Femtosecond laser-induced microwelding of silver and copper

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Femtosecond (fs) laser irradiation has been shown to be effective for welding transparent materials and for transparent materials to metals. However, to date there is little work regarding similar applications in welding/bonding of metals. In this article, we for the first time to the best of our knowledge report on fs laser-induced microwelding of Ag microwires and Cu substrates. The influence of laser pulse number and fluence on fs laser microwelding is studied to explore an optimum welding window. Morphology analysis indicates that the primary weld of the Ag microwire and the Cu substrate was located at the edge of the Ag microwire and produced via the redeposition and local melting-induced welding of the ablated materials.

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1. Introduction

Lasers are excellent devices for welding because of their ability to introduce a high power density into a small zone [1]. Recently, with the development of miniaturization, laser welding has been applied in the production of microelectronic and biomedical devices [2–5]. In the microelectronics industry, electronics packaging is of major importance and wire bonding represents more than 90% of the packaging market due to its cost-effectiveness and flexibility [6]. Ultrasonic Au wire bonding is the predominate wire-bonding technology, but the high cost of Au has led to the study and high-volume applications of Cu wire because of its significant cost savings [7]. Compared to Au, Cu wires have many advantages, such as better thermal and electrical properties, excellent ball neck strength, high stiffness, and high-loop stability, which result in better wire sweep performance [8]. However, ultrasonic bonding of Cu wires has many challenges. For example, a shield gas is required to inhibit oxidation, while higher ultrasonic energy and greater bonding forces are needed to achieve a good joint because Cu wires have higher hardness and stiffness than Au wires. It has been found that an increase in ultrasonic energy and a higher bonding force can damage the Si substrate [9,10].

Femtosecond (fs) laser welding is a promising way of overcoming these problems in bonding with Cu wires. The fs laser has a very high peak power, but it causes a limited heat-affected zone in laser–matter interaction because of its ultrashort pulse duration. As a result of the unique properties of this type of laser–matter interaction, fs lasers have been widely studied for applications in precise machining operations, such as cutting [11,12], drilling [13,14], and other microfabrication techniques [15,16]. Recently, a number of applications of fs laser welding have been reported. Since Tamaki *et al.* [17] first reported welding of glass using fs laser pulses at low repetition rate, welding of other transparent materials has also been studied [18–20]. Ozeki *et al.* [21]

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successfully welded glass and copper, and achieved $a > 16$ MPa tensile joint strength. Sano *et al.* [22] have discussed the welding of polyethylene terephthalate and copper. However, to date, no similar experimental results but several theoretical calculations have been reported on the feasibility of fs laser welding of bulk metals. For instance, Lee [23] calculated the feasibility of ultrafast laser microwelding of metals based on the generation of a molten pool and came to the conclusion that metals could be welded by combining a large focal radius, a high pulse energy, and high fluence.

In this paper, we report the results of an experimental study designed to determine the feasibility of microwelding of metals with fs laser pulses. As a specific example, we have examined the role played by fluence and pulse number on the welding of an Ag microwire to a Cu substrate using irradiation with fs laser pulses. We also discuss some important aspects of the laser–matter interaction during welding and determine the possible fs laser-welding mechanism under our experimental configuration.

2. Experiment

Microwelding studies were carried out using an fs laser system (1 KHz, 800 nm, Coherent, Inc.) with a maximum pulse energy of 3.5 mJ and a pulse duration of 35 fs. Commercial 25 μm diameter pure Ag microwire and 125 μm thickness pure Cu sheet were used. Two different fixture setups are used to ensure the tight touch of the Ag microwire and the Cu sheet. One is a glass–tape fixture and the other is mechanical clamping fixture, which exposes ~2 mm long Ag microwire to the laser irradiation. The welding configuration with the glass–tape fixture is shown in Fig. 1, where the Cu sheet and the Ag microwire are covered by glass to make sure they contact tightly. The long axis of the Ag microwire is parallel to the direction of laser polarization (*S* polarization). Before laser irradiation, the Cu sheet was washed with dilute nitric acid to remove any surface oxide. Subsequently, both the Cu sheet and the cover glass were carefully cleaned with alcohol and then deionized water. To ensure reproducible welding conditions, the fluence was varied by changing the pulse peak power and the beam diameter separately. The pulse peak power was changed using a neutral density filter (Thorlab Inc.) and the beam diameter was varied by adjusting the distance of the convex lens to the sample. The pulse number was controlled using a shutter.

