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A State-of-the-Art Review of Laser Welding of Polymers — Part II: Weld-Quality Studies

This paper aims to provide an understanding of weld-quality evaluation from multiple research angles

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ABSTRACT

The study of the output quality of any manufacturing process is as significant as the studies for discovery of new processes. The studies performed by researchers over time provide various points of view and insights that eventually contribute to a greater understanding when brought together and reviewed collectively. In Part I, the influence of different processing parameters — such as laser power, scanning speed, stand-off distance, and clamping pressure — were discussed. Part II of this paper attempts to offer the reader an extensive understanding of weld-quality evaluation from various angles. It reviews different optimization methods and the significance of finite element modeling along with a few simulation studies. This paper also covers morphological characteristics to offer the reader a property-structure-process linkage perspective.

KEYWORDS

• Polymers • Laser Welding • Optimization • Morphology • Finite Element Method

Introduction

The present paper, which is divided into three sections based on optimization, simulation, and morphological characterization, focuses on performance characteristics and weld quality. The primary purpose of simulations is to explore more possibilities of improvement in methodology without expending as much time and money as real experimentation. In addition, simulation results can potentially assist in a better selection of process parameters and their ranges. The final part provides the morphological characteristics of welded joints. Morphological factors, such as weld pool geometry, are also analyzed as output parameters. Looking through a morphological perspective gives the researcher deeper insight into the weld quality and how it is affected by various factors at a structural level. It also helps evaluate the welding process accurately without, or with little, testing of the sample. Morphological characterization also paves the way to form property-structure-process linkages, which is another rapidly growing research area.

Because the content covered in this study is based on an engineering point of view, some prominent factors of materials sciences, such as additives and types of polymers, were not reviewed.

Performance Characteristics and Weld Quality

Laser welding performance has been generally measured in terms of an increase in welding speed, weld quality, and joint cost. Weld quality can be accessed based on an improvement in mechanical properties (joint strength, failure force, hardness, fatigue strength, etc.) and morphological characteristics (nonisothermal crystallization, the growth rate of germs, material crystallinity, and the dimensions of the heat-affected zone [HAZ] induced by recrystallization) with reduction or elimination of weld defects.

Optimization-Based Studies of Through-Transmission Laser Welding (TTLW)

Optimization is performed to find the appropriate combination of values from a given range of process parameters and obtain the best possible weld quality. The weld quality is evaluated based on factors such as breaking load, joint strength, or shear strength as well as morphological factors such as weld width and depth of penetration in the joining parts. There are various welding parameters (laser power, scanning speed, spot size, clamping pressure, etc.) that in-

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fluence the weld quality (joint strength, weld width, depth of penetration, etc.). Optimization techniques applied to the welding process are necessary for continuous improvement of the welding process. Depending on the nature of the TTLW process, researchers have applied different optimization techniques for response/parameter optimization to improve the weld quality.

Kumar et al. (Ref. 1) applied grey relational analysis to solve the multiresponse (i.e., joint strength and weld width simultaneously) and convert multiple optimization problems into a single objective problem. Grey relational analysis was coupled with the Taguchi method to analyze and optimize the TTLW process. Similarly, Hubeatir (Ref. 2) applied the Taguchi method and grey relational analysis to perform multi-objective optimization of polymethyl methacrylate (PMMA) laser welding using an infrared (IR) semiconductor. While larger weld widths resulted in stronger welds, the authors noted that deeper penetration resulted in a weaker weld due to the formation of bubbles and porosity.

An experimental investigation of acrylic TTLW was conducted by Acharjee et al. (Ref. 3). They chose Taguchi orthogonal array for the design of the experiment and optimization of process parameters (i.e., power, welding speed, and focal distance). They determined the best parametric combination for the maximum weld strength was a laser power of 28 W, welding speed of 5 mm/s, and focal distance of 9 mm. From the analysis of variance (ANOVA) results for weld strength, laser power was the most significant factor, followed by focal length and welding speed.

To investigate the effects of individual process parameters from a minimum number of tests, Mazumdar and Hoa (Ref. 4) adopted the Taguchi method. Studies on the optimization of CO_2 laser welding parameters for polypropylene (PP) clay nanocomposite welds have also been conducted using the Taguchi method (Ref. 5) and response surface methodology (RSM) (Ref. 6).

