variation on this existing design for fiber laser beam delivery.

There is no requirement for separate optical Isolator and the beam expands within the glass to give lower power density at exit, with no loss of beam quality.

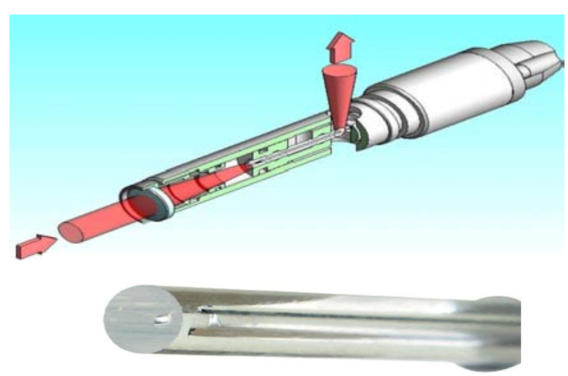


Figure 3: PIPA fiber delivery termination

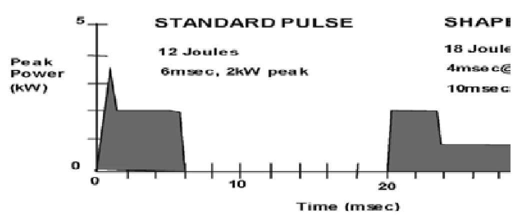
Pulsed / Modulated Performance (Nd: YAG vs. Fiber)

An area where there is a significant difference between lamp-pumped YAG and fiber laser performance is pulsed operation. Lamp-pumped lasers are capable of producing long, multi-ms, pulses with peak powers many times the rated average power of the laser, provided that the duty cycle is sufficiently low. This ability stems from the flash-lamp itself which is often more constrained by the maximum average thermal load than the peak power output (Figure 4a). By contrast, while the semiconductor laser diodes used to pump a fiber laser can be on-off modulated over a wide frequency range as shown in Figure 4b (from DC to tens of kHz in most industrial applications), they cannot typically be over-driven for long periods (multi-ms), in the same way as a flash-lamp, without reducing the lifetime of the device to an un-acceptable level.

Considering the differences in beam quality and pulsed performance between the two types of laser, there are different operating regimes for the two types of laser. The lamp-pumped YAG laser is characterised by long high-energy pulses but poorer beam quality, and the fibre laser with high repetition rate on-off type modulation, single-mode beam quality but low pulse energy.

For the micromachining applications perspective, both of these regimes have their advantages and these are highlighted the following sections.

a)



b)

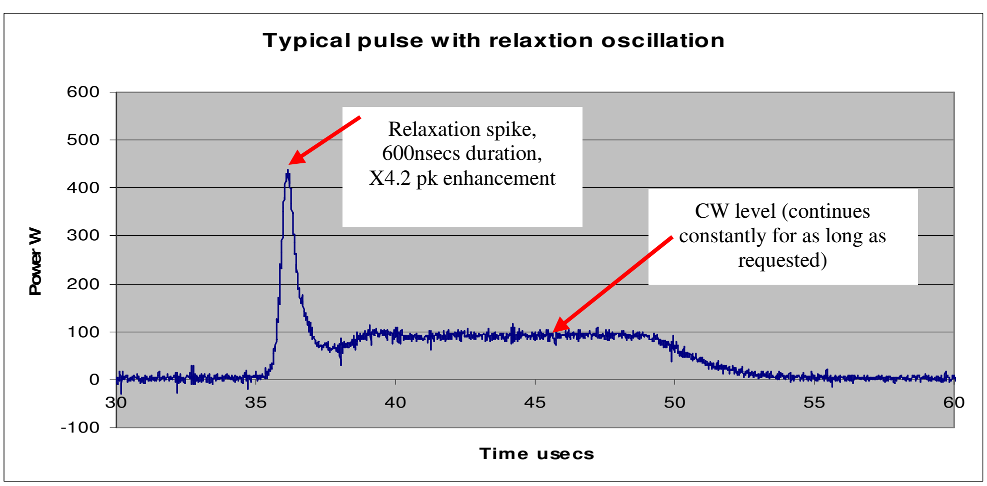


Figure 4: Temporal pulse shapes; a) pulsed Nd: YAG laser; b) single mode fiber laser

Experimental work

Micromachining tests (i.e. microcutting, microdrilling and microjoining) were carried out with two different type of laser sources i.e. pulsed lamp pumped and single mode (SM) fiber laser.

