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Parameters Affecting the Welding of Transparent Materials Using Femtosecond Laser Pulses

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Abstract
There is a pressing need for an accurate process in industrial laser applications such as welding transparent materials. Femtosecond laser pulses, which depend on the nonlinear absorption properties, can be utilized to weld transparent materials. This technique can be applied not only in welding different transparent materials such as glass and polymers, but also in welding opaque materials such as metals, depending on the selection of an appropriate laser wavelength. The parameters that affect the technique such as Keldysh parameter, pulse energy, pulse repetition rate, pulse duration and nonlinear absorptivity were studied. To explain the welding process, an example of an experimental setup and its requirements was described. Besides that, the challenges for the welding process and their voids were also discussed.

Keywords Femtosecond laser · Laser welding · Nonlinear absorption · Transparent materials

Introduction

Transparent materials can be discovered anywhere and everywhere. Glass has a predominant function due to its excellent chemical, mechanical and optical properties. Transparent materials are considered essential because of the growing industrial needs of high-quality devices. In this modern age, traditional methods of cutting, welding and drilling transparent materials are still being used. Welding transparent materials is one of the essential industrial procedures in various industries such as healthcare, optoelectronics and accuracy machine industries. The use of femtosecond (fs) laser to weld

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transparent materials without using any glue is considered as a scientific breakthrough [1]. The distinctive characteristics of fs laser have spread new avenues in material processing via ultrashort pulse widths and very high peak intensities [2]. Nevertheless, due to the increased complexity of the process, the before and after heating process can be a problem for industrial and scientific applications. In fact, welding cannot be achieved with the readily accessible laser source due to the linear absorption properties. An absorbent material can solve this issue as glass is usually transparent for this wavelength range. For pulsed laser fusibility welding, it is possible to cancel the requirement through absorbent [3]. Laser welding is a preferred method as it is a versatile technique which can be used widely in several fields. It also has advantages of high precision, high speed and regular weld integrity [1]. It is advisable to use opaque materials (the center is a light-absorbing layer) for welding process [3]; however, there may be additional complexity to the above-mentioned method. On the other hand, the classic use of fs laser for welding process comes with an important feature of high peak intensity; thus, it can be used to weld transparent materials without adding any intermediate layer [4] and yet still has the advantage of nonlinear absorption technicality. The ultrafast pulse laser welding practice can be applied in welding transparent-transparent materials or different ones such as transparent-opaque materials [5]. The main advantage of laser welding is that the energy is applied to the workpiece without any physical touch and it can be attached selectively to the required welding part [6]. The invention of the ruby laser in 1960 provided much higher laser intensities. The laser application has been advancing swiftly since then and is applied for material processing. Recent advancement in this area of research is considered as a new breakthrough for the processing of transparent materials [7]. Available fs laser systems can achieve more kW/cm2 through the use of advanced techniques of mode-locking and pulse amplification. The transparent materials will be ionized in these intensities and will display a nonlinear behaviour and structural modification [4]. Fs laser is a powerful tool to handle materials. Fs laser may show several important advantages due to its individual properties of ultrashort and much higher peak pulse compared to the skills of basic laser process that uses lengthier pulses and /or nonstop wave laser. The advantages of fs laser include the repression of heat-affected zone (HAZ) formed over the irradiated region, the peak spatial resolution on the far side of diffraction border and inconstancy in the expression of materials that may be processed. High peak power, which includes the absorption of multiphoton and/or tunneling ionization, contributes to the flexibility of fs laser that mainly depends on the nonlinear interactions between fs laser beam and transparent materials [8]. Therefore, the fs laser can be used to treat not only transparent and opaque materials, but also fragile materials like glass. The optical absorption area of short-pulse laser has the ability to locate the substantial part of a material at the primary focus of a nonlinear interface [9]. The majority of research on fs laser welding has focused on similar or slightly dissimilar material bonding such as glass-glass, with either an fs laser or picosecond (ps) pulse. Therefore, there is a limited knowledge regarding the bonding of extremely dissimilar materials. Most of the research in this area focus on the bonding of glass-silicon material with each fs and ps system. There are also limited publications on glass and metal welding to prove the principle of confirmation that affect fs techniques, including fixed material mixtures [10]. In 1987, primary researches on fs laser micromachining were realized via ultrafast excimer laser, which was used to remove the surface of polymethyl methacrylate

(PMMA) [4]. The use of ultrafast lasers with picosecond pulses in material processing was first reported in 1987 by Sugioka [2]. Research in this field had expanded rapidly in the 1990s and these experiments had considerable effectiveness [2]. Ultrashort laser pulses were used for the first time in 2005 to weld transparent materials [11]. Watanabe et al. demonstrated the welding of transparent-opaque materials via fs laser and they explained the parameters that affected the welding by altering the energy of laser pulse [6]. An unfamiliar technique of welding transparent materials (silica glass) via 85 fs, 800 nm and 1 kHz fs laser pulse with pressure support was first reported [1, 5, 12].

