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Micromachining electrical grade steel using pulsed Nd-YAG lasers

M.J. Jackson [a,*], G.M. Robinson [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

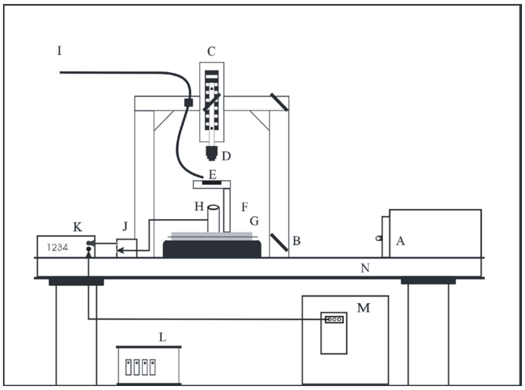
Purpose: Multi-wavelength capability allows diode pumped, solid state (D.P.S.S.) lasers to perform operations such as micro machining in a variety of materials such as ceramics, metals, and polymers. Results from this study reveal how traditional plasma-controlling gases have a detrimental effect on the surface morphology of machined components. The paper explains how the machining of thin plates of silicon steel can benefit the rapid production of electrical components such as transformer cores and dynamo pole pieces.
Design/methodology/approach: A series of experiments was performed to investigate how shielding gas environment and gas pressure affect the ability to cut and machine silicon steel. The experiments were designed to show the differences between the use of various assist gases that shield the machining zone.
Findings: The results of the work indicate that oxygen shielding gases allow silicon steel to be machined at a faster rate than using helium, argon, and air. However, the surface roughness produced is highly dependent on assist gas used and the pressure at which it is delivered.
Research limitations/implications: The results presented imply that assist gases perform a variety of functions and further research is required to understand how the assist gases improve machinability when machining different workpiece materials.
Practical implications: The practical implications of this research indicate that a significant amount of research effort is required to optimize the type of assist gas used in laser micromachining of engineering materials.
Originality/value: The paper reveals how assist gases interact with both laser and the surface of workpiece materials. It is of practical value to microengineers and micromachinists working in the field of micro and nanomanufacturing.
Keywords: Micromachining; Lasers; Micro Electro Mechanical Systems (MEMS)

1. Introduction

High efficiency manufacturing techniques are required in the micro-machining arena to realise the potential benefits applied to electrical engineering industries [1-5]. Micromachining with lasers is an area that is receiving increasing attention due to the development of industrially rugged, diode-pumped, solid-state (D.P.S.S.) lasers operating at short wavelengths with excellent beam quality and short pulse lengths. These factors result in a small kerf width, a small heat affected zone, and increased machining rates. Therefore, an effective manufacturing process incorporating lasers can be established. Factors that limit the efficiency and precision obtainable using laser sources are important parameters that need to be quantified. This paper focuses on the effects of gas environments and inlet gas pressure on the quality of micro machined silicon steel plates.

2. Experimenal method

The experimental apparatus used for the experimental investigations is shown in Figure 1. Experimental samples were placed in an experimental unit fixed to the y-axis of a high precision, linear air bearing, x-y-z co-ordinate worktable, with a working envelope measuring 200x200x150mm. The laser used in the series of tests was a diode pumped solid state Nd:YAG laser. Maximum average powers of 8 W, 5W and 3W are available at 1064 nm, 532 nm, and at 355 nm. The material used to perform the experiments was 4.5% silicon steel.



A = Laser head B = Turning mirror C = z-axis
D = Microscope objective E= Sample F = Sample holder
G = x-y table H = Filter and photodiode I = Argon feed pipe
J = Photo-amplifier circuit K = Timer counter L = U500 controller
M = Chiller N = Optical table

Fig. 1. Schematic diagram of laser machining apparatus

It should be noted that the distance between the nozzle exit and the workpiece was 1mm. This allowed the gaseous environment to completely engulf the area of processing. Once machining had begun, average pulse energies were measured with a calorimeter, and laser spot sizes were found using a pinhole and fast photodiode arrangement. An argon side jet was used to prevent damage to the optics when processing in air. When the samples were in a satisfactory position to be machined, a gaseous environment was used to protect the surface of the material and to aid the action of machining. The gases used were oxygen, air, argon and helium. Machining was carried out using a range of velocities between 0.1mm/min to 50mm/min. As most samples exhibited a significant re-cast layer of molten material, experimental samples were observed after processing using optical and scanning electron microscopes.