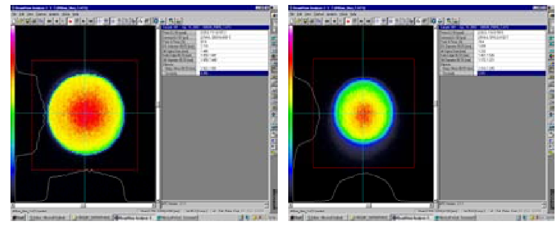
Pulsed lamp pumped Nd: YAG lasers

Three lasers with different beam qualities and laser parameters (Table 1) were used during the micromachining trials. These lasers with their enhanced control and complex pulse shaping facilities offer greater flexibility for processing a range of materials including highly reflectivity materials i.e. aluminium and copper based alloys. The beam from these laser is transmitted through optical fibers which homogenizes the power distribution across the laser beam giving a top hat profile (Figure 5), which produces consistently very round holes (entry and exit). This is very important when producing small holes.

Table 1: Performance data of JK pulsed lasers

Laser parameters	JK100	JK125	JK300
Maximum average power[1]	100W	125W	300W
Maximum peak power[1]	10kW	5kW	9kW
Maximum pulse energy[1]	0.25J	17J	56J
Pulse width range	15µs-200µs	0.1-20ms	0.1-20ms
Maximum frequency	350-2000Hz	1000Hz	1000Hz
Pulse to pulse stability	±1% from cold	±1% from cold	±1% from cold
Beam quality[2]	5 mm.mrad	7 mm.mrad	16 mm.mrad
Fiber diameter	100 um	150um	300µm
Pulse shaping	-	20 sectors	

[1] rated at the end of lamp life; [2]half angle radius



End of optical fiber At focus position

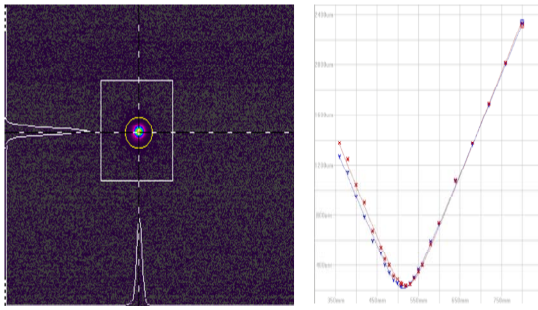
Figure 5: Pulsed laser beam profile

SM fiber lasers

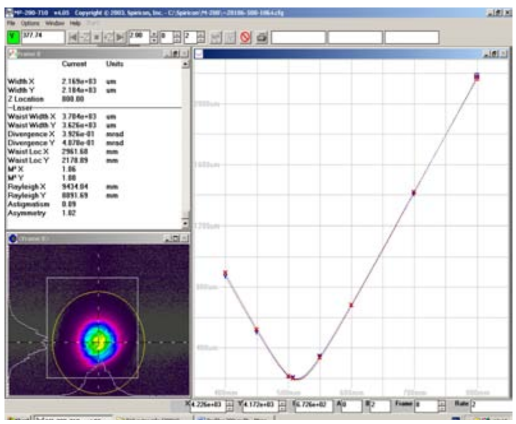
A single mode Ytterbium fiber laser operating at 1080nm wavelength emits a gaussian beam with an M^2 ~ 1.10 (Figure 6). These fiber lasers are capable of producing high brightness and high power densities as high as 10^8 W/cm^2, which is sufficient for cutting and welding thin metals. These CW fiber lasers can also be modulated and provide pulsing capabilities with pulse widths ranging from microseconds to milliseconds. Performance data for these SM fiber lasers is highlighted in Table 2.