Nowadays, a lot of attention has been given to the interaction of fs laser pulses with transparent materials because the material alteration is induced by nonlinear absorption. When the fs laser pulses are concentrated within the extent of a material, the intensity can be highly adequate for non-linear absorption. Laser welding with a laser beam can allow a more precise and localized welding with various advantages such as its simple operation [5]. When the energy of a laser pulse is absorbed by a substrate, a portion of the absorbed energy is converted into heat. Thermal energy diffuses out of the centric bulk after an acceptable amount of time, which returns to room temperature. In addition, if the next laser pulse is absorbed within a very short time, heat will not be able to spread completely out of the focal volume before another pulse is reached and the thermal energy is collected [3]. One major advantage of fs laser welding is that it decreases heat dispersion to the surrounding area of processed region. Another noteworthy feature of fs laser processing is that nonlinear absorption (multiphoton absorption) can result from an intense absorption, even in materials that are transparent to the wavelength of ultrafast laser beam. Multiphoton absorption allows not only surface processing, but also three-dimensional processing within the substrate of transparent materials such as polymers and glass [2]. A recent study was conducted on parameters that affect the welding of transparent materials, in which a critical analysis of these parameters was considered in the study. To the best of our knowledge, there was no report published on the effects of these parameters towards welding transparent materials using fs laser. In addition to the occurrence during the interaction between the fs laser and transparent materials, the welding of transparent material with an opaque material such as metal is investigated. Besides that, the nonlinear phenomenon and the challenges of the welding process are discussed. Figure 1 summarises the parameters that influence the welding of transparent materials.

Femtosecond Laser Interaction with Transparent Material

Firstly, nonlinear optics are defined as phenomena that happen as a result of the modification of optical characteristics of a material system in the presence of intense light [13, 14]. Generally, high-power CW lasers are applied for laser welding; however, it is only used to weld an opaque material because the welding process is based on the linear absorption. Alternatively, the ultrashort pulse laser has confirmed to be a strong instrument for welding transparent materials in the last twenty years. The extraordinarily short pulse duration allows a nonlinear procedure that varies considerably from conventional light-matter interaction techniques [11]. The application of fs lasers in altering the texture of transparent materials has attracted much attention in recent years. All these manifestations depend on a nonlinear absorption [15].

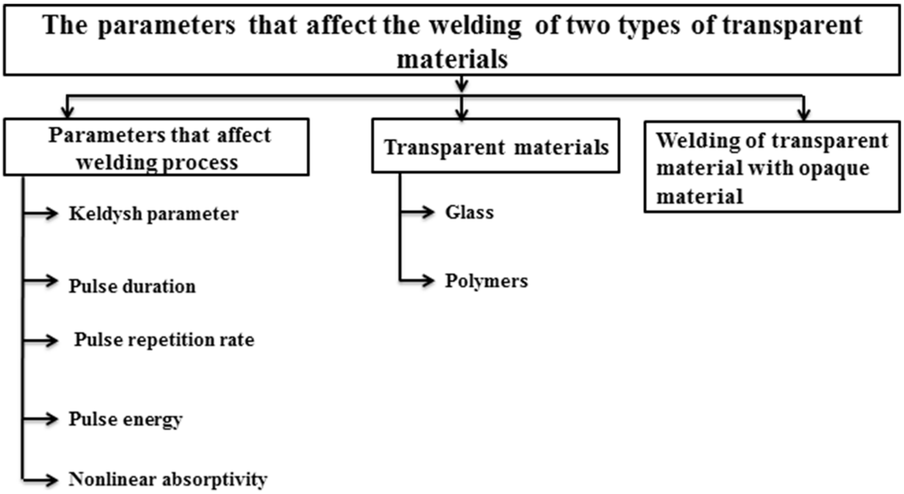

Fig. 1 The parameters that affect the welding process using fs laser

As illustrated in Fig. 2, a nonlinear absorption produced by fs pulses of laser results in a highly non-equilibrium state in a fixed volume for different material modifications to be performed. For the interaction of transparent material with fs laser, the nonlinear absorption takes place on a time range that is normally shorter than the time needed to transfer the energy from the electrons to the lattice. Therefore, the laser pulse excites the electrons in the conduction band much faster than they relax by scattering electron-phonon, generating a non-equilibrium state that excites the electrons in a cold lattice [11].

