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Determination of optimum parameters using grey relational analysis for multi-performance characteristics in CO_2 laser joining of dissimilar materials

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ABSTRACT

This study concerns the employment of grey relational analysis to determine the optimized joint characteristics in CO_2 laser lap joining of dissimilar materials classes. The joint characteristics, namely weld strength, weld width and kerf width are optimized as a function of laser power, its stand-off distance and the speed of welding. Due to a number of experimental constraints pertaining to joining polymer and glass-ceramic substrates, a full-factorial experiment is considered. Detailed images of the welded samples show the formation of crystallized glass leading to the failure of the joint. Thereafter, grey relational analysis (GRA) is employed to characterize the multiple quality characteristics of welded joint in terms of a relational grade. The set of the optimized processing parameters is determined based on the highest grade at 40 W laser power with a welding speed of 10 mm/s at a stand-off distance of 37 mm. Analysis of variance (ANOVA) is then carried out to ascertain the relative influence of process parameters on the joint characteristics. It was found that the weld speed has dominant effect on joint characteristics in comparison to stand-off distance at a fixed laser power.

1. Introduction

The demand for efficient, low cost and reliable products has encouraged the use of non-conventional manufacturing processes and non-metallic materials. The objective of achieving functional and smart micro-electro-mechanical systems (MEMS) sensors has led to the extensive use of combined materials constitute of polymers, glass, metal and ceramic that can sustain high-temperatures, fluctuating pressures and oxidation/corrosion surroundings. MEMS based sensors have gained particular importance due to limited capabilities of silicon-based sensors in adverse conditions. However processing of these materials can be delicate especially while joining two or more dissimilar materials due to large differences in chemical and physical properties.

In recent year′s use of Lasers in manufacturing processes has increased considerably. Compared to conventional techniques it offers a number of advantages. For instance conventional welding techniques such as gas tungsten arc welding offer reliability but may lead to significantly larger heat affected zone (HAZ). On the other hand, laser joining leads to localised non-contact thermal heating process resulting in small heat-affected zone. In addition, it allows materials to be welded where accessibility is virtually difficult especially in MEMs packaging and micromachining.

In a typical laser lap joining process, the top material is usually transmissive while material at the bottom is absorptive. At the interface, as a result of generated heat and subsequent localized melting, a joint is created. The selection of the type of laser and its optimum operating parameters is dependent on material′s absorptivity at a particular wavelength and is often responsible for achieving strong weld joint. For joining dissimilar materials, various types of lasers have been used such as Nd:YAG, diode and fibre lasers at various combination of power (or energy) and wavelength. For instance, Wahba et al. [1] investigated the use of a 700 W diode laser (807 nm) to weld thixomolded Mg alloy and polyethylene terephthalate (PET). In their investigation, high joint strength was characterised by bubbles expansion of different morphologies. An increase by 15% was reported if the alloy is grounded prior to joining, creating non-structured pores that allow melted plastic to flow into and consequently form an additional mechanical anchor effect. On the other hand, Mian et al. [2] utilised a significantly low power of 2.2 W fibre laser

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(1100 nm) for joining polyimide to titanium. At this state, joint strength was influenced by adherence of re-solidified polyimide to titanium surface. They found that large bond width offers substantial weld strength. Instead of using continuous wave (CW) laser mode, Yusof et al. [3] employed a pulsed Nd:YAG laser (55.8 J/pulse at 1064 nm) to weld aluminium alloy (A5052) and PET. Their analysis showed that pulse duration has insignificant effect on weld strength as compared to pulse energy. They also reported high weld strength attributed to the formation of molten pool at the interface with sufficient depth that also resists shear deformation. The shear strength was found to increase by 36% if the alloy is anodized prior to joining.

A recent review by Tamrin et al. [4] points to the fact that there is fewer literature available pertaining to the use of CO_2 laser for laser lap joining of dissimilar materials classes owing to a number of reasons. For instance the CO_2 wavelength has high absorption coefficient. In certain non-metallic materials this can lead to chemical degradation, melt shearing and vapourisation. Also, due to its large wavelength, CO_2 laser has large beam spot size in comparison to other lasers. Consequently, this causes large bond width which is undesirable when laser is applied to heat-sensitive device and material. For these reasons, the use of CO_2 laser is mainly for the cutting and drilling purposes since it interacts well with many ferrous and non-ferrous metals, and non-metals.

While bio-compatible polymers, used in MEMS and Bio-MEMS, can be easily decomposed due to high absorption coefficient at CO_2 wavelength. Choudhury et al. [5] demonstrated the application of a 500 W CO_2 laser trepanning on polymethyl methacrylate (PMMA) and acrylonitrile butadiene styrene (ABS) polymer sheets. As described by Powell [6], interaction with CO_2 laser causes PMMA to undergo vapourisation while PMMA is subjected to melt shearing. Since vapours are easily ejected by assist gas than the liquid, PMMA produced good circularity as compared to ABS.