Table2: Performance data of SM fiber lasers

Laser Model	JK50 FL	JK100FL	JK200FL	JK400FL
Output Specification				
Average Laser Power	50W	100W	200W	400W
Beam Quality	M2 <1.1, TEM00			
Operating Modes	CW & Modulated. FiberPierceTM option		CW & Modulated	
Wall Plug Efficiency	>25% (@ Spec Power)			
Output Power Dynamic Range	20% - 100%	10% - 100%	10% - 100%	10% - 100%
Min Rise/Fall Time	5µs			
Mod frequency	Maximum 50kHz			



100W SM fiber laser



400W SM fiber laser

Figure 6: Beam profiles of SM fiber lasers

Results and discussion

Microcutting

Thin sheet metal cutting is one of the largest laser cutting applications. Up to recently pulsed lamp-pumped lasers have been preferred cutting laser for fine detailed cutting applications. The high energy densities and fine focused spot size (30um) makes this laser very suitable for fine cutting small features and components in thin metals. Work has demonstrated that very fine cuts can be produced in a range of materials with pulsed Nd: YAG laser [4]. However, the some of new microcutting applications require cutting fine feature <25µm kerf width with very good cut quality i.e. dross free cuts, minimum heat affect zone and distortion of the component.

The microcutting results show that SM fiber produced the best cutting results compare to lamp pumped pulsed laser, so only data obtain with the fiber lasers are reported in this section. Cutting trials were carried out with oxygen and nitrogen assist gases in a range of materials including silicon wafers, alumina ceramics and carbon fiber reinforced plastic composites.

The cutting data for ferrous materials show that the cutting speeds with oxygen assist gas are much faster compare to nitrogen assist gas [5]. When cutting with inert gas, the cutting speed is reduced considerably; however the cut quality is much better. For majority of micro cutting applications edge quality is more important than cutting speed, hence for most microcutting applications inert gas (nitrogen) is normally used.

One of the biggest laser microcutting applications is in the medical industry and use of fiber lasers instead of pulsed lamp pumped Nd: YAG laser has increased. Medical devices are generally quite small for two basic reasons, they often must fit into small areas, or they are made of expensive materials and minimizing their size is cost- effective. Lasers, which can work in areas that require tolerance of only several microns, are an ideal solution for small, costly devices. Probably the most demanding application for micro- cutting in the medical device industry is the cutting of stents. A Stent is a small, lattice-shaped, metal tube that is inserted permanently into an artery. The Stent helps hold open an artery so that blood can flow through it. Stents are cylindrical metal scaffolds that are inserted inside a diseased coronary artery to restore adequate blood flow. The materials used for stents may be 316L stainless steel or nickel- titanium alloys (shape memory alloys). The typical tube diameters are between 1 and 10mm, (Figure 7) with a wall thickness of approx. 100um. The key requirement is a small kerf width (15-20um) and this requires high beam quality and very good laser power stability with the fiber laser offers. The laser cut must have a very good surface quality with very little heat affected zone and no dross. Figure 8 shows SEM micrographs of a typical Stent cut with a 100W SM fiber laser with inert gas. The modulated output produces dross free cuts with very high contour accuracy (< 5µm). Typical cutting speed for 0.5mm thick 316L stainless steel with single mode laser output is approx 5m/min with nitrogen assist gas.

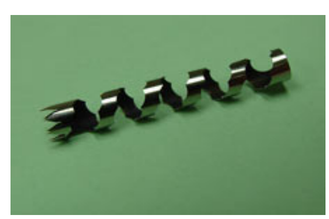


Figure 7: Nitinol tube (nickel- titanium alloy); 50W fiber laser; modulated output, spot size 12µm, argon assist gas