Linear absorption occurs in opaque materials, whereas nonlinear absorption occurs even in transparent materials at high power laser. The interface of two materials is marked as a dashed line [16]. Micro fabrication by the laser of pulse duration varies from low intensity (kW/cm^2) laser fabrication systems as CW or of ns pulse duration due to nonlinear optical effects from high intensity (> MW/cm^2) laser pulses. Within this intensity range, specific materials turn opaque due to intense nonlinear absorption, allowing the fabrication of any sort of material regardless of the laser

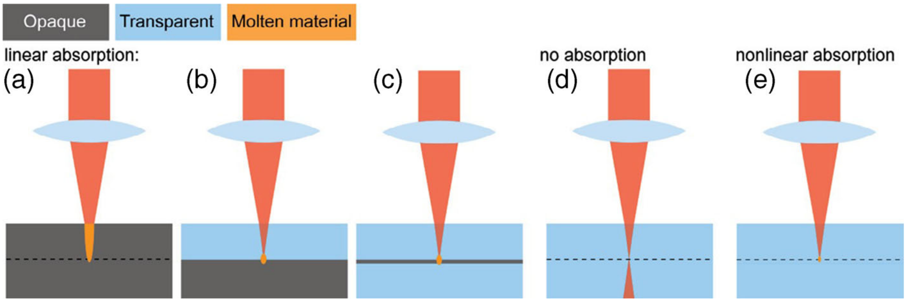

Fig. 2 Comparison of the laser-induced melting of various material combinations utilising linear absorption (a – c) and nonlinear absorption (e) [16]

wavelength [17]. Processing via fs laser is often referred to as a non-thermal process that is different from processing with longer pulses. Such variables are identified as a swift energy deposition in the substance [5]. As fs laser has unique advantages such as ultrashort pulse duration (< 200 fs) and high peak intensity (> kW/cm^2), it reveals a new track for material processing, particularly for transparent materials with large band gaps such as fused silica (e.g., 9 eV) and single crystal sapphire (e.g., 9.9 eV). Compared to a nanosecond pulse laser, fs pulse laser has several distinctive characteristics such as lower heat affected zone, negligible cracks, high precision and minimum recast. Because of its properties, fs laser welding method can perform welding by excluding the middle layers [4]. When a fs laser is focused on two clear substrates, reactions tend to occur due to the nonlinear absorption. The materials can be welded via re-solidification process. This process is known as laser bonding or laser welding [1, 3, 11, 12, 15].

The density of laser power tends to encourage multiphoton ionization. The density of charged particles grows very fast, which can reach between 50 and 100 fs [18]. The level of temperature can be checked quickly while managing the pulses at high repetition rates [5]. Thermal equilibrium of distributed electrons is often achieved after being exposed to pulses of the fs laser, which usually takes 100 fs to 10 ps. However, the time required to trigger thermalization and move the energy from the electron subsystem to the lattice is less than 100 ps, depending on the electron-phonon coupling strength of the object. This period of time is considered much longer than the time required for the electrons to reach thermal equilibrium. Therefore, the fs laser can increase the time required for heating electron, which is resulted from a hot electron gas that is away from the equilibrium of the lattice.

Thus, nonthermal treatment can be achieved by converting a very small part of the laser energy to heat. The result of nonthermal treatment is high precision and high-quality nanofabrication. The fs laser will still generate heat when it falls on the sample; the main important parameter of fs laser processing is the development of heat-affected zone (HAZ) which is limited due to the excessive short pulse widths between 50 and 200 fs [5].

Parameters Affecting the Welding Process

There are many factors that affect the welding process of transparent materials and they are briefed as follows:

Keldysh Parameter

Tunneling ionization, which is one of the various methods of nonlinear absorption, can lead to trigger electrons rather than multiphoton absorption in terms of high laser power intensity and depressing frequency. Initially, the unusual electric field of fs laser causes extreme deformation in the potential energy of the molecules of a sample during the tunneling ionization process. Hence, when the length of barrier is reduced, electrons will be channeled throughout the barriers so that the electrons will escape from a molecule to become free electrons.

In the interaction of fs laser with transparent materials, the probability of nonlinear absorption processes, including tunneling ionization and multiphoton absorption, must follow the Keldysh parameter γ [8, 11]:

$$\gamma = \frac{w}{e}\sqrt{\frac{m_e c n \varepsilon_o E_g}{I}} \tag{1}$$

Where, w is the laser repetition ratio, I is the laser power intensity, m_e is the electron effective mass, e is the fundamental electron charge, n is the linear refractive index, c is the speed of light, E_g is the band gap of the material, and ε_o is the permittivity of free space.