A scanning electron microscope (SEM, JEOL-JSM-6460) and a high-resolution scanning electron microscope (HRSEM, LEO 1530 Zeiss, Germany) were both equipped with an electron diffraction spectroscope (EDS), and were used to analyze the microstructure within the laser irradiation area and the weld to determine the nature of the laser–matter interaction and the mechanisms associated with microwelding under fs irradiation conditions.

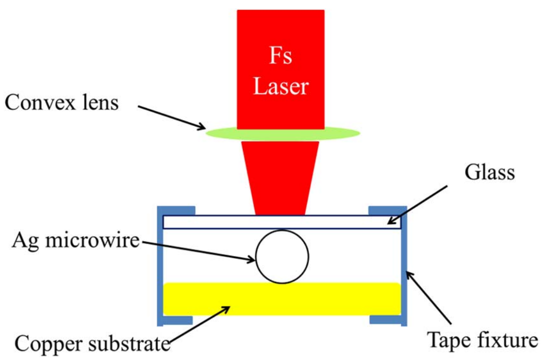

Fig. 1. (Color online) Schematic of fs laser microwelding experimental.

3. Results and Discussion

A. Effect of Pulse Number and Fluence on Weld Formation

Figure 2 shows SEM images of the samples (glass–tape fixture) after irradiation with different numbers of fs laser pulses. As shown in Figs. 2(a) and 2(b), there was no bonding between the Ag microwire and the Cu substrate after up to 1000 pulses at a fluence of 0.25 J/cm^2; only a deep indentation was left on the Cu substrate after the Ag wire fell off during sample handling. These indentations appear to be caused by the shockwave induced by the fs pulses. Along the indentation, an accumulation of matter was found, and EDS analysis [Fig. 2(b)] shows that its chemical

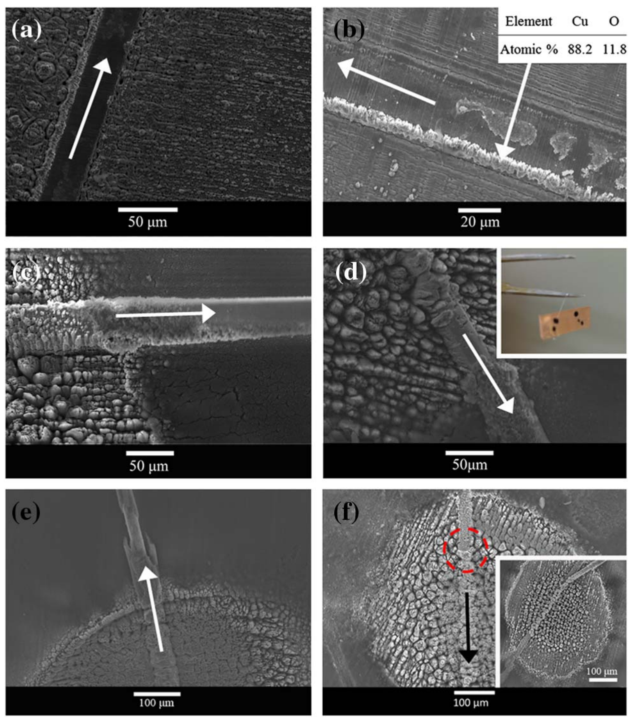

Fig. 2. (Color online) SEM images and EDS results of fs laser irradiated samples with glass–tape fixture: (a) 0.25 J/cm^2-500 pulses, (b) 0.25 J/cm^2-1000 pulses, (c) 0.25 J/cm^2-2000 pulses, (d) 0.25 J/cm^2-3000 pulses, (e) 1.02 J/cm^2-1000 pulses, and (f) 1.02 J/cm^2-2000 pulses. The arrows show the position and direction of the Ag microwire.

composition was primarily Cu together with a small amount of O. It indicates that this material resulted from redeposition of the fs laser ablated Cu particles along the edge of the Ag microwire. Moreover, we found that some parallel grooves on the surface of the Cu substrate formed along the direction of indentation [Fig. 2(b)]. These grooves correlate with the Fresnel diffraction pattern of the wire.

When the number of overlapping pulses increased to 2000–3000, as shown in Figs. 2(c) and 2(d), the Ag microwire could be successfully bonded to the Cu substrate. The figure in the inset in Fig. 2(d) clearly shows that the Ag microwire has bonded to the Cu substrate. However, under these conditions, laser irradiation caused serious damage to both the Cu substrate and the Ag microwire. The diameter of the Ag microwire was thinned out due to laser ablation, which removes material from the top of the wire; the substrate in the irradiated area was divided into small island-like structures, and cracks were generated on the substrate outside the irradiated area. These would probably affect the strength of the bond.