3. Experimenal results

An attenuation of machining rate is observed if the etch rate experiments are conducted on a variety of materials with varying thickness. The extent of attenuation is shown in Figure 2. It is interesting to observe how the etch rates are similar up to 10 GW/cm^2. Above this value of intensity, the thickness of the material affects the etch rate. Below this value, etch rates are very similar. Below 10 GW/cm^2 the material is ejected through small-scale evaporation of the metal. Experiments concerned with quantifying the effects of changing the gaseous atmosphere were performed in the same way as the previous experiments with the exception of using a gas jet to investigate how etch rate and geometry of the machined part were affected [6-12].

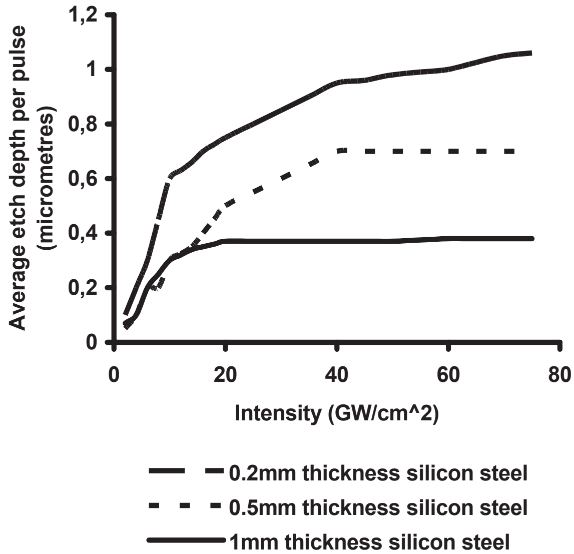


Fig. 2. Etching rate as a function of intensity machining 0.2mm, 0.5mm, and 1mm thickness silicon steel at 1064nm wavelength

The gases chosen for the exercise were helium, oxygen, air, and argon. Each of the gases led to a reduction in machining rate with an oxygen jet leading to the greatest attenuation in etch rate. From Figure 2, we can see that the maximum average etch rate in ambient air when using 1mm thickness silicon steel was 0.4µm per pulse. The attenuation in machining rate is shown in Figure 3.

Figure 4 illustrates how the etch rate varies as a function of oxygen pressure. As the pressure is reduced, then the etch rate is shown to increase. Again, this supports the explanation of the suppression of the ejection mechanism with the high-pressure gas jet. Machining experiments involved machining 0.2mm and 0.5mm thickness silicon steel at feed rates between 0.1mm/min and 50mm/min.