The power intensity of laser determines the probability of nonlinear absorption which includes multiphoton absorption and tunneling ionization processes. Therefore, laser intensity, which is on top of a specific critical value depending on the type and pulse duration of a material, will be higher if the pulse duration is shorter. It stimulates the nonlinear absorption in an efficient way [8, 11].

If the Keldysh parameter, γ, is less than 1.5, the tunneling process controls the photoionization process. For $\gamma \sim 1.5$, photoionization is a series of multiphoton ionization and tunneling processes; if γ overrides 1.5, the multiphoton ionization is prevalent [4].

Pulse Duration

The photoionization rate increases as the duration of pulse decreases. As the pulse duration increases, only a number of seed electrons are supplied by photoionization, whereas avalanche ionization is the controlling process for generating free electrons. Subsequently, the absorptivity depends on the pulse duration. The represented mechanisms are highly nonlinear and depend on simplified samples. Therefore, further experimental outcomes are needed to confirm the effect of pulse duration on the absorptivity and quantity of molten material.

The melting range decreases with increasing pulse duration; this statement supports that the absorptivity of fs laser pulses reduces with increasing pulse duration. When the time between laser pulses is shorter than the time of heat diffusion within the sample, the temperature of the processed space will increase gradually and apparent heat accumulation will occur [11].

Furthermore, exemplary fs pulses are two orders lower in duration than the time of electron-phonon relaxation process; thus, the laser-affected zone is evaporated faster than the energy transferred to its embracing regions, creating potential accuracy of the fabrication process. These limitations will first arise as a result of fabrication that is usually performed with parameters below the critical self-focusing end in order to avoid filamentation, which is an unwanted impact for the stated fabrication ways [17]. The effect of pulse duration can be concluded as the influence of fs pulses, which is more than the ps pulses, on the material modification [19].

Pulse Repetition Rate

Two different regimes of fs laser welding are specified: the low repetition rate regime with the range of 1–200 kHz and the high repetition rate regime which is higher than the standard one. Nevertheless, it still depends on the pulse duration. Figure 3 shows the effect of pulse repetition rate on the welding process via fs laser. It is obvious that the pulse with high repetition rate has the best welding effect.

The material alteration is generated by a solitary pulse. The difference in material alteration occurs because of the heat progressive effect [6, 12].

Heat aggregation of consecutive pulses takes place when the time for two laser pulses is shorter than the time for heat propagation out of the focal magnitude (around 1 microsecond in fused silica). As a result, even the material embracing the focal patch is molten at high-energy intensity. The use of fs laser pulse at high repetition rates as a domestic heat source shows its diverse advantages.

Since no support step is required to prove the bonds, it is easy to weld materials with more various thermal expansion coefficients [16]. Laser pulses with high repetition rate offer various advantages, which include extremely higher processing speeds and possibility of dominant structural modifications due to the effects of thermal accumulation [3].

It is shown that the nonlinear absorptivity increases when the pulse repetition rate increases with the pulse energy provided. This is because the temperature of the sample is increased due to heat accumulation at higher pulse repetition