Kumar et al. (Ref. 7) performed multi-objective optimization of TTLW of dissimilar plastics using the RSM. They considered power (7.60–11.60 W), scanning speed (0.66–2.34 mm/s), and frequency (198.86–451.13 kHz) as input parameters. The breaking load and weld width were measured as responses. The optimum parametric combination for maximization of the breaking load and minimization of the weld width was obtained using the desirability function analysis with a laser power of 7.60 W, welding speed of 1.26 mm/s, and frequency of 372.09 kHz. It was also found that the power and scanning speed were the most significant factors for the breaking load and weld width, respectively.

Shin and Choi (Ref. 8) studied the design of energy optimization for the laser polymer (acrylonitrile butadiene styrene [ABS] and polycarbonate [PC]) joining process. The HAZ and melt-zone measurements were performed to find the joining energy threshold and the mechanical properties of the welds.

Acherjee et al. (Ref. 9) investigated the effects of process parameters — namely laser power, welding speed, size of the laser beam, and clamp pressure — on the lap-shear strength and weld width for TTLW of acrylic PMMA using a diode laser system. They used the RSM to develop the mathematical relationships between the welding process parameters and the output variables of the weld joint as well as determine the welding input parameters that led to the desired weld quality. Bideskan et al. (Ref. 10) performed a similar study on a polymeric laminate structure made of PMMA and aluminum 6061-T6 using laser welding.

Wang et al. (Ref. 11) developed a thermal model based on a combination of the finite element method (FEM), RSM, and a genetic algorithm (GA) to improve the accuracy of the model prediction with a minimal number of trials. In another study, Wang et al. (Ref. 12) used the central composite rotatable design to plan the experiments for TTLW of thermoplastic samples. The input parameters considered were laser power, joining velocity, clamp pressure, and scanning number. The responses selected were weld strength, width, and cost. Among all the process parameters, both velocity and scanning number had a considerable effect on the joint cost. In addition, the authors concluded that the RSM models were more suitable to represent the relationship between the process parameters and the responses. The RSM models also assisted in creating an intuitive understanding of this relationship.

Bhattacharya et al. (Ref. 13) investigated the effects of power, frequency, and scan speed on the geometry of the weld made between PC and acrylic using TTLW. They used an empirical model with the RSM and further performed ANOVA to identify the significant parameters with respect to the responses. Jiao et al. (Ref. 14) optimized the joint quality of carbon-fiber-reinforced thermoplastic/stainless steel joints using the laser power, scan speed, and clamping pressure as process parameters. The joint quality was assessed based on the joint strength and the thermal defect zone width. Katsiropoulos et al. (Ref. 15) applied a generic optimization concept using the LSTM-OPT software tool for the thermal process cycle and laser welding unit parameters for both the quality and cost of the produced part (thermoplastic composite materials). Vidal et al. (Ref. 16) designed and developed a tailored laser system to obtain high-quality weld seams with weld widths between 0.7 and 1.4 mm. During laser-assisted processing of thermoplastic composites, the individual effects of input parameters on the responses could not be easily separated unless a large number of experiments were carried out.

To investigate the effects of individual process parameters from a minimum number of tests, the Taguchi method was adopted by Mazumdar and Hoa (Ref. 17). They selected L9 orthogonal arrays for the experimental design, and the ANOVA technique estimated the percentage contribution of each factor to the quality of bonding. Amanat et al. (Ref. 18) studied the effect of process parameters, namely laser power (40–80 W) and irradiation time (10–50 s), on the bond quality of quasi-simultaneous (QS) laser-beam-welded polyetheretherketone (PEEK). They found the laser power to be the determining parameter for bond strength, while irradiation time had little effect. Additionally, they found that the optimal laser power for bonding was 65–75 W, which resulted in bond strengths ranging from 20 to 45 MPa.