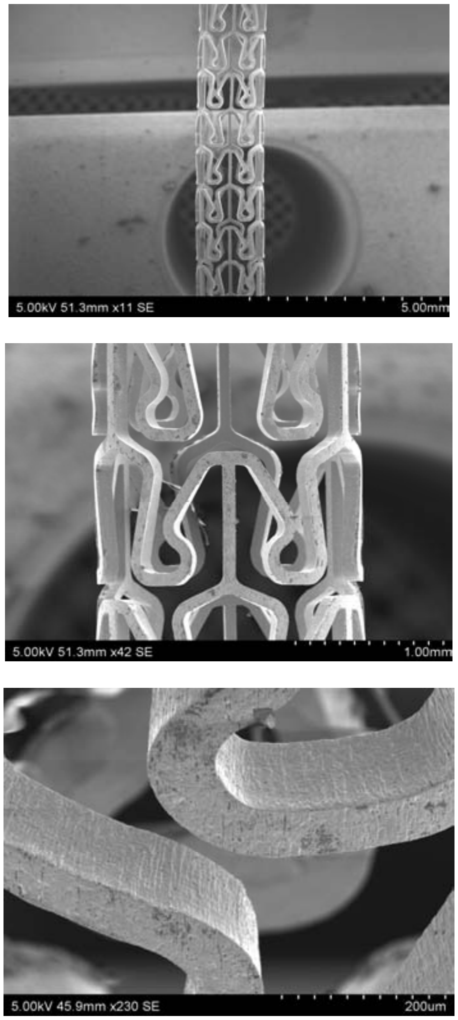


Figure 8: 316SS, nitrogen assist gas, 10µm spot size; modulated output

Another market sector where SM fibers are making big difference is in solar cells and semiconductor. As the cost of the conventional energy continue to increase, the use of solar technology for the production of alternative source of energy is becoming more and more important. This has led to the increase in the production of solar cells and the demand for the right laser source to cut the rectangular wafers from the flat faces of the octagons than further processed to become a solar cell. The laser offers a number of advantages when cutting these very brittle and fragile wafers i.e.

- energy delivered with high directional precision
- high processing speed
- high resolution ,accuracy and high flexibility

For the most applications, they grow silicon in form of wafers that are typically 0.2-1.8mm thick and 100-300mm diameter. From the flat faces of the octagons they laser cut a flat rectangular wafer that is then further processed to become a solar cell. Cutting speed and yield are important to reducing costs. The main requirements for cutting of silicon wafers are dross free and crack free cut edges in a range of thicknesses. Work carried out in the past [6] with both pulsed Nd: YAG and SM fiber lasers on mono and polycrystalline wafers have shown that both lasers are capable of cutting these materials successfully. The SM 100W fiber laser with its very small spot size is very good for producing very smooth cut edges in thin sections <1.0mm. The edge quality is slightly batter than that achieved with a pulsed Nd: YAG lasers because striations appeared to be orders of magnitude less than those with Nd: YAG lasers. To cut thick section wafers (i.e. >1mm thick) with SM fiber laser, high power (200-400W) is required to produce good quality cuts i.e. dross free and reasonably high cut speeds.

The result also show that the pulsed laser with its high peak power and short pulse widths is also well suited for cutting a range of thicknesses (up to 2mm). The microcracking which was < 10µm in length was very similar for both laser sources tested. Typical micrographs of the cut edges for both lasers are shown in Figure 9-10.

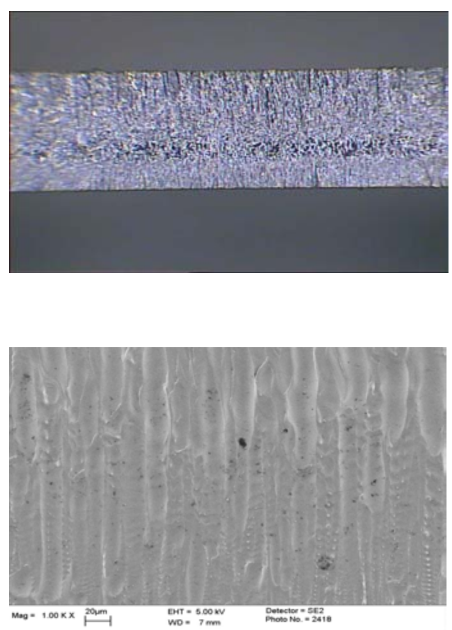


Figure 9: SM fiber cut; 1.8 mm thick wafer, 10 kHz, 350W, >3.5m/min; nitrogen assist gas