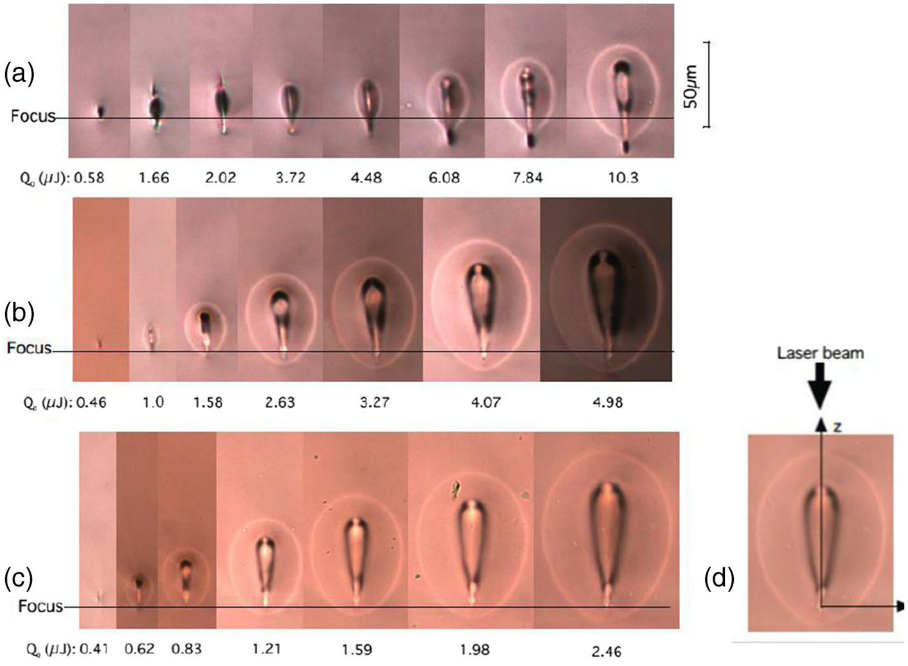

Fig. 3 Cross-sections obtained at different pulse repetition rates f of (a) 50 kHz, (b) 200 kHz and (c) 500 kHz [20]

rates; thus, the number of thermally excited free electron to conduction band increases [21, 22]. In accordance with the absorption of a laser pulse, the temperature increases quickly and cools down until the next pulse arrives. Finally, the temperature is saturated when the energy transferred from the laser pulses equals to the heat propagation in the embracing material [11].

For example, to achieve the highest nonlinear absorption, the shortest pulse duration of 220 fs is further used to ensure adequate heat accumulation at a repetition rate of 570 kHz [23]. As a result, the nonlinear absorptivity is strongly influenced by the pulse repetition rate.

Pulse Energy

Welding dynamics are diverse during the change of pulse energy at the supposed focal posture. It is comprehensible that a set of these values can afford perfect welding outcomes; thus, a reliance on the welding efficiency of pulse energy was explored in published researches [17]. The pulse energy can be determined by inserting intensity filters. Meanwhile, by using an electromagnetic shutter, the exposure time will be regulated [1]. The increase in laser pulse energy increases the width of welding; therefore, the actual welding region will grow with the increase in pulse energy [5]. Besides that, it allows a successful weld to be obtained upon larger gaps [24, 25]. By using the same laser pulse energy at a pulse duration of fs, the peak power is three orders of magnitude greater than the pulse duration of picosecond [19]. As a result, the absorptivity is enhanced with increasing pulse energy due to the increase in photoionization rate [22]. Besides that, materials with bigger band gap provides lower nonlinear absorptivity at high pulse energy [21].

Nonlinear Absorptivity

Assuming that the reflection and scattering of the laser energy by laser-induced plasma in the transparent materials are negligible, the nonlinear absorptivity, A_{EX}, is given by [20–22]:

$$\mathrm{AEX} = 1 - \frac{Q_t}{Q_o}\frac{1}{(1-R)^2} \tag{2}$$

where, Q_o is the energy of incident laser pulse, Q_t is the transmitted laser pulse energy through the transparent material and R is the reflectivity. The nonlinear absorptivity increases with rising pulse energy; however, the value of increase is larger at higher repetition rates, indicating that the nonlinear absorptivity increases with increasing pulse repetition rate [20]. The pulse duration of picoseconds is considered suitable for topical melting because the laser energy is first given to the electron system before moving to the lattice. On the other hand, the use of fs laser will result in greater nonlinear absorptivity compared to longer pulses [8]. Lastly, estimating nonlinear absorptivity remains difficult as the accuracy of fated nonlinear absorptivity is not obvious [20].

Transparent Materials that Welding by Femtosecond Laser Is Divided into

Glass

Glass has been used extensively in different applications such as optics, electronics, telecommunications, biomedicine, fabric industry and design due to its excellent chemical and physical properties [6, 26]. Many of these applications demand the welding of two or more glass parts. For this reason, different welding technologies have been developed, with each one of them having particular properties that are considered useful only to a limited field of application. The considerable damage of a glass is the difference between the mount material and the thermal expansion coefficients of glass. Thus, there are several weaknesses in different welding technologies such as gluing. Moreover, the glues are usually perceived as dangerous to human health. Laser welding by linear absorption was successfully explained in the case of fused silica through the use of a continuous wave of CO_2 laser. During the cooling process, the different types of glasses appear to have different properties that can cause cracks [11, 18]. The glass material has a high level of transmission, so the glass-glass welding via traditional laser (CW, long pulse duration) requires an opaque material acting as an interlayer between the glass pieces to absorb the laser energy [6].