Labeas et al. (Ref. 19) studied the optimization of the TTLW process for thermoplastic composite parts using thermo-mechanical simulation. Dwivedi and Sharma (Ref. 20) applied the central composite RSM to optimize the TTLW of polyethylene terephthalate (PET) and 316L stainless steel. They determined the optimum value of laser power, joining speed, and stand-off distance was 18 W, 100 mm/min, and 2 mm, respectively, to get the maximum joint strength (predicted: 88.48 MPa). The central composite design (CCD) and regression analysis methods were effective in determining the optimized carbon source, nitrogen source, and inducer for xylanase activity of Streptomyces sp. P12-137 (Ref. 21). The CCD matrix and RSM were applied in designing the experiments to evaluate the interactive effects of the input variables on the degradation of AR 274 azo-dye solution by wet air oxidation conditions (Ref. 22).

In the research by Wang et al. (Ref. 23) and Acharjee et al. (Ref. 24), an artificial neural network was utilized to establish the relationships between laser transmission joining process parameters with joint strength and joint seam width. Wang et al. (Ref. 23) applied the desirability function coupled with a GA to carry out the optimization of the joint strength and joint width. In contrast, Acharjee et al. (Ref. 24) used multiple regression models for the prediction of responses.

The effects of the laser-power intensity and travel speed on the joint performance of PET glycol and stainless steel have been extensively investigated by Tillmann et al. (Ref. 25). They concluded that increasing the laser power and decreasing the travel speed increased the fracture load to an optimum level. This is because sufficient melting of the polymer and wetting on the steel side were achieved without decomposing the polymer sheet; hence, a high joint strength was obtained (Ref. 25). Kagan (Ref. 26) also studied innovations in laser welding of thermoplastics and multicriterion optimization of the mechanical performance of a welded joint produced by TTLW technology and requiring basic processing parameters and materials properties.

Simulation-Based Studies of TTLW

The finite element simulation of the transient temperature distributions during the TTLW process can help to optimize the material and processing parameters. Accurate temperature estimations depend on accurate descriptions of the laser heat source at the weld interface as well as the properties of the work material. In the research by Chen et al. (Ref. 27), a model was developed to describe the laser-energy distribution in light-scattering polymers. The model contained two parameters, namely the beam-scattering ratio and the scattering standard deviation. Afterward, the models were validated using polyamide 6 (PA6), PA6 glass fiber (GF), and PP parts. A three-dimensional (3D) FEM model was constructed by Chen et al. (Ref. 28) to simulate heat transfer in contour TTLW of an amorphous polymer (i.e., PC). The modeling results were supported by the experimental observations of weld width and weld-initiation power. Additionally, the simulation results indicated that, in contour welding of PC, welding initiated when the temperature at the weld interface reached the maximum 200°C.

Geiger et al. (Ref. 29) also used the FEM to understand the influence of the optical parameters of PP on the temperature field and molten pool geometry during the joining process. They claimed that their approach can be advantageous in detecting the heat earlier, such that the welding portion could be redesigned. In another study, an FEM model was developed to simulate the heat input during laser welding of a polyethylene film and PP substrate as well as predict the effect of input parameters on the peel force (Ref. 30). They then used a GA to optimize the peel force with respect to the process parameters of power, scan speed, and spot diameter. In a study done on quasi-simultaneous laser welding of PC by Acherjee (Ref. 31), a 3D FEM on the ANSYS platform was used to simulate heat transfer. The process variables — including power, weld speed, number of passes, and line energy — were optimized by considering temperature profile, weld pool geometry, and time temperature trend as output parameters.

Aden (Ref. 32) studied the temperature profile and heat propagation in joints with respect to Gaussian- and M-shaped beams for TTLW of PC (nonscattering polymer) and polybutylene terephthalate (PBT) (strong-scattering polymer). He found that for PCs, the Gaussian beam generated a nonhomogeneous weld seam, while an M-shaped beam produced a seam with a constant thickness and width. In the case of PBT, he found that both the types of beams generated similar seams. Aden attributed the similarity in seams of PBT to the strong-scattering nature. In a later study by Chen et al. (Ref. 43), a rotary-Gauss body heat source was coupled with a Gaussian plane heat source to develop a 3D FEM model and predict the temperature distribution and weld pool geometry during the welding of fiberglass-doped PP and fiberglass-doped ABS.