As the fluence was increased to 1.02 J/cm^2 [Fig. 2(e)], bonding of the Ag microwire to the Cu substrate could still be achieved and similar damage morphology was observed in the irradiated area. However, when the samples were irradiated with a large number of pulses at high fluence, part of the wire in the irradiated area became separated from the substrate and the bond tended to fail in the thinned out area of the wire. As shown in Fig. 2(f), under fs laser irradiation of 2000 pulses with fluence of 1.02 J/cm^2, the rim of the Ag microwire became separated from the substrate. We suggest that this can be attributed to the impact of the high-speed ablated material. As Salle *et al.* [24] have reported, the expansion speed of ablation products normal to the surface of Cu can reach 4.6 km/s during irradiation with 75 fs laser pulses at fluence of 21 J/cm^2. Although the laser fluence in this work was about 0.025–0.05 of that in Salle *et al.*'s study, the samples were subjected to several thousand overlapping pulses and the repetitive impact of high-speed ablated material could cause failure in the bond.

Similar phenomena were observed in samples irradiated in a mechanical clamping fixture. Figure 3 shows that after replacing the glass–tape fixture with mechanical clamping, the Ag microwire could be welded to the Cu substrate at a laser fluence of 0.08 J/cm^2, which is much lower than that required when welding with the glass–tape fixture. This is probably due to the attenuation of the damaged glass, since the pulse fluence in the glass–tape fixture experiment ($\geq 7.3 \times 10^{12}$ J/cm^2) is higher that the damage threshold of glass. When the samples were irradiated by 3000 and 4000 laser pulses [Figs. 3(a) and 3(b)], diffraction and interference-induced damage to the Cu substrate was serious but no welding was obtained. However, it is evident that when the pulse number increased from 3000 to 4000, melting of redeposited material occurred at the edge of the wire, as shown in Figs. 3(a) and 3(b). Welding of the Ag microwire to the Cu substrate could be achieved as well when the pulse number was increased to 6000 [Fig. 3(c)], and EDS analysis shows that the weld consisted of both Ag and Cu, indicating that a metallic weld can be produced in air by fs laser irradiation. Upon a further increase in the pulse number to 10,000 [Fig. 3(d)], the Ag microwire was severed by the intense laser ablation. At higher laser fluence (0.15 J/cm^2), only 1000 pulses were needed to produce a weld as shown in Figs. 3(e) and 3(f), and it was observed that material redeposited beneath the Ag microwire was melted and was welded to the wire. This significantly improves the strength of the weld, but under these conditions, the Ag microwire located at the center of the laser spot was seriously thinned out [Figs. 3(e) and 3(f)], which has a deleterious effect on weld strength. This effect arises from the higher power intensity at the center of the laser spot.

Microbonding of Ag microwire to a Cu substrate using fs laser pulses under different excitation conditions of different fluence and pulse numbers have also been studied, and the results are shown in Fig. 4. It is apparent that there is a relatively narrower fluence window for the production of successful welds between the Ag microwire and the Cu substrate with the mechanical clamping fixture than with the glass–tape fixture. In both weld configurations, the minimum number of pulses required to

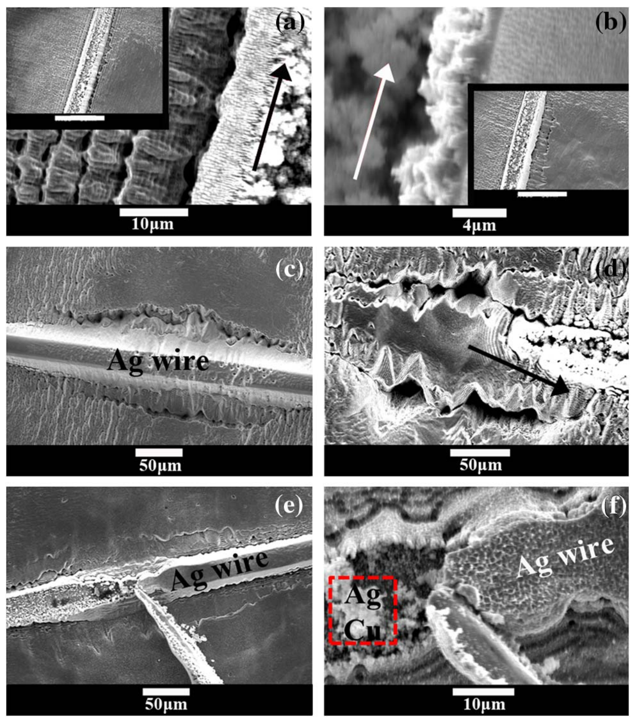

Fig. 3. (Color online) SEM images of the fs laser irradiated samples with mechanical clamping fixture: (a) 0.08 J/cm^2-3000 pulses, (b) 0.08 J/cm^2-4000 pulses, (c) 0.08 J/cm^2-6000 pulses, (d) 0.08 J/cm^2-10,000 pulses, and (e), (f) 0.15 J/cm^2-1000 pulses. The scale bar in the inset figures is 100 μm, and the arrows show the location and direction of the Ag microwire, which was removed.