The ultrafast laser glass welding is considered as a solution for all these obstacles. A filament connects the two specimens when the fs laser pulses are focused at the intersection of the two glass specimens. The filament energy can sometimes be high enough to initiate absorption under certain conditions. Induction of electron-ion plasma is produced through the non-linear absorption. Processes such as melting tend to occur in samples, which is then followed by re-solidification process [12, 21]. Therefore, fs glass welding usually requires the use of high repetition rate laser systems of 1 MHZ [11, 18]. In addition, using the double pulse of the shortest laser pulses is efficient in obtaining high performance welding of glass samples [27–29].

Polymers

Classical laser welding of transparent polymers depends on linear absorption through CW laser, a complete absorption technology with the use of an additional opaque material between them. This results in the use of fs laser to weld different types of polymers [23]. Polymethyl methacrylate (PMMA) [30], which is one of the most important polymers, has many possible applications in the electrical, optics and biomedical fields because of its high optical transparency, process capability and low cost [31]. The disadvantage of PMMA such as glass is that there are only a few welding techniques which are readily available. Most of the adhesive agents or interlayers are used in these techniques which may cause poor thermal, mechanical and chemical stability. Fs pulse laser welding is considered as one of the most promising styles for welding polymers at room temperature in ambient air [19]. Besides that, the welding of ceramics, which appears to be the absent key in recent manufacturing, can be performed successfully via fs laser [32].

The Welding of Transparent and Opaque Materials

Welding via fs laser can be extended to the welding of a transparent and an opaque material. Imitative laser welding techniques also require transparent materials at selected wavelengths [12]. For instance, the silicon material and borosilicate glass are welded by applying fs laser [5].

In welding different materials, wherever only one material is transparent to the laser beam, the merit of fs laser reposes in the collection of hardly limited thermal zones and the ability to excite both nonlinear absorption in the transparent substrate and linear absorption in the opaque substrate. Then, the interface figuration of plasma in both substrates leads to a tiny heated zone within each other.

Therefore, a true weld is created when the plasma blends and cools [16, 33]. The welding process tends to create a linear relationship for the absorption process. Decreasing the precision of the laser focal depth position can preserve a small heat influenced region. However, it needs welded materials that are transparent. Such a small heat influenced region allows different materials to be welded.

Figure 4 shows instances of transparent and opaque materials which are successfully welded [9]. In a complete state, a linear absorption is better than nonlinear absorption. Consequently, the desired medium power for each of the two materials does not alter significantly. The moderate power requested for welding transparent materials is higher than the opaque materials due to the shortage of linear absorption. Laser of limited wavelength should be used for transparent substrates. For instance, laser of Nd: YAG has a wavelength of 1064 nm and the welding of silicon-glass should follow a specific process. Firstly, the laser beam is transferred out of the transparent material for a nonlinear absorption to occur. Secondly, the laser beam is absorbed as a linear absorption in the opaque sample, which is the silicon [16].

Example of an Experimental Setup

To explain the welding process of transparent material, an example of an experimental setup and its requirements is described. Figure 5 shows the graphical view of the test set-up for welding transparent materials via fs laser [3]. The laser is Nd: YAG Laser, which is equal to the pulse repeater rating between 50 kHz and 8.2 MHz at 200 fs with a wavelength of 1064 nm. The attainable average laser power on the substrate can be adjusted by the two-wave plate. The sizes of regular focal spot range from 2 μm to 6 μm. The beam concentrate altitude is set by the z-translation stage and the substrate is motorized at a x-y translation level that can achieve the translation rate of approximately 300 mm/s.

Before conducting laser handling, an optical connection between the substrates is required. The optical contact should be sufficiently powerful to hold the specimens. With an accuracy of ±0.03°, both components are vertically positioned with the laser beam [18, 19].

The focal spot of the laser is adjusted accordingly to complete the welding process. At the final stage, the focal depth is modified depending on the welding variables such as speed and average power to be used. Once the variables are determined, the resulting stage (x-y) is accelerated. The scanning speed depends on the type of materials to be welded. The laser is triggered on once the speed reaches the given amount. Through the