Aden et al. (Ref. 33) developed a thermal simulation for polyamide (PA) 66 polymer to calculate the temperature distribution. The distributions perpendicular to the scan direction were compared to the microtome cuts of the joint. The temperature distribution in a plane parallel to the joining zone was used to calculate an area where the temperature was above the melting temperature and below the degradation temperature of the polymer. Mayboudi et al. (Ref. 34) concluded that when scattering of the laser beam was accounted for in the thermal model, the agreement between the thermal imager and model improved significantly. As a result, beam scattering is an important factor to be considered in thermal modeling of the TTLW process. A two-dimensional thermal model was developed by Becker and Potente (Ref. 35) to simulate the heating phase of the TTLW process along the moving-beam direction using a FEM model. They validated the results with collected data from experiments with PP.

Hadriche et al. (Ref. 36) proved the reliability of a numerical model based on the finite difference method by calculating the soundness variables for diode laser welding of PP thermoplastic polymers. Microscopy observation of experimental PP welds validated the numerical model. The authors concluded that the thermal cycle endured by the welded parts involved an isotherm cooling that produced morphological changes due to nonhomogeneous recrystallization. An integrated experimental-simulation study was carried out by Lambiase et al. (Ref. 37) to optimize the laser-assisted joining of metals and plastics. In the research conducted by Casalino and Ghorbel (Ref. 38), a model was developed for PP in the keyhole and conduction modes in butt and overlap configurations. They found that the maximum strain and stress values were very low for deep penetration welding (0.000889 and 1.36195 N/mm^2, respectively) as compared to conduction welding (0.0008056 and 1.25272 N/mm^2, respectively).

A numerical model was made by Zoubeir and Elhem (Ref. 39) using the following process parameters: a constant laser incident power of 100 W, a constant beam scanning speed equal to 110 mm/s, and a clamp pressure that varied between 0.3 and 0.5 MPa to study the temperature field and residual stresses distribution for diode TTLW of a PP minitank. A model was made for PET and PP polymer welding to find the relationship of welding parameters, molten pool geometry (width and depth), and shear strength (Ref. 40). The authors found that the width and depth increased in the whole design space with a higher laser power, lower welding speed, and shorter stand-off distance. The results also suggested the molten pool depth-to-width ratio had a significant influence on the shear strength.

Modeling was developed by Liu et al. (Ref. 41) for the laser heat source by considering light scattering during TTLW. They used the energy-transformation algorithm to transform the line-energy intensity into the point-energy intensity. The weldability of a polymeric material through simulation was also studied by Ilie et al. (Ref. 42). Using IR thermography, the results of the simulation were validated. The welding of fiberglass-doped PP and ABS was difficult because of the low laser transmittance. Chen et al. (Ref. 43) investigated the relationship of welding parameters, namely the molten pool area and shear strength in the welding of fiberglass-doped PP and ABS using simulation and experimentation. Coelho et al. (Ref. 44) compared weld quality and efficiency for beam spots with circular and elliptical geometry. They found that the joint strength was higher for larger-beam spot diameters, and elliptical-beam spots increased weld efficiency, thus resulting in higher processing speeds and/or decreasing required laser power. They attributed the higher strength in the case of the elliptical beam to the longer contact, which caused higher heat input to the joint. TTLW of polymers causes high thermal stress in the joint region. Improper welding parameter combinations can destroy the joint structure or result in thermal degradation of the polymer (Ref. 45).

A numerical model was developed by Flock et al. (Ref. 45) that allowed the prediction of the HAZ as well as the resulting maximum temperature in TTLW that permits an initial optimization of the joining process in advance and helps to shorten the process development time. An efficient tool was developed by Ilie et al. (Ref. 46) for determining the weldability of polymeric materials for the reduction of time and costs with experimental exploration. A thermal simulation model for simultaneous welding of the semicrystalline polymer was developed that supports the determination of the HAZ size, weld width, and shear strength (Refs. 47, 48). They found that the calculated size of the HAZ showed a high concordance with the dimensions of the HAZ found using light microscopy (Ref. 47).