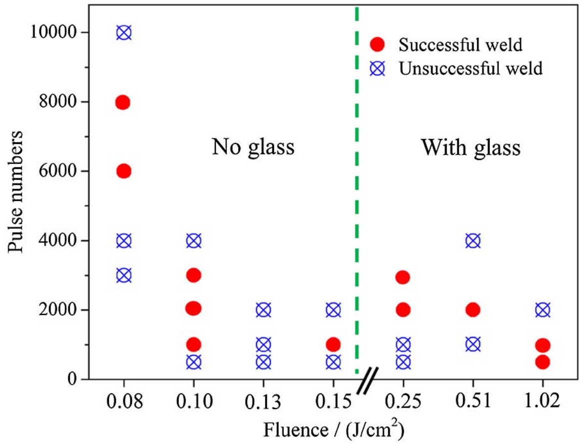

Fig. 4. (Color online) Summary of fs laser-induced microwelding of Ag microwire and Cu substrate.

obtain a successful bond was found to decrease with increasing laser fluence.

B. Microstructure and Characteristics of the Weld

To further study the formation of the weld between the Ag microwire and the Cu substrate, cross-sectional morphologies of the irradiated samples with the glass–tape fixture have been obtained. Figure 5 shows cross-sectional morphologies of the contact area and edge area of the samples after irradiation at a fluence of 1.02 J/cm^2 and indicates that Ag microwires were welded to the Cu substrate via a bridge of redeposited material. As shown in Figs. 5(a), 5(c), and 5(e), the gap between the wire and the substrate in

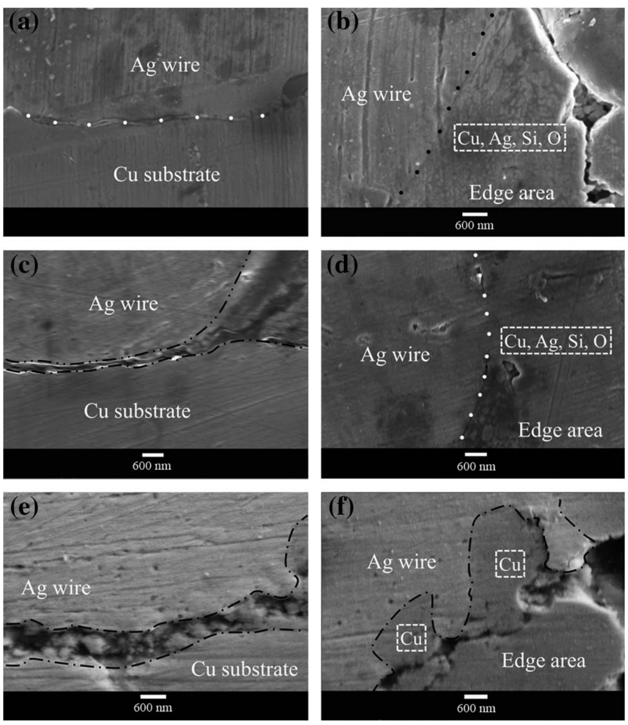

Fig. 5. Cross-sectional morphologies of the contact area (left) and edge area (right) in the samples irradiated at fluence of 1.02 J/cm^2 with different pulse numbers: (a), (b) 500 pulses; (c), (d) 1000 pulses; and (e), (f) 2000 pulses.