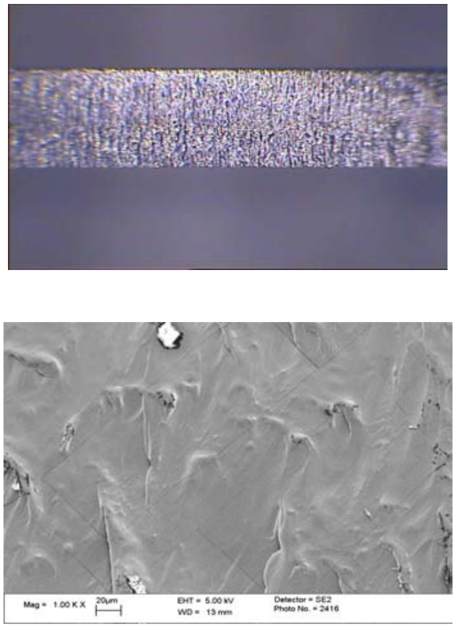


Figure 10: Pulsed laser cut; 2.0 mm thick wafer, .>0.15m/min; nitrogen assist gas

One of the advantages of CW SM fiber lasers is that they can be on-off modulated over a wide frequency range. This can be very useful when machining materials which are prone to thermal degradation i.e. carbon fiber reinforced plastic composites (CFRP). The work carried out with SM fiber lasers so far has shown that it is possible to use the new generation of fibre lasers in both a macro-application of laser cutting and a micro-application of laser surface texturing for adhesive bonding of aerospace structures [7]. The cut edge quality compared to mechanical cutting is superior as highlighted in Figure 11.

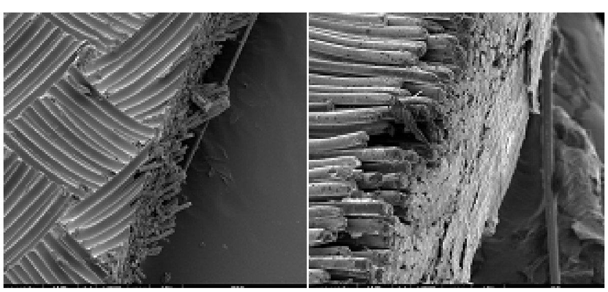


Figure 11**:** SEM image on the left, mechanical cut 500X. SEM image on the right fibre laser cut 1200X

Surface texturing of composites is a viable replacement to mechanical abrading giving better control over the final structured surface. The fibre laser systems have shown that they can machine CFRP with a fine control over the depth of material removed and a high quality surface finish. This ability to machine on the micro scale could give fibre lasers a new role in the aerospace industry as a new tool for laser milling of fine structures in CFRP (Figure 12).

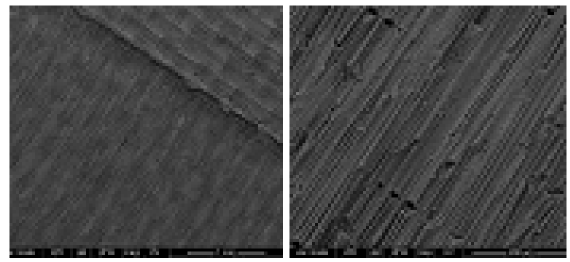


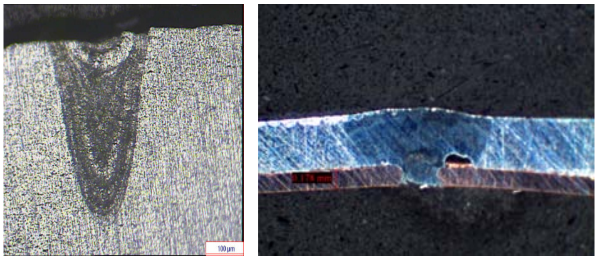
Figure 12: JK200FL micromachined composite surface 200mm/sec, Air. Left: 80X, Right: 500X

Microjoining

Laser welding of dissimilar materials is good example where both laser sources can play very important role. The use of dissimilar material joints is expanding in the rapidly growing advanced energy sector including batteries, large scale energy storage, fuel cells, Gen IV nuclear power, and solar power; as well in advanced oil & gas, and fossil fuel power systems.