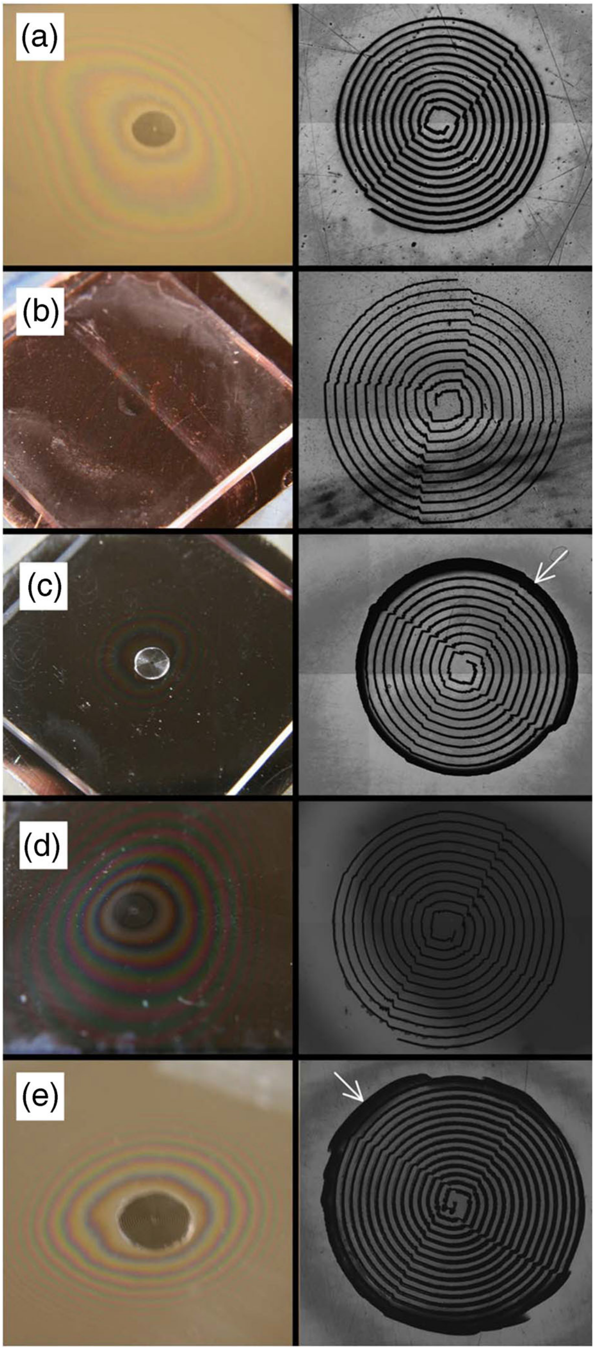

Fig. 4 Left; photographs and right; microscope images of: A. Al to SiO_2, B. Cu to SiO_2, C. stainless steel to borosilicate, D. Si to SiO_2, and E. sapphire to stainless steel. White arrows denote cracking in stainless steel samples [9]

laser processing, the average speed is kept fixed and the laser is then triggered off before the sample slows down.

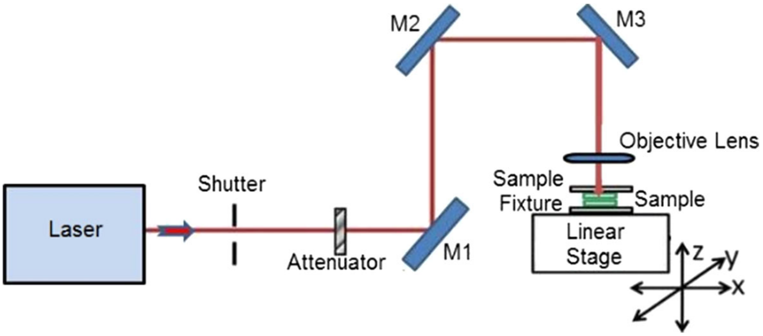

Fig. 5 Graphical of the experimental setup

Challenges for the Welding Process

Many challenges are encountered in the process of welding transparent materials. One of the major challenges is to weld two materials at considerable differences in melting points and coefficients of thermal expansion [4]. This situation can be observed through welding silicon carbide and fused silica with each other via fs laser pulses [34]. The splits can sometimes occur over the laser beam axis due to the inner stress in the fragile structure of the glass.

As shown in Fig. 6, the forming of cracks and defects are classified into two categories. The first group comprises cracks that are created in a cold environment [18]. The second group relies on cracks wherever the area grows so large, and the cracks are induced by thermal expansion and contraction. Due to small thermal expansion coefficient of fused silica, these kinds of defects in such material cannot be identified.

Generally, since the gap between samples is more than a quarter of the wavelength of the laser light, the welding process cannot be carried out successfully due to the ablation on the surfaces [35]. At gaps larger than 0.4 μm, cracks can occur inside the welding stitching. Although the glass sheets are connected to each other via glass material, the cracks will greatly reduce the durability of the seam. This is because a utilized capacity can cause rough individual pressure domains at the ends of the crack. For suitable great gaps, the glass that melts from the welding joint can escape into the gap [35]. It can be demonstrated that an active welding region is not the only operator affecting the shear connection solidity. Laser ablation is known to be the latter critical factor that influences the welding goodness. Laser ablation is considered to be quite suppressed within the laser-irradiated area via low pulse energy. Therefore, it has a small negative effect on the clip-joining force. Nevertheless, when the pulse energy reaches the critical value, laser ablation could no longer be well subdued in the focal zone. The laser ablation produced on an interface of the samples without pre-optical contact is commonly considered to have a negative effect on the welding modality [5].