the contact area increased from ~100 to ~500 nm with an increase in the number of overlapping pulses. This is consistent with the analysis in Fig. 2(f), where the Ag microwire becomes separated from the Cu substrate after multiple impacts of high-speed ablated material. Images at the edge of the wire [Figs. 5(b), 5(d), and 5(f)] also show the impact effect of the ablated material. It is evident in Fig. 5(b) that a continuous boundary was formed between the Ag microwire and the redeposited material when the sample was irradiated by 500 laser pulses. No evident boundary between the Cu substrate and redeposited material was found. This indicates a bond was achieved between redeposited material and the Ag microwire/Cu substrate. Qualitative EDS analysis [shown by the red dashed square in Fig. 5(b)] indicates that the deposited material consisted of Cu, Ag, Si, and O. A similar effect was observed when the sample was irradiated by 1000 laser pulses [Fig. 5(d)], and suggests that weld between the Ag microwire and the Cu substrate can be achieved when ablated material is in contact with the Ag wire/Cu substrate and is then exposed to additional laser pulses. When the pulse number is increased to 2000 [Fig. 5(f)], redeposited material becomes incorporated into the Ag microwire. Under these conditions, some cracks appear between the wire and the redeposited material, but there is still a good welding over localized areas between the wire and the redeposited material. We find that this material is primarily composed of Cu [shown by the red dashed square in Fig. 5(f)], indicating that Si and O impurities can be eliminated by appropriately controlling irradiation parameters. Ordinarily, under the conditions of our experiments, Si and O do appear in the redeposited material as a result of damage to the cover glass. This will be further discussed in a later section.

As noted, a continuous boundary formed between redeposited material and the Ag microwire, suggesting that redeposited material has melted and wetted the wire. We attribute this melting to the heat accumulation at these locations. Although the interaction between fs laser radiation and these materials is nonthermal on a pulse-by-pulse basis [25], heat transfer does take place after the end of the laser pulse, causing an accumulation of heat in the sample after irradiation with many overlapping pulses [26]. In addition, since there is an air gap between the glass and the Cu substrate, any plasma produced by the fs laser-induced multiphoton and tunneling ionization of air [27,28] at high fluence and plasma-induced high pressure can enhance thermal energy coupling to the workpiece [29]. Finally, nano- or microparticles ablated by the fs laser and redeposited at the edge of the Ag microwire will form microscale cavities on the surface of the Ag microwire; these cavities could enhance the absorption of incident laser radiation by multiple reflection [30], form "hot spots"; at the interface between particles of redeposited material and the Ag wire, and contribute to the melting of redeposited material in the interface.

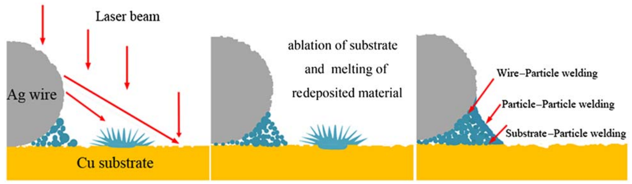

Fig. 6. (Color online) Schematic of fs laser microwelding process.

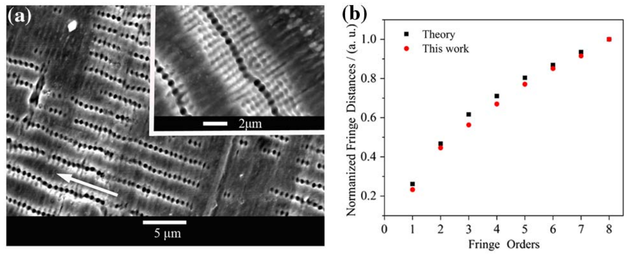

Fig. 7. (Color online) SEM morphologies of Cu substrate irradiated by 1000 laser pulse irradiation at a fluence of 0.25 J/cm^2: (a) periodical grooves and microholes and (b) comparison of experimental and calculated Fresnel diffraction pattern.

Based on the above analyses, we conclude that the primary weld between the Ag microwire and the Cu substrate occurs along the edge of the wire. This is probably because the area at the edge is directly exposed to fs laser radiation as well as to laser-induced plasma. Enhanced absorption of laser radiation via microstructure and surface plasmon resonance, as well as thermal coupling of plasma energy [29,30], will generate a higher temperature along the edge area than in the contact area resulting in the melting and welding of redeposited material. Figure 6 illustrates the geometry of the "bridging" weld generated when a debris field consisting of ablated Cu particles interacts with incident laser radiation and develops "hot spots." These "hot spots" are responsible for the fusion zone observed at the Ag wire–Cu particle and Cu particle–Cu substrate interfaces as well as the welds that exist between Cu particles in the space between the Ag wire and the Cu substrate. The overall effect is then to produce an extended network between the Ag wire and the Cu substrate made up of a loosely welded framework of linked Cu particles.

The integrity of laser-welded samples with glass–tape fixture was evaluated from the pull strength obtained using a Dage 4000 multipurpose tester, where the end without joint was taped to the surface of the Cu substrate. We find that the failure of the weld usually happens in the loosely welded framework of redeposited material, and the pull strength is $\leq$1.2 MPa. We attribute the low pull strength to the loosely welded framework and the presence of Si and O impurities in the weld [31].