Sooriyapiragasam and Hopmann (Ref. 49) studied the thermomechanical simulations for determining TTLW residual stress distribution in the weld seam depending on the welding parameters. A nondestructive method (IR thermography) was used for measuring the temperature of the joint interface for real-time monitoring of the welding process. The temperature profiles acquired by IR thermography for a PMMA–ABS/PC couple were compared with numerical simulations during the heating and cooling process. The authors validated the numerical model with the experimental data (Ref. 50).

In the work of Mayboudi et al. (Ref. 51), thermal imaging observations of TTLW with a stationary laser beam were carried out for different surface coatings. The model was created for the joint between two polyvinyl chloride parts using the first principles of heat transfer. This model utilized contact conduction that is a function of temperature and pressure, Gaussian laser distribution, and many material properties that vary with temperature, including the absorption coefficient (Ref. 52). A thermal joint conductance model, which was experimentally validated, was developed using principles of contact mechanics and basic material properties to predict the thermal conductance of metal/polymer joints (Refs. 44, 53). Bronnikov et al. (Ref. 54) proposed an empirical equation to relate Young's modulus to the thermal expansion of highly oriented polymers. This was experimentally validated over a wide temperature range (from cryogenic to melting temperatures).

The isothermal and nonisothermal melt crystallization kinetics of isotactic PP (iPP) were investigated via differential scanning calorimetry by Mubarak et al. (Ref. 55) and Albano et al. (Ref. 56). The isothermal melt crystallization kinetics were analyzed using the Avrami equation (Refs. 55, 57). Kneip et al. (Ref. 58) developed a model of energy exchange based on the FEM to determine the thermal field for semitransparent polymers irradiated by laser. The experimental part of the study was performed using a diode laser source and an IR thermography camera.

An analytical model based on Green's function method was developed to analyze the temperature distribution and heated regions in a material irradiated by a high-energy laser beam (Ref. 59). It was found that their parameters (beam-power diameter, defocused distance, and material properties) had a significant effect on the heat shape and size of the heated region or HAZ. The model of a laser-diode stack based on the Zemax ray-tracing software that operates in a nonsequential mode was developed and validated by comparing the simulated and experimental transverse irradiance profiles at different positions along the caustic formed by a lens (Ref. 60).

Naqwi and Durst (Ref. 61) presented a mathematical model of a diode laser beam based on Gaussian and Lorentzian distributions. This is appropriate for monomode diode lasers with active layers thinner than the wavelength. Ai et al. (Ref. 62) conducted a numerical and experimental study of PET TTLW and Ti-6Al-4V to analyze the weld geometry, molten pool, fluid flow, and porosity formation. They identified the porosity in the high-temperature region due to the PET decomposition, which was also observed in the experimental results. The thermal degradation of materials strongly influenced the joint strength in TTLW. Joint strength decreased at high temperatures because of material thermal degradation (Refs. 63, 64). As a result, Wang et al. (Ref. 63) and Potente et al. (Ref. 65) developed a 3D transient thermal model combining a pyrolysis kinetic model to predict the thermal degradation and melt displacement of PA 66. In the research of Wilke et al. (Ref. 66), simulation was conducted for the quasi-simultaneous and simultaneous laser welding process, including the heating and cooling phase, using temperature-dependent data. The convective cooling and emissivity at the surface of the adherends were also taken into consideration.

Simulation methods were used to predict the weld performance parameters (i.e., joint strength, weld geometry, HAZ, etc.) with respect to the process parameters (i.e., power, scan speed, beam diameter, etc.) based on the thermal-energy profile throughout the weld pool. The FEM was preferred for the temperature distribution in the weld pool and its surroundings. Thermal models were used to predict degradation of the material and/or the geometry of the weld pool, which can, in turn, predict the joint strength. These simulations can be a major step in avoiding costly mistakes by constructing a sound design.