An oxygen jet allows faster machining rates than those obtained when processing with the other gases used in the exercise. This illustrates the contrast between machining and drilling. The results show how the geometry of the interaction event in machining enables the ejection of melt from the bottom of the kerf, and the suppression of plasma, thereby allowing machining to proceed at a faster rate. The exothermic oxidation reaction can add a significant amount of energy to the machining process. Figure 3 shows a scanning electron micrograph (S.E.M.) of a machined trench in 0.5mm thickness silicon steel using 1064nm radiation at 47GW/cm^2 and an 8 bar pressure oxygen jet. The trench is surrounded by a coloured residue that is easily removed. The predominant alloying element is silicon. Unfortunately, silicon inhibits the laser machining process by preferentially migrating to the surface of the melt as a result of its high affinity for oxygen. Silicon initially reacts with the oxygen in the gas jet to produce a surface layer on the cut front of silicon dioxide (SiO_2). This forms a semi-impermeable seal over the underlying material, thereby inhibiting the reaction between the oxygen and the melt. Movement of the melt under the influence of the jet continuously ruptures the outer layer and allows the passage of oxygen to migrate to the front of the cut. The edges left after removal of the residue have different material and mechanical properties from the bulk of the material, and therefore further processing that involves various etching and plating processes must be performed to prevent deterioration of mechanical properties and affecting the performance of a laser machined component. In contrast, machining with an inert gas results in the formation of a pronounced recast layer that stands proud of the surface as shown in Figure 3. Figure 3 shows a laser-machined trench in 0.5mm thickness silicon steel at a feed rate of 1mm/min using helium as the assist gas. Machining with helium, or argon, leads to the formation of an oxide-free edge, which when examined with a S.E.M. shows a considerable re-cast layer of high hardness that is difficult to remove. Figure 3 shows the effects of processing in air and argon using 8 bar inlet gas pressure. Again, an extensive re-cast layer is observed.

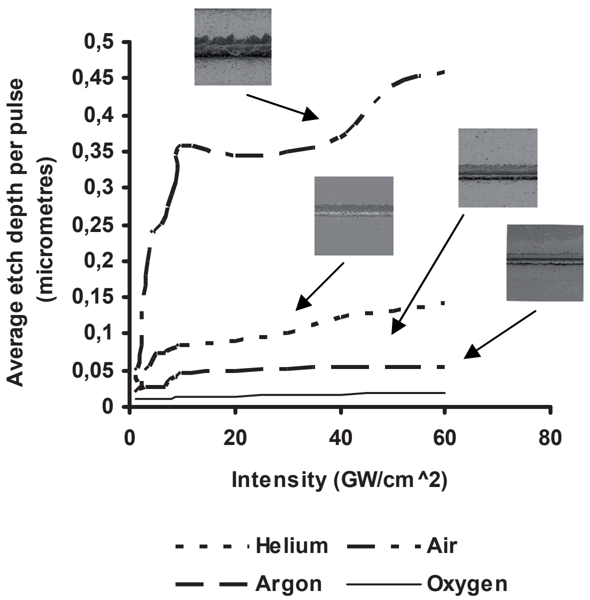


Fig. 3. Etching rate as a function of intensity machining 1mm thickness silicon steel using assist gases at a pressure of 8 bar