The crucial challenge in laser welding is to put two materials into sufficiently close contact so that they are both within the focal depth of the laser and can reserve the plasma when it is created [9]. The large gap between two samples also allows the plasma to flee and ablate; therefore, the pressure used for lessening the gap through the two glass samples is needed so that the glass will not be completely flat or enveloped

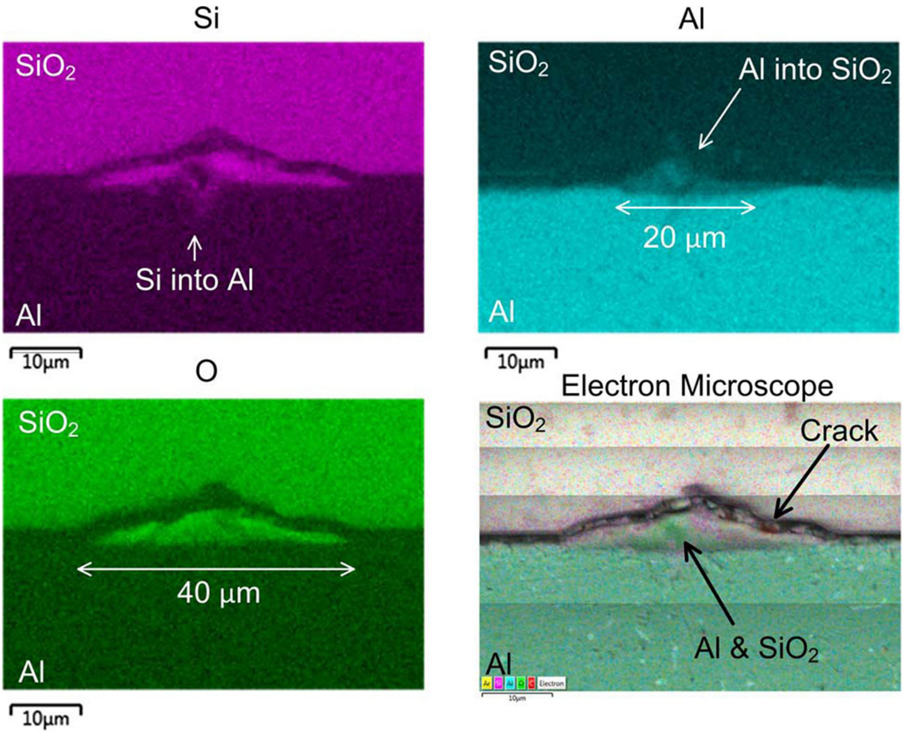

Fig. 6 XPS analysis and electron microscope of Al-SiO_2 welding which shows a mix of Si, Al, and O in the region of welding. The cracking of glass has been noted through polishing and cutting the outside region of welding [9]

with impurities [17]. Another challenge in fs laser is welding transparent materials and opaque materials. It is guaranteed that the two materials are close enough to prevent the plasma from escaping out of the focal bulk. Generally, it requires an optical contact or close to optical contact separation of two material samples. While it is easily attainable for glass surfaces, it is more challenging for metal surfaces because some pretreatment and power are required to push the two surfaces into contact [10]. In another case, a micro cracking scale was noted in the process of welding of glass sheets and aluminum sheets. This crack was caused by the reinforcement of internal stresses, which was created through the occurrence of chemical reaction between aluminum and glass as well as the differences in conductivity and thermal expansion between both materials [36]. However, the absorption dynamics require the balancing of linear processes in the metal and nonlinear processes in the glass, which may not scale in a readily expected fashion [37].

Conclusion

The last published researches on the welding of transparent materials have been demonstrated. The parameters affecting the welding process were discussed. It is found that the welding process is clearly affected by the Keldysh parameter γ. The effects of pulse energy, duration and repetition rate on the welding process were studied. The increase in pulse energy and pulse repetition rate was found to improve the efficiency of welding process, but the efficiency decreases with the increase in pulse duration. An example of an experimental setup for the laser welding of transparent materials and its requirements was described. The challenges of welding transparent-transparent and transparent-opaque materials were mentioned, which included the differences in thermal expansion's coefficients and melting points, defects, and cracks occurring within the welding vortex.

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