Today's requirements on vehicles with internal combustion engine are characterised by more sophisticated emission regulations, rising fuel prices and higher driver's demand on driving dynamic, comfort in line with increased environmental awareness. For that reason, more and more car manufacturers throughout the world are focusing on electric vehicles. The battery technology currently in use is lithium ion batteries because these are smaller and lighter than current automotive power batteries (generally, Nickel Metal Hydride). This technology can provide power equivalent to current technology at a smaller size and lighter weight, or more power at an equivalent size and weight.

The batteries used in the electric vehicle batteries (EVB) are constructed from a combination of different materials and these materials and poses particular challenges to be joined together. In battery and pack manufacture there are a number of similar and dissimilar materials that need to be joined as shown in Figures 13-14.



Al 3003; 0.5mm depth; 0.5mm Al 3003 + 0.25mm C101 copper

Figure 13: 400WSM fiber laser, CW output, spot size 43µm

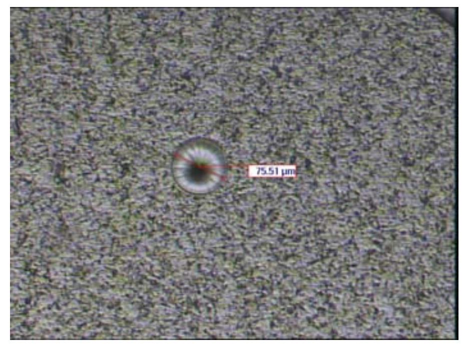
Cu/Al spot welds; Cu battery terminal spot welded

Figure14: Spot welds made with pulsed Nd: YAG laser

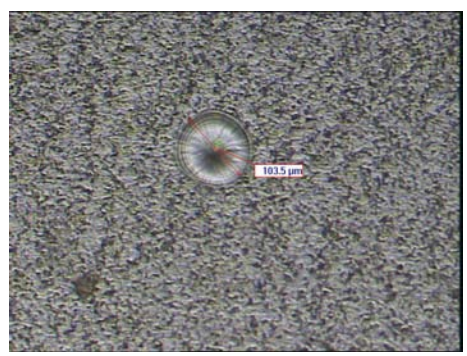
The result show that pulsed Nd: YAG lasers (125-300W) with its pulse shaping capabilities and high peak power can either spot or seem weld a range of materials up 3m thickness, whereas with SM fiber laser it was only possible to join thin material sections up to 2mm thick stainless steels and <1mm with reflective materials i.e. copper and aluminium alloys. The average power needed to join reflective material was 400W and because of its small spot size i.e. 43µm, a grater attention was paid to the jigs and fixturing to make sure that fit of the parts was good. For spot welding applications of reflective materials, pulsed Nd: YAG laser was better than the SM fiber laser. Pulsed laser produces spot welds with large interface width, which is very import to produce strong welds.

Whereas the pulsed Nd: YAG is very good for spot reflective materials, SM fiber laser is best suited for spot welding thin stainless foils. Laser spot welding (20-200um) sheets of stainless steel, which are extensively used extensive, used in electronic industry welding hard disc drive flexures. An essential component of hard drives, suspension assemblies are used in virtually every size and model on the market today. The disk drive flexure components are thin 300 series stainless steel parts with spot welds that join the separate pieces via lap welds. For a number of years lamp pumped pulsed Nd: YAG lasers with an adequate beam quality have been the laser of choice for spot welding Flexures (weld dia approx. 120µm). However, as these devices are getting smaller and smaller, it is very important to have a laser, which has a very good beam quality to produce small spot size to weld these small parts (weld dia <110µm) with consistent weld quality. Because of the high beam quality of the fiber laser, a scanning head can fitted to the laser for this application and this will reduce the cycle time compare to laser/welding solution.

The spot welding tests carried out with a SM 100W fiber laser in thin (20-150µm) 304 stainless foils show that with proper optimisation of laser and processing parameters, it was possible to produce spot welds of various diameters without any spatter. Figure 15 highlights micrographs of the spots welds made with **Gaussian Beam** profile.



