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Multiple-objective optimization in precision laser cutting of different thermoplastics

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ABSTRACT

Thermoplastics are increasingly being used in biomedical, automotive and electronics industries due to their excellent physical and chemical properties. Due to the localized and non-contact process, use of lasers for cutting could result in precise cut with small heat-affected zone (HAZ). Precision laser cutting involving various materials is important in high-volume manufacturing processes to minimize operational cost, error reduction and improve product quality. This study uses grey relational analysis to determine a single optimized set of cutting parameters for three different thermoplastics. The set of the optimized processing parameters is determined based on the highest relational grade and was found at low laser power (200 W), high cutting speed (0.4 m/min) and low compressed air pressure (2.5 bar). The result matches with the objective set in the present study. Analysis of variance (ANOVA) is then carried out to ascertain the relative influence of process parameters on the cutting characteristics. It was found that the laser power has dominant effect on HAZ for all thermoplastics.

1. Introduction

Thermoplastics are increasingly being used in biomedical, automotive and electronics industries due to their excellent physical and chemical properties. In particular, thermoplastics offer significant advantages over thermoset and elastomer because of their fatigue resistance and high fracture toughness upon reheating and remoulding processes. As the name implies, thermoset cannot be reheated and remoulded once formed. Although elastomer possesses exceptional elastic property, it is limited to applications where large deformation is soughed while structural rigidity is compromised and thus it is being used in flexible tubing. Examples of mostly used thermoplastics are polymethylmethacrylate (PMMA), polycarbonate (PC) and polypropylene (PP).

PMMA is considered as a breakthrough polymer with excellent biocompatibility especially with human tissues and superior resistance to chemically adverse environments. PMMA has been used for bone cement, prostheses, intraocular lens and dentures [1]. Due to low frictional coefficient, PMMA has also been found useful as a main substrate in biomedical micro-electromechanical systems (Bio-MEMS), such as biosensors and biomechanical devices [2]. On the other hand, PC appears to be good electrical as well as thermal insulators. Use of PC is gaining popularity especially in consumer electronics products substituting glass substrate which is inherently brittle and heavy. PC is usually found as a protective cover for display screens (e.g. LCD, plasma, e-ink). Although PP possesses inferior mechanical properties compared to PC, however use of PP in automotive parts is reported to be 5.5 times more than PC [3] particularly in door panels, instrument panels, bumpers and door trims. This is primarily due to its reasonable impact/stiffness balance (deformability) and light weight nature.

Since applications of polymers are myriad, the demand for efficient manufacturing processes producing high-volume, low cost and reliable products has spurred the employment of non-conventional manufacturing processes and non-metallic materials. In the past decade or thereabout, lasers of different wavelengths and characteristics have been used extensively in manufacturing industry to manufacture various electromechanical components for automotive, aerospace, electronics, and biomedical applications. The overall advantages of lasers appear far outweigh conventional cutting techniques in terms of improved cut quality, reduced heat-affected zone (HAZ) and speed of cutting process. Since it is a non-contact process, laser cutting does not introduce any unwanted mechanical stresses which also allows thin materials of several hundreds microns to be cut with ease and precision. In certain applications where accessibility is virtually impossible,

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laser cutting seems superior in many aspects. Similarly, lasers can also be used to cut complex three-dimensional shape and geometry.

Laser cutting is a straightforward but the process itself is intrinsically multifaceted underpinned by complex interaction between various laser processing parameters (laser power, speed of cutting, assist gas pressure) and materials properties. PMMA, PC and PP are grouped under thermoplastics and laser cutting of these thermoplastics is predominantly influenced by melt shearing [4]. Zhou and Mahdavian [5] showed that the effect of cutting speed is more significant than that of laser power on the depth of cut of PMMA. The variation in cut depth is more pronounced for cutting speed less than 20 mm/s. The study however did not consider the effect of assist gas for removing molten plastic. By neglecting the effect of assist gas pressure, the cut depth was found to decrease exponentially with cutting speed at various laser powers ranging from 6 W to 60 W. In addition, a theoretical model was introduced to estimate the depth of cut as a function of material properties and cutting speed. The model however did not include the influence of laser power.

Following this, Davim et al. [6] evaluated the effect of cutting velocity and laser power on surface qualities of a two-dimensional irregular PMMA substrate, namely surface roughness, dimensional precision and HAZ. Nitrogen was used as an assist gas for the experiments at a constant pressure of 0.5 bar. It was found that the HAZ increases with laser power but decreases with cutting velocity. On the contrary, the surface roughness increases with a decrease in laser power and increase of cutting velocity. Davim et al. [7] further investigated the effect of laser processing parameters on HAZ and burr characteristics of PMMA, PC, PP and thermoset plastics. In this extensive study, the input parameters (laser power, cutting speed and assist gas pressure) were varied randomly resulting in a total of 59 experiments. The HAZ for all three types of polymers exhibit similar pattern as the earlier study suggested [6] while the cut quality of PMMA was found relatively better than the rest. The experiments can be considered costly and time consuming due to non-utilization of appropriate experimental design techniques.