Morphological Characterization-Based Studies of TTLW

Morphological factors of a weldment, such as surface roughness, geometry of the weld pool, cracks, etc., assist in the formulation of a characteristic understanding of the effects of process parameters on the welding process and the joint itself. The influence of process parameters, both the laser power (20–40 W) and the welding speed (3–6 mm/s) on the geometry and the microstructure of the diode laser-welded PP were investigated by Ghorbel et al. (Ref. 67). They determined the effects of selected welding parameters on the seam geometry, defects, and material crystallinity at different zones of the welded part. They found that the increase in the laser power and decrease of the scanning speed led to a larger volume of the weld zone and depth of penetration. Higher values of laser power and a low scanning speed can lead to an undesirable degradation of structural, morphological, and optical properties of polymers (Ref. 68). This was evident using the microscopic Fourier-transform infrared (FTIR) spectroscopy method, which showed that diode laser welding induces thermal degradation of the PP by random chain scissions. Additionally, an increase of the crystallinity along the cross section of the welding joint was observed with a maximum crystallinity in the center of the weld zone.

Thermal energy from the laser gets trapped within the polymers and may lead to a rise in temperature in deeper regions (Ref. 69). Some process parameters produced the occurrence of a void due to the thermal decomposition and the vaporization of the PP (Refs. 67, 70, 71). Prabhakaran et al. (Ref. 72) found that low laser power at lower laser speeds resulted in maximum weld strength. It was found that the partially melted iPP can crystallize very quickly at high temperature (unmelted material can accelerate the primary nucleation rate, and the ordered structure of polymer melt can speed up the linear growth rate of spherulite). The Avrami equation describes the initial stage of nonisothermal crystallization (Ref. 73). A considerable decrease in the crystallization rate was observed, which is associated with a decreased molecular mobility due to an increase in molecular weight. It is also associated with a crystallinity decrease due to the structural defects introduced along the chains by the branching process. To get rid of the self-nucleation phenomenon, it is necessary to bring the polymer to temperatures where degradation is already present (Refs. 70, 74). During the study of excimer laser on biodegradable polymer, Hsu et al. (Ref. 75) discovered that polymer crystallinity decreased as a function of laser fluence. Xu et al. (Ref. 76) studied the effect of GF and crystallinity on light transmission during TTLW of thermoplastics. They learned that the apparent reflection increased with crystallinity due to the increased backscattering. However, for GF-reinforced polymers, the apparent reflection displayed a complex behavior. Various compounding ingredients were added to the polymer matrix, which influences the transmission characteristics, including the laser wavelength (Refs. 77, 78).

In TTLW of thermoplastics, carbon black (CB) is often used to absorb laser energy and convert it into heat in the absorbing polymer. Acherjee et al. (Ref. 79) stated that the dosage of CB determines the optical penetration depth. Wang et al. (Ref. 80) presented a technique for quantifying the CB morphology in the PA6 and PC used in laser welding applications. The microstructure of the CB was observed by transmission electron microscopy (TEM). The TEM photomicrographs of CB were quantitatively analyzed using an image-processing technique. The microstructural parameters — such as size, shape, and distribution of CB particles and aggregates — were obtained. TEM photographs of the joint demonstrated that 304 stainless steel and the PET had bonded at the atomic, molecular, or nanostructural level through a Cr-oxide film (Ref. 81). Abed et al. (Ref. 82) studied the TTLW of PP using a diode laser. They found that the crystalline morphology observed in different zones in the welded part was related to the specific thermal cycle. Meyer et al. (Ref. 83) used optical coherence tomography to study the quality of the weld in silicon chip bonding. They concluded that, by using appropriate wavelengths of light, variable refractive indices of the joining materials could be compensated to accurately assess the quality of the weld.

A similar study was performed by Frick and Schkutow (Ref. 84) in which they observed that scattering decreased with a wavelength increasing from 800 to 2500 nm. Cosson et al. (Ref. 85) developed an optical method to calculate the extinction coefficient and weldability of semitransparent plastics using a laser light source and a camera to measure the light transmitted through the samples. They related the thickness of the sample to the melting. They suggested this method could be used to optimize the power along the weld. Optical coherence tomography was also found to be a promising nondestructive technique to assess the quality of the weld formed by TTLW (Ref. 86). In the work of Ma et al. (Ref. 87), synthesis and characterization of poly(propylene carbonate) glycol-based waterborne polyurethane with a high solid content was investigated. The particle size and distribution of the emulsions were measured and analyzed by a submicron particle size zeta-potential analyzer and TEM. Hansch et al. (Ref. 88) observed that the pigment had a limited and intensive range of absorption in the visible range. It was concluded that polymers have different absorption characteristics from laser energy in the near-IR region.