Ceramic is widely used in similar applications as insulators due to its high resistance to heat. Ceramic has high toughness and can stand high temperatures, but it is brittle and tends to crack/facture due to thermally induced stresses. Interestingly, Lumley [7] showed the possibility of using a CO_2 laser to cut ceramic using a technique known as controlled fracture. Tsai et al. [8] extended the technique to demonstrate cutting of up to 10 mm thick ceramic using two different lasers. They had to initially scribe a crack grooved using a focused Nd:YAG laser before subsequent induced thermal stress generated by a defocused CO_2 laser.

Use of CO_2 laser in cutting of polymers and ceramics is fairly wide. However joining of these materials using CO_2 laser is usually cumbersome. It is desirable as well as cost-effective to use a single type of laser for cutting as well as joining processes. The aim of study is to utilise a CO_2 laser for simultaneous cutting and subsequent joining of polymer and glass-ceramic. However, the latter process is the focus of this study. Here an attempt has been made to use the available CO_2 laser for laser joining of glass-ceramic and plastic.

Usually laser welds are characterized by their strengths, heat affected zone and weld width. These depend on a number of processing parameters including power of laser source, speed of welding, laser stand-off distance, assist gas pressure and laser wavelength. Therefore joining these two materials is difficult and needs characterisation. In order to study such high process variability, generally statistical methods are employed to determine the optimum process parameters.

This study uses Grey rational analysis (GRA), a statistical technique proposed by Deng [9], to optimise process parameters based on multiple quality characteristics of dissimilar material laser joining. Grey system theory has been widely used for laser joining of similar materials and has shown useful results especially in situations where the data is limited and/or incomplete. Investigating the laser joining process of thermoplastic materials, Acherjee et al. [10] used Taguchi method along with GRA technique to determine the optimized weld strength as a function of power of laser, speed of weld and defocal position. In the case of laser joining using a pulsed laser, one has to deal with numerous process parameters such as (1) types of shielding gas and its pressure, (2) laser energy, (3) welding speed, (4) defocal position, (5) pulse repetition rate, and (6) pulse width and shape. To characterize such high process variability for welding titanium alloy plates, using similar technique Pan et al. [11] acquired weld strength with (1) high ultimate tensile stress, (2) small HAZ, (3) large depth to width ratio of weld, and (4) low roughness of surface. However, the applications of GRA for optimizing laser lap joining process of dissimilar materials classes having multiple quality characteristics have not been yet studied. Here we report a full-factorial method in combination with GRA to optimise the laser lap joining process with consideration of multiple weld qualities such as joint strength, width of weld and HAZ. The experiment is described in the following section.

2. Experimental methods and measurements

2.1. Laser lap joining process

In a laser lap joining, two pieces of clamped materials are illuminated using a concentrated laser beam. Usually, the transparent material at the top transmits laser heat to the lower absorbent surface to allow melting at the interface. The joint is formed once the material′s interface re-solidifies. Detailed description of laser lap joining process and parameters affecting the process and weld strength are discussed by Tamrin et al. [4].

2.2. Specification of laser

All experiments were performed using a CO_2 laser (Zech Laser ZL1010 workstation and ZLX5 beam generation system) having maximum output power of 500 W with mode structure of TEM_{01}. A three axes CNC-controlled working table is also used for the experiments. It is noted that the laser power can be varied in the interval of 100 W from 100 W to 500 W. During preliminary tests it was observed that within this power range, the absorbed heat source causes the ceramic to be cut into two pieces instead of producing the intended joint. This clearly shows that the power used was far beyond the requirement of the laser joining process. For this reason, the laser power was turned down to a factory-fixed power at 40 W. As a result, the effect of laser power on the intended measurements can no longer be investigated. Therefore, all experiments were conducted using laser operating at 40 W in the continuous mode.

2.3. Selection of welding parameters

The process involves a number of fixed and variable parameters. The fixed parameters are nozzle diameter, material thickness and laser power whereas the variables are welding speed, and stand-off distance. In the experiments, the supply of assist gas (a mixture of compressed air and nitrogen gas) was turned off. Although assist gas helps to contain excessive burning of ceramic (flame observed) but removal of molten ceramic during the process by the assist gas results in thinner ceramic joint. This consequently results in much reduced weld strength.

The clamping pressure is kept constant at an optimum pressure. The optimum clamping pressure was found through a series of experiments at different clamping pressure with fixed laser processing parameters. The highest measured tensile load was