For this reason, in our previous article [8], several analytical models were proposed to predict the performance and optimal response by correlating various process parameters. Surface response methodology (RSM) was also employed to systematically develop some of the mathematical models relating laser cutting parameters (laser power, cutting speed and compressed air pressure) with surface quality of the cut, such as surface roughness and HAZ of PMMA, PP and PC substrates. The HAZ was found to have linear proportionality with laser power, while an inverse trend was observed with the cutting speed. Both trends conform with the earlier findings [5–7]. In addition, for the first time, it was established that HAZ is also inversely proportional to the compressed air pressure. Nevertheless, it was found that the effect of laser power is more dominant compared to both cutting speed and compressed air pressure. Moreover, surface roughness is inversely proportional to all input parameters.

Although RSM showed some success in formulating the mathematical relationships between multiple input and optimized response variables using a sequence of designed experiments [9,10]; the problem becomes more complicated and challenging if more output parameters are considered with higher number of samples. In brief, the number of mathematical models that needs to be developed in RSM can be calculated as the product of the number of output parameters and the number of samples. This is considered mathematically exhaustive and laborious if RSM were to be fully-utilized in laser cutting of different materials.

Additionally, multi-objective optimization techniques have proved useful at determining the optimized set of process parameters by taking into consideration all measured cutting characteristics. For instance, due to limitation of single-objective optimization of Taguchi method, Dubey and Yadava [11] resorted to principal component analysis with orthogonal array to determine the multi-objective optimization of Nd:YAG laser cutting of nickel-based superalloy sheet. The corresponding optimized process parameters for minimum cut characteristics (kerf taper, kerf deviation along the length and kerf width) were found at low oxygen pressure, short pulse width, medium pulse frequency and low cutting speed. Using ANOVA analysis, cutting speed (48%) was found to be the most significant factor followed by pulse width (33%). In a different study, Pandey and Dubey [12] combined Taguchi method with fuzzy logic theory to optimize multiple responses in laser cutting of highly reflective and thermally conductive Duralumin sheet. The set of optimized parameters were determined based on the highest fuzzy multi-response performance index at high gas pressure, high cutting speed, low pulse width and low pulse frequency. In this particular study, oxygen gas pressure (61.3%) was the most dominant factor followed by pulse frequency (34.5%). Chen et al. [13] employed Grey relational analysis to optimize CO_2 laser cutting of 6 mm thick PMMA. By considering two performance characteristics (high transmittance ratio and small surface roughness), the optimized parameters were determined at medium assisted-gas flow rate, minimum defocussing distance, low pulse frequency and high cutting speed. Of these factors, assisted-gas flow rate and beam defocussing distance have the dominant influence on the quality of cut surface. For more details readers are referred to a comprehensive review of single-objective optimization techniques by Benyounis and Olabi [14].

This study uses Grey rational analysis (GRA), a discrete statistical analysis proposed by Deng [15], to optimize process parameters based on multiple laser cut quality characteristics of different thermoplastics. Use of GRA was demonstrated useful for multiple-objective optimization in laser joining of similar [16] and dissimilar [17] materials, aimed at achieving high joint strength [18] with reduced HAZ. Since laser cutting is similar to laser joining in nature, GRA has proven to be effective in laser cutting of materials [13,19,20]. However, the applications of GRA for optimizing laser cutting process of different polymers having multiple cut quality characteristics have not been yet studied. In this regard, GRA is foreseen to be vital in high volume, precision laser cutting for automotive, aerospace, electronics, and biomedical applications, with objectives to get precise cut as close as the desired dimension with minimal heat affected zone. Here we report the use of GRA to optimize the laser cutting process of different thermoplastics (PMMA, PC and PP) with consideration of multiple cut qualities such as HAZ and cut precision. The experiment is described in the following section.

2. Experimental methods and measurements

2.1. Laser cutting process of thermoplastics

Laser cutting of non-metallic materials involves three mechanisms namely, melt shearing or fusion, vaporization and chemical degradation [4]. Generally, one of those mechanisms is dominant over the rest for a particular type of material. In the case of thermoplastic polymers, laser cut characteristics are largely influenced by melt shearing. The process also depends on the wavelength of the adopted laser source, that is, infrared laser works differently from ultraviolet laser with respect to material's absorptivity. Usually, a CO_2 (infrared) laser is employed as it couples well with thermoplastics. When a laser beam is incident onto a polymer substrate majority of the thermal energy is absorbed