Grewell et al. (Ref. 89) conducted a study on the relationship between the optical characterization of colored and noncolored polyamides and laser welding process parameters. The authors concluded that the addition of pigments can enhance the scattering of laser radiation, which can increase the effective weld time or minimal energy requirement to make a weld. Wehner et al. (Ref. 90) investigated the diode laser in the manufacture of microfluidic devices. A transparent PC plate cover was welded onto the PC base plate with varying CB dosages. The authors recommended the higher CB content due to the shallower weld seam. Haberstroh et al. (Ref. 91) examined the influence of CB content on the formation of the weld seam when joining thermoplastics in microtechnology applications. The CB content varied from 0.5 to 1.5%. It was noticed that, with an increase in the CB content, the penetration depth decreased from 29 to 9 μm. Liu et al. (Ref. 92) developed a new method to replace the CB absorbant with an Fe-wire absorbant and found it resulted in a cleaner and stronger weld. They attributed the higher strength to the higher thermal conductivity of metal than CB. Bray et al. (Ref. 93) investigated the effect of specific nylon composition factors, such as fiberglass, mineral, impact modifier content, and color version on the near-IR transmission.

Schmailzl et al. (Ref. 94) constructed an experimental setup by integrating a pyrometer with a 3D scanner to detect gaps in the weld during QS welding by measuring the differences in variation in the measured temperature. They were able to successfully identify weld gaps in the joints made between sheets containing fiber up to 30% of the weight. Laser-light transmission through thermoplastics (PA6 and PC) as a function of thickness and laser incidence angle was studied by Azhíkannickal et al. (Ref. 5). They concluded that, for a given thickness, the transmission on both materials decreased as the laser angle of incidence increased. Additionally, for a given laser incidence angle, the transmission decreased with the increase in thickness (Ref. 96). The scattering was increased by increasing the number of interactions between laser light and phase boundaries either by increasing the particle concentration (i.e., GF level and crystallinity) or increasing part thickness (Ref. 97).

In the research of Liangbin et al. (Ref. 98), it was found that high pressure could increase the crystallization rate and promote the thickening process of PET lamellar crystals. Amanat et al. (Ref. 99) studied the influence of laser power (10 or 20 W), scan speed (4, 8, 16, 32, or 64 mm/s), and material morphology (amorphous or semicrystalline) on the lap-joint bond strength of PEEK joined using TTLW. They found that the amorphous PEEK was susceptible to heat damage at higher power, while no visual evidence of heat damage was found in semicrystalline PEEK. Additionally, semicrystalline PEEK weld strengths were greater than the amorphous PEEK weld strengths at all speeds and power settings. Bubbles were also present within the weld line in both semicrystalline and amorphous PEEK; this is most likely due to the vaporization of absorbed water molecules within the PEEK (Ref. 99).

Villar et al. (Ref. 100) constructed a special setup to monitor the temperature and irradiation time during the laser welding of polyetherketoneketone (PEKK) to keep the maximum temperature from touching material degradation. In their more recent study of the effect of high-performance PEKK as a packaging material for laser transmission welding of two thermoplastic samples, Villar et al. (Ref. 101) observed that the temperature at the center of the weld zone reached a sufficient level to cause enough melting and mobility of polymer chains. They added that the joint appeared to be strong.

Schmailzl et al. (Ref. 102) used a calibrated 3D scanner equipped with an integrated pyrometer to measure the core temperature of the joint during QS welding of PA6. Brodhun et al. (Ref. 103) studied the effect of various process parameters on temperature distribution during the welding of thermoplastic fasteners and fiber-reinforced plastic surfaces and, in turn, on the quality of weld. They found that the scanning path has the most significant effect on the temperature. Pelsmaeker et al. (Ref. 104) proved that thulium-fiber laser welding can be successfully used to join transparent plastics without the application of additives to yield shear strengths of up to 5 Mpa and provide efficient leak proof against microfluids. They found that the material properties of ten types of polymers can be conveniently used to justify the high strengths achieved. Pereira et al. (Ref. 105) studied the effect of the number of passes on the shear strength of lap and scarf joints made with PA6 using a Nd:YAG laser. They observed that in the case of a single pass, scarf joints were stronger than lap joints, while lap joints were made almost doubly stronger by a double pass. Azimzadegan and Mousavi (Ref. 106) investigated the causes and nature of hot cracks in the welds of HASTELLOY® X formed using Nd:YAG laser welding. They observed that the solidification cracks originated from liquation cracks in the base metal.