30+200µm 304SS; weld dia 76µm



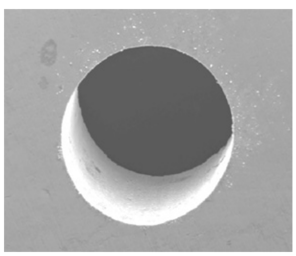
30+30+200µm 304SS; weld dia 104µm

Figure 15: Spot welds with SM 100W fiber laser, fitted with scanning head, spot size 26µm dia

Microdrilling

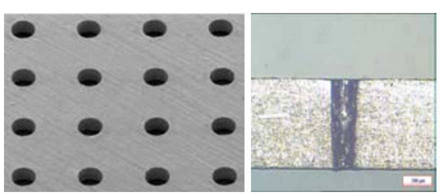
Currently there is a great deal of interest in a number of industries including automotive, aerospace and electronic to drill small (50-70µm) diameter holes in metals and non metals .The quality of these micro drilled holes is very important i.e. taper free, very round ,minimum recast layer and heat affected zone. Microdrilling tests carried out in a range of materials including materials such which are prone to cracking i.e. ceramics, silicon wafers etc. The results show that SM fiber is very good for drilling holes small holes (<50µm diameter) in thin metals (<1mm thick), whereas the pulsed laser with is very good for percussion drilling metals and non metals. Typical examples of micro drilled holes are shown in Figures 16-17.

0.2mm thick 1000 Al alloy; 30µm dia

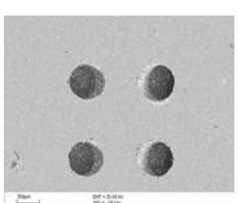


0.5mm thick 304SS; 50µm dia

Figure 16: 100W SM fiber laser, percussion drilled; modulated output



1.5mm thick nickel based alloy; 150µm dia



0.6mm thick alumina ceramic; 50µm dia

Figure 17: Pulsed Nd: YAG laser, percussion drilled

Summary

Laser micromachining has become a key enabling technology in ever-continuing trend of miniaturisation in microelectronics, micro optics and micromechanics. The new laser sources with its high beam quality and small spot sizes can open doors for the new applications i.e.

- Small spot welds/seam width
- Cut very features in a range of materials
- Able to drill small dia holes
- Reduce the cycle time
- Improve the samples quality
- Easy of integration (because of its high beam quality it will be possible to use the scanning head)

Micromachining work carried out with both single mode fiber and a pulsed Nd: YAG laser shows that:

Microcutting

SM fiber laser with its high beam quality and small spot size is the best choice for the microcutting applications. The fine features (10-15µm wide) can be cut with either CW or modulated output. The most important requirement with microcutting applications is the accuracy and not the process speed so it is possible to reduce the laser power and still be able to cut at reasonable cut speed. The output power dynamic range for the fiber lasers is 10-100%, so with 100W SM fiber, it is still possible to produce very stable output at 10W.

Microwelding

Both lasers are capable of welding a range of materials, however the pulsed Nd: YAG laser Nd: YAG laser with high peak power and enhanced control and complex pulse shaping facilities offer greater flexibility for microwelding a range of materials. With correct shaping of the temporal energy variation in pulse (pulse shaping) it is possible to produced good quality welds in a range of materials including highly reflectivity materials i.e. aluminium, copper alloys and dissimilar materials. Low power (50-100W) SM fiber laser is very good for fine spot welding application in thin foils.

Microdrilling

Low power (100-125W) pulsed Nd: YAG laser with its high pulse energies and peak power capabilities is best suited for fine percussion drilling in a range of materials including crack sensitive materials i.e. alumina ceramics, silicon wafers etc. SM fiber is ideally for drilling holes <50µm dia in thin foils.

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Meet the author

Dr. Mohammed Naeem is Materials Process Development Group Leader. He received an MTech degree in metallurgical quality control from Brunel University (UK) in 1981 and a Ph.D. in glass fibre composites from Loughborough University of Technology (UK) in 1985. He has over 18 years of experience in the support of industrial lasers with GSI Group, Laser Division and has published over 150 papers on laser material processing. He has previously served as Materials Processing Manager and held several Important Engineering Development roles.