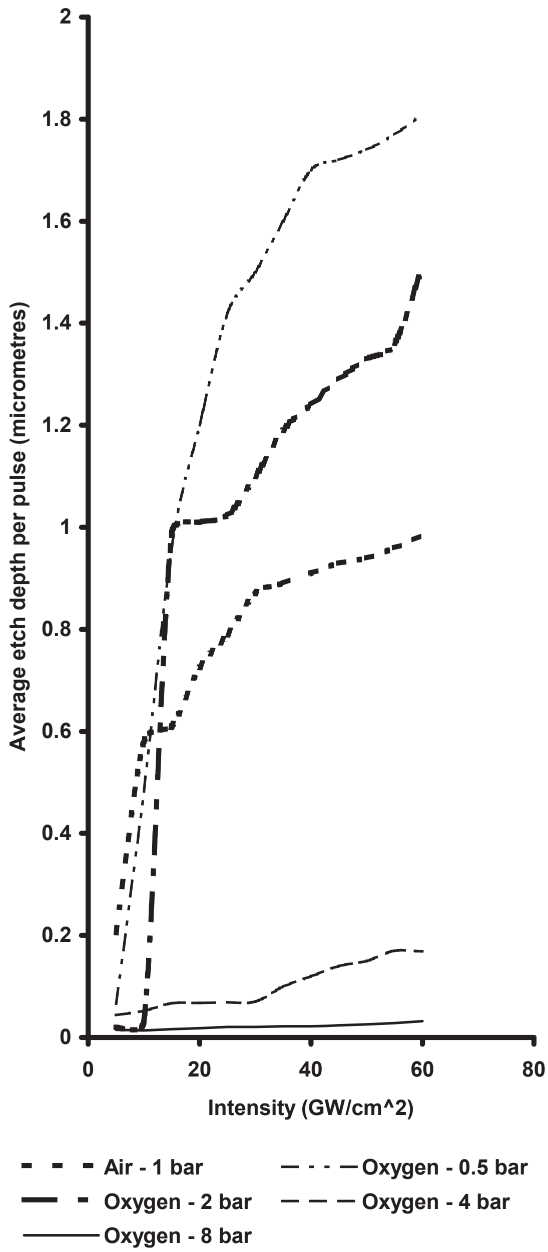


Fig. 4. Etching rates as a function of intensity as gas pressure at the surface increased

4. Discussion

There are a number of reasons for the attenuation of etch rate observed when using the gas jets, including the formation of various oxide particulates that attenuate the incoming beam. Results from previous experimental work [8] have shown how a gas jet can both help and interrupt the drilling event. The jet was shown to impede the ejection of the melt from the hole. When the laser had penetrated the material, the assist gas was shown to help the ejection of the melt and vapor from the hole. Therefore during drilling significant attenuation of the incoming beam interacting with the material in the hole reduces the etch rate due to melt and vapor ejection. The acoustic retort associated with the process was observed to be significantly louder when processing with 8 bar pressure of argon gas than the retort observed when processing with air. Conversely, when processing in 8 bar pressure of helium gas, the retort was significantly less than the retort in air. The oxygen retort is attenuated as the laser etches through the material, eventually becoming virtually inaudible. Again the retort is significantly less than the retort heard when using argon gas. Acoustic retorts are associated with the ejection of material through a number of mechanisms [9]. These include evaporation pressure [10], differential thermal expansion, and spallation. Machining experiments involving the use of a high-pressure helium gas jet are significant. Although processing with oxygen allowed machining to proceed at a faster rate than when processing in air, helium or argon, by observing the fluorescence of a fluorescent card placed underneath the laser beam it was observed that helium was able to penetrate the material at considerably faster velocities than when applying any other gas environment. Examination of the helium processed samples by optical microscopy and S.E.M. showed that the cut tracks had sealed behind the cut front unlike cuts made using oxygen gas. The momentum transfer occurring between the incoming directed jet of helium and the ejected metal particles and vapor is insufficient to remove the metal from the kerf. Very little plasma activity is observed during helium gas processing. Helium has a pronounced cooling effect on the ejected particulates and metal vapor, causing re-solidification of the melt and incomplete ejection of the particulates. A considerably reduced retort is observed, thereby implying the formation of significantly attenuated shock waves, which will significantly reduce the mass ejected during processing. S.E.M. analysis of a helium cut shows the formation of considerably smaller melt droplets due to condensation of the metal vapor resulting in reductions in the size of molten particles ejected due to attenuation of the acoustic retort. Recent studies have indicated that similar difficulties can occur when processing other materials such as M2 tool steel [11-12], tool steels [13] and silicon surfaces [14-15].

5. Conclusions

Processing of silicon steel in a controlled environment using directed gas jets has its associated problems. Therefore, careful optimisation of the gas jet, laser wavelength, and intensity is needed to ensure optimum processing of silicon steel. During percussion drilling experiments using a directed gas jet the etching rate is seen to decrease, whereas in a machining situation, a high-pressure gas jet leads to an increase in machining efficiency. There are problems associated with the use of gas jets leading to post processing issues that need to be addressed before large scale manufacturing of pole pieces and transformer cores can take place. For some manufactured parts, the associated heat affected zones, sub-surface micro cracking, and recast layers when processing with a nanosecond pulsed D.P.S.S. laser are unacceptable. Therefore other processing options must be investigated such as the use of ultra-fast laser machining techniques, and changes in the design of nozzles that deliver shielding gases, which should lead to significantly reduced recast layers and heat affected zones.

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