In the field of medicine, Rodts et al. (Ref. 107) found that surface-welded woven fiber fabrics displayed far greater wear resistance under compression than traditional woven fabrics that were used for cartilage replacement in bone joints. Visco and Scolaro (Ref. 108) studied the effects of absorbed thermal energy and the wt-% of filler material on the laser-welded joint made in polyethylene containing biomedical-grade nanocomposites. They found that the surface roughness was reduced while the permeability of the joint toward biofluids was simultaneously increased. They also observed that higher tensile strengths were observed in the case of white polyethylene as compared to its darker composites. Furthermore, in the case of white polyethylene, they found that the highest tensile strength was obtained at 0.016 wt-% of filler material.

A morphological characterization study of a weld shows that the primary factor dictating the microstructure of the weld is the process of material crystallization during and immediately after the scan. This crystallization, in turn, is affected by the thermal energy transmitted, trapped, and propagated during the welding process. The effects of excessive energy absorption, such as thermal degradation, which causes vaporization of the material, leading to cavities, were also studied. The heat transmission and absorption were regulated with the power input, scan speed, and various additives, such as CB to the base materials.

Future Aspects of the TTLW Process

This survey of literature indicates that people have started researching several areas of laser welding. As far as TTLW of the polymer is concerned, publications are not found to be rare. But at the same time, literature in this context is not rich either. Indeed, different aspects (process optimization, characterization, FEM, etc.) of laser welding of plastics have been addressed by the researchers. There are certain aspects of TTLW that are yet to be addressed and can be studied in the future. Additional efforts are required to study the parametric influences on metallurgical characteristics and morphology of laser-welded surfaces as well as the base materials. Most of the researchers do not consider many key welding parameters, such as mode of operation, beam-travel direction, beam polarization, frequency, laser beam angle of incidence, material morphology, depth of focus, etc. A deep and broad understanding of the laser welding process to enable the eventual realization of a fully controlled manufacturing process is required. The requirement is to produce the desired quality of weld, including reducing scrap rate, reducing welding cycle time, and increasing product throughput. This is still a challenge to the researchers, technologists, and practicing engineers. Quality, in turn, depends on many factors such as product-processing parameters, molding machine, etc. It is obvious that welding parameters influence the quality of the weld. In the domain of polymer TTLW, a strong and rich knowledge base is to be developed. This knowledge base may be created only through continued and extensive research covering various aspects of polymer TTLW.

Conclusion

TTLW has some process benefits over conventional welding, including faster and deeper penetration, higher productivity, better weld quality, etc. Laser welding was first demonstrated for thermoplastics in 1970. Since late 1990, it has been used in mass production. Recently, considerable research has been carried out to investigate the TTLW process by various researchers. From the above discussion, the following conclusions have been drawn:

- Laser welding has been found to be the most suitable technique for polymer welding of complex geometries, both for transmitting and reflecting materials.
- The important parameters found by researchers affecting laser-weld qualities are laser parameters (laser power, frequency, mode of laser beam), material (type, thickness, morphology), and process parameters (scanning speed, stand-off distance, clamping pressure, number of repetitions, line energy).
- A parametric influence of laser welding parameters on quality characteristics has been analyzed with the help of experimental models developed using design of experiment, FEM, and image analyzer-based techniques (scanning electron microscopy, TEM, x-ray diffraction, FTIR, etc.).
- The essential weld-quality characteristics (joint strength, weld/seam width, depth of penetration, and HAZ) required for characterizing the process were optimized through single- and multi-objective optimization of the process by using different optimization techniques.
- The use of diode laser has become more popular in recent years for the welding of thermoplastics.

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