C. Laser–Matter Interaction

Further information on the nature of the enhanced damage found in the Cu substrate close to the edge of the Ag wire on the weld can be obtained by examining the laser–matter interaction in more detail. Figure 7 shows the surface morphology of the Cu substrate after irradiation with 1000 overlapping laser pulses at a fluence of 0.25 J/cm^2. Figure 7(a) and the inset figure show that grooves accompanied by a periodic ripple and hole structure appear on this surface and are oriented parallel to the long axis of the microwire (as indicated by the arrow). This periodic ripple structure, which has been studied in some detail, can be attributed to interference between the incident laser light and excited surface plasmon polaritons [32–35]. We suggest that the grooves are caused by enhanced intensity due to Fresnel diffraction of incident laser light by the straight edge of the wire. Copper removed from these grooves is responsible for some of the redeposited material along the edge of the Ag microwire. To confirm this interpretation, we have compared our experimental data with that calculated from Fresnel diffraction [36] by taking the distance of the eighth fringe as 1; the error of the measured value is 1%. As seen in Fig. 7(b), the measured distances and the orders of the grooves away from the edge of the wire are in good agreement with the theory, indicating that Fresnel diffraction is important in determining the overall distribution of the laser field intensity during irradiation. For the holes, we measured the diameter of 100 holes in the grooves and found that the most prominent hole diameters are 275($\pm$30) and 330($\pm$30) nm. Because the wavelength of the incident light did not change when it passed through the glass (this was proved by comparing the distances of the ripples on the surfaces of irradiated Cu substrates with and without cover glass, where the distances were the same), it implies that nonlinear plasmon–photon interactions [37,38] at the Ag and Cu surfaces caused doubling and tripling of the laser frequency, and that radiative fields at these frequencies were present in the interaction region. This can be seen from the morphology of the surface of the damaged glass. Figure 8(a) shows the bottom surface of the cover glass, and indicates that the surface of the glass was damaged. This damage takes the form of circular craters with diameters between ~2 and 20 μm [Fig. 8(b)]. The internal surface of these craters is covered with ripples having a periodicity of 330($\pm$30) nm, as shown in the inset of Fig. 8(b). This periodicity is expected if the glass was damaged by the laser light reflected from the surface of the Cu substrate, where the frequency of reflected laser light doubled or even tripled due to the nonlinear

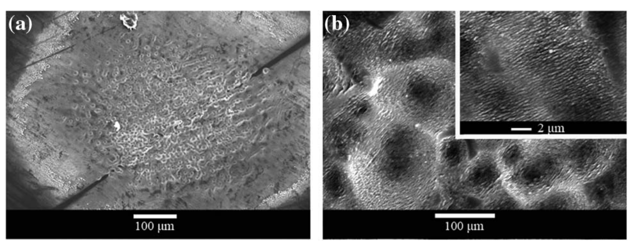

Fig. 8. SEM morphologies of the damaged cover glass: (a) general view and (b) craters and ripples.

interaction between incident fs laser light and the substrate as discussed above, and it suggests that the glass was damaged by the intense radiative field resulting from interference effects accompanying scattering and reflection of the laser light. The presence of short wavelength laser radiation in the region between the Cu substrate and the cover glass could enhance ionization of the gas and result in enhanced thermal energy coupling to the sample [29]. This indicates that nonlinear laser–matter interactions are important under the experimental conditions presently used for fs laser microwelding. Ultrahigh-repetition-rate picosecond laser sources may be an attractive alternative for increasing productivity in practical applications given the low fluence required for joining under these conditions.

4. Conclusions

In this study, we have demonstrated that it is possible to weld Ag microwire to a Cu substrate with pulsed excitation from an fs laser by controlling the diffraction-enhanced redeposition of Cu particles, which are generated from the ablation of the Cu substrate, even though the primary effect of fs laser irradiation of metals is known to produce ablation. Most of the welding between Ag and Cu occurs at the edge of the Ag microwire and is attributable to localized heating at the Cu particles, particles–Ag wire, and particles–Cu substrate interfaces. Microstructure-enhanced absorption of laser light on surfaces of Ag wire and Cu substrate, ablated nanoparticle-induced plasmon resonance, and plasma-enhanced thermal coupling are the main causes of localized heating, and produce a unique welding regime in which a fusion bond occurs at the interfaces between the Cu particle and the Ag microwire–Cu substrate, with bonding between these locations arising from welding of Cu particles. With the mechanical clamping weld configuration, a pure metallic weld between Ag microwire and Cu substrate is obtained, but there is a narrow range of laser fluence for successful weld. Replacing the mechanical clamping fixture with a glass–tape fixture can widen the laser fluence window for successful welding; however, the interaction of incident laser radiation with the glass cover sheet introduces impurities into the weld and negatively influences weld strength.

