超短脉冲激光微焊接玻璃进展

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摘要　近年来,随着元器件不断小型化及人们对产品高密度、高可靠性要求的提高,有效的微连接已成为微加工的重要环节之一。虽然目前已有多种方法可以实现同种材料或异种材料间的微连接,但对于玻璃等透明易碎材料,实现有效的微连接一直是一个挑战。目前激光已被广泛应用于焊接各种材料,但普通长脉冲激光的能量不易被玻璃吸收而且热膨胀易使玻璃碎裂,并不适合微焊接玻璃等透明材料。超短脉冲激光与透明材料相互作用具有热效应小及非线性吸收的特点,非常适合透明材料的微焊接,目前已经成为微加工领域的研究热点。介绍了超短脉冲激光微焊接玻璃的机理、存在的问题以及潜在应用,并对其未来发展进行了展望。

关键词　材料; 超短脉冲激光; 微连接; 微焊接; 玻璃; 飞秒激光; 皮秒激光

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Recent Progress in Ultrashort Pulsed Laser Microwelding of Glasses

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Abstract　In recent years, with the continuous miniaturization of components and the requirements for more compact and highly reliable products, effective microjoining has become one of the important parts of micromanufacturing. Several methods have been successfully used to microjoin similar or dissimilar materials. However, for transparent and fragile materials, such as glasses, the effective microjoining has been a challenge. Nowadays, a few kinds of lasers have been widely used for welding many materials, but for lasers with long pulse width, the energy can hardly be absorbed and the thermal expansion may make the glasses broken, which is not suitable for glasses microjoining. Due to the excellent characteristics of little thermal effect of heating materials and nonlinear absorption, ultrashort pulsed lasers are very suitable for microjoining glasses, which has become a hot research field of micromanufacturing. The mechanism of ultrashort pulsed laser microwelding of glasses, the existing problems and the potential applications are elaborated. The future trends of ultrashort pulsed laser microwelding of glasses are also prospected.

Key words　materials; ultrashort pulsed laser; microjoining; microwelding; glasses; femtosecond laser; picosecond laser

OCIS codes　160.2750; 320.7090; 350.3390

1　引　　言

微连接是指以提供机械耦合、封装集成、电连接或隔离保护而过程中并不对器件功能和可靠性产生影响的连接技术。近年来微连接技术已被广泛应用于包括植入式医疗器件、微型传感器、转换器、电池、光电子器件等在内的微型元器件、装置或系统的制造或组装过程,过程中并不对器件的功能和可靠性产生影响[1]。

现有的微连接方法包括胶粘剂粘接、阳极键合、固相连接、熔融微焊接等。粘接是使用胶粘剂将两个表面连接起来。虽然胶粘剂可以连接不同材料,但是胶粘剂释放气体、光致漂白导致过早老化,可能导致周围

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器件受到污染,同时在如航空应用和高功率激光器设计等需要经受巨大的温度变化的情况下,胶粘剂热降解和热膨胀的应力积累会减少胶粘剂的使用寿命[2]。阳极键合[3]是将抛光后的玻璃同半导体或金属叠放在一起,然后加热至300 ℃~500 ℃,再将金属或半导体做正极,通200~2000 V直流电,等到电路中电流稳定再缓慢冷却至室温完成连接。阳极键合具有所需温度相对较低、键合界面牢固、长期稳定性好、连接速度快且可连接不同材料等优点,在微机电制造和微流体领域得到了广泛应用,但是该技术的不足在于需要两键合材料的热膨胀系数相近,否则在键合的冷却过程中会因较大的内部应力导致破碎。固态微连接是指材料不发生熔化,主要依靠原子之间的扩散或塑性流动实现的连接方式,通常有固态扩散焊、超声波焊、摩擦焊、爆炸焊等多种实现方法。不同固态连接有各自的优缺点,如扩散焊可以焊接不同金属、陶瓷以及复合材料而且能实现大面积焊接,但是待焊表面制备要求高且焊接时间较长。熔融微焊接是通过局部加热使材料融化再凝固实现连接。因热源不同,熔融微焊接分为电弧微焊接、激光微焊接、电子束微焊接等。因熔融焊接过程中有内在的高温相变,材料内部形成热影响区而使不同热膨胀系数的材料焊接容易出现破裂。