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References

1. W. W. Duley, *Laser Welding* (Wiley, 1999).
2. Y. Zhou, A. Hu, M. I. Khan, W. Wu, B. Tam, and M. Yavuz, "Recent progress in micro and nano-joining," J. Phys. Conf. Ser. **165**, 012012 (2009).
3. B. Tam, M. I. Khan, and Y. Zhou, "Mechanical and functional properties of laser-welded Ti-55.8 Wt Pct Ni nitinol wires," Metall. Mater. Trans. A **42**, 2166–2175 (2011).
4. G. S. Zou, Y. D. Huang, A. Pequegnat, X. G. Li, M. I. Khan, and Y. Zhou, "Crossed-wire laser microwelding of Pt-10 Pct Ir to 316 low-carbon vacuum melted stainless steel: part I. Mechanism of joint formation," Metall. Mater. Trans. A **43**, 1223–1233 (2012).
5. Y. D. Huang, A. Pequegnat, G. S. Zou, J. C. Feng, M. I. Khan, and Y. Zhou, "Crossed-wire laser microwelding of Pt-10 Pct Ir to 316 LVM stainless steel: part II. Effect of orientation on joining mechanism," Metall. Mater. Trans. A **43**, 1234–1243 (2012).
6. Z. W. Zhong, "Wire bonding using copper wire," Microelectron. Int. **26**, 10–16 (2009).
7. L. England and T. Jiang, "Reliability of Cu wire bonding to Al metallization," in *Proceedings of Electronic Components and Technology Conference* (IEEE, 2007), pp. 1604–1613.
8. H. Chen, S. W. Ricky Lee, and Y. T. Ding, "Evaluation of bond ability and reliability of single crystal copper wire bonding," in *Proceedings of High Density Microsystem Design and Packaging and Component Failure Analysis Conference* (IEEE, 2005), pp. 1–7.
9. S. Y. Hong, C. J. Hang, and C. Q. Wang, "Experimental research of copper wire ball bonding," in *Proceedings of the Sixth International Conference on Electronic Packaging Technology* (IEEE, 2005), pp. 1–5.
10. Y. H. Tian, I. Lum, S. J. Won, S. H. Park, J. P. Jung, M. Mayer, and Y. Zhou, "Experimental study of ultrasonic wedge bonding with copper wire," in *Proceedings of the 6th International Conference on Electronic Packaging Technology* (IEEE, 2005), pp. 389–393.
11. N. Bärsch, K. Körber, A. Ostendorf, and K. H. Tönshoff, "Ablation and cutting of planar silicon devices using femtosecond laser pulses," Appl. Phys. A **77**, 237–242 (2003).
12. C. Li, S. Nikumb, and F. Wong, "An optimal process of femtosecond laser cutting of NiTi shape memory alloy for fabrication of miniature devices," Opt. Lasers Eng. **44**, 1078–1087 (2006).
13. Y. Li, K. Itoh, W. Watanabe, K. Yamada, D. Kuroda, J. Nishii, and Y. Jiang, "Three-dimensional hole drilling of silica glass from the rear surface with femtosecond laser pulses," Opt. Lett. **26**, 1912–1914 (2001).
14. G. Kamlage, T. Bauer, A. Ostendorf, and B. N. Chichkov, "Deep drilling of metals by femtosecond laser pulses," Appl. Phys. A **77**, 307–310 (2003).
15. T. Kondo, S. Matsuo, S. Juodkazis, and H. Misawa, "Femtosecond laser interference technique with diffractive beam splitter for fabrication of three-dimensional photonic crystals," Appl. Phys. Lett. **79**, 725–727 (2001).
16. B. Tan, N. R. Sivakumar, and K. Venkatakrishnan, "Direct grating writing using femtosecond laser interference fringes formed at the focal point," J. Opt. Pure Appl. Opt. **7**, 169–174 (2005).
17. T. Tamaki, W. Watanabe, J. Nishii, and K. Itoh, "Welding of transparent materials using femtosecond laser pulses," Jpn. J. Appl. Phys. **44**, 687–689 (2005).
18. T. Tamaki, W. Watanabe, and K. Itoh, "Laser micro-welding of transparent materials by a localized heat accumulation effect using a femtosecond fiber laser at 1558 nm," Opt. Express **14**, 10460–10468 (2006).
19. W. Watanabe, S. Onda, T. Tamaki, K. Itoh, and J. Nishii, "Space-selective laser joining of dissimilar transparent materials using femtosecond laser pulses," Appl. Phys. Lett. **89**, 021106 (2006).
20. I. Miyamoto, A. Horn, J. Gottmann, D. Wortmann, and F. Yoshino, "Fusion welding of glass using femtosecond laser pulses with high-repetition rates," J. Laser Micro. Nanoeng. **2**, 57–63 (2007).
21. Y. Ozeki, T. Inoue, T. Tamaki, H. Yamaguchi, S. Onda, W. Watanabe, T. Sano, S. Nishiuchi, A. Hirose, and K. Itoh, "Direct welding between copper and glass substrates with femtosecond laser pulses," Appl. Phys. Express **1**, 082601 (2008).
22. T. Sano, S. Iwasaki, Y. Ozeki, K. Itoh, and A. Hirose, "Femtosecond laser direct joining of copper with polyethylene

terephthalate," presented at Materials Science & Technology, Houston Texas, 17–21 October 2010.
23. D. Lee, "Feasibility study on laser microwelding and laser shock peening using femtosecond laser pulses," Ph.D. thesis (University of Michigan, 2008).
24. B. Salle, O. Gobert, P. Meynadier, M. Perdrix, G. Petite, and A. Semerok, "Femtosecond and picoseconds laser microablation: ablation efficiency and laser microplasma expansion," Appl. Phys. A **69**, S381–S383 (1999).
25. D. Linde, K. Sokolowski-Tinten, and J. Bialkowski, "Laser–solid interaction in the femtosecond time regime," Appl. Surf. Sci. **109/110**, 1–10 (1997).
26. S. M. Eaton, H. Zhang, and P. R. Herman, "Heat accumulation effects in femtosecond laser written waveguides with variable repetition rate," Opt. Express **13**, 4708–4716 (2005).
27. H. M. Milchberg, T. R. Clark, C. G. Durfee, T. M. Antonsen, and P. Mora, "Development and applications of a plasma waveguide for intense laser pulses," Phys. Plasma **3**, 2149–2155 (1996).
28. C. Guo, M. Li, J. P. Nibarger, and G. N. Gibson, "Single and double ionization of diatomic molecules in strong laser fields," Phys. Rev. A **58**, R4271–R4274 (1998).
29. A. Y. Vorobyev and C. Guo, "Enhanced energy coupling in femtosecond laser metal interactions at high intensities," Opt. Express **14**, 13113–13119 (2006).
30. A. Y. Vorobyev and C. Guo, "Enhanced absorptance of gold following multipulse femtosecond laser ablation," Phys. Rev. B **72**, 195422 (2005).
31. S. Nisaratanaporn and E. Nisaratanaporn, "The anti-tarnishing, microstructure analysis and mechanical properties of sterling silver with silicon addition," J. Metals Mater. Miner. **12**, 13–18 (2003).
32. A. Y. Vorobyev and C. Guo, "Direct femtosecond laser surface nano/microstructuring and its applications," Laser Photon. Rev., 1–23 (2012).
33. A. Borowiec and H. K. Haugen, "Subwavelength ripple formation on the surfaces of compound semiconductors irradiated with femtosecond laser pulses," Appl. Phys. Lett. **82**, 4462–4464 (2003).
34. A. Y. Vorobyev and C. Guo, "Spectral and polarization responses of femtosecond laser-induced periodic surface structures on metals," J. Appl. Phys. **103**, 043513 (2008).
35. J. Bonsea, J. Krüger, S. Höhm, and A. Rosenfeld, "Femtosecond laser-induced periodic surface structures," J. Laser Appl. **24**, 042006 (2012).
36. Y. L. Vladimirsky, A. Bourdillon, O. Vladimirsky, W. L. Jiang, and Q. Leonard, "Demagnification in proximity x-ray lithography and extensibility to 25 nm by optimizing Fresnel diffraction," J. Phys. D **32**, L114–L118 (1999).
37. F. Brown, R. E. Parks, and A. M. Sleeper, "Nonlinear optical reflection from a metallic boundary," Phys. Rev. Lett. **14**, 1029–1031 (1965).
38. N. B. Grosse, J. Heckmann, and U. Woggon, "Nonlinear plasmon-photon interaction resolved by k-space spectroscopy," Phys. Rev. Lett. **108**, 103802 (2012).