激光微焊接是指使用激光在至少一个维度上实现尺寸小于100 μm的焊接技术[1,4-7]。作为精密电阻点焊的替代方案,激光微焊接具有连接强度高、精度高、灵活、非接触、热影响区和热畸变极小、工件形状限制少以及单步操作等优点,已在电子、汽车和医学等领域的微元件焊接中发挥了重要作用,并在工业领域中得到了迅速发展。例如激光微焊接已应用于CD机微型电机的组装、硬盘驱动器悬架中的不锈钢薄层、光学光纤连接器、汽车元件聚合物的透射焊接等[8],图1所示为激光微焊接在锂离子电池和微发动机方面的应用。

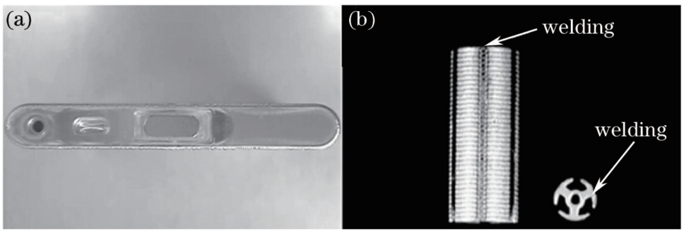

图1 激光微焊接应用。(a) Nd:YAG脉冲激光焊接锂离子电池; (b) Nd:YAG脉冲激光微焊接小发动机[8]

Fig.1 Applications of laser microwelding. (a) Welding of lithium ion battery by pulsed Nd:YAG laser; (b) Nd:YAG laser microwelding of small motor[8]

虽然激光微焊接技术已被广泛应用到工业加工制造中,但微焊接玻璃等透明材料却比较困难,原因在于激光能量很难被透明材料吸收,同时玻璃材料质地本身较脆,焊接过程中的热膨胀容易使其破裂,此外热效应也会极大地影响玻璃的透射率等性能,以至于玻璃的微焊接被广泛认为是一大难题。

通常有两种方法解决激光微焊接透明材料。一种是在焊接界面加入中间层或者将下层材料的上表面涂上波长不透明的颜料来增加光束能量在界面的吸收[9],然后通过热传导将吸收的能量传递到上层材料,经过材料融化再凝固的过程实现透明材料的焊接。另一种方法即采用超短脉冲激光微焊接[10]。超短脉冲激光是指脉冲宽度为皮秒(10^{-12} s)至飞秒(10^{-15} s)尺度的脉冲激光,其具有加工精度高、热影响区小、不易破裂、连接强度较高、可空间选择性加工等突出优点,近年来在微焊接领域受到越来越多的重视。当超短脉冲激光的光强超过一定阈值[11-12],会在透明介质内部产生非线性吸收,并使材料在焦点处熔融以实现透明介质的微焊接。超短脉冲激光不同于连续和长脉冲激光只能加工对其波长不透明的介质表面。图2显示不同激光微焊接透明材料方法,图2(a)和(b)均使激光能量被线性吸收实现焊接,图2(c)为超短脉冲激光在透明材料内部非线性吸收。

超短脉冲激光微焊接透明材料具有很多优点。首先,因为超短脉冲激光的超强光强特性,在透明介质内部产生非线性吸收,可以实现透明材料三维空间的选择性微焊接[13]。其次,超短脉冲激光作用透明介质因多光子吸收的阈值效应和激光光束的高斯特性,使得超短脉冲激光加工的结构尺寸可以突破光学衍射极限,甚至可以实现小于激光波长的纳米尺寸的精密加工。另外,超短脉冲和材料相互作用时间极短,有效避免了材料出现明显的热扩散,进而避免长脉冲加工过程的冲击波等对材料的热损伤,有效避免了材料因不同热膨胀系数导致热应力产生裂纹和溅射物,且加工的范围仅在焦斑附近,加工区域边缘平滑,极大地提高了加工精度。相比粘接等其他连接技术,超短脉冲激光微焊接玻璃还不需在焊接材料中间加入填充物或中间层,焊接后材料的连接强度也较高,适用于对结构强度要求较高的航空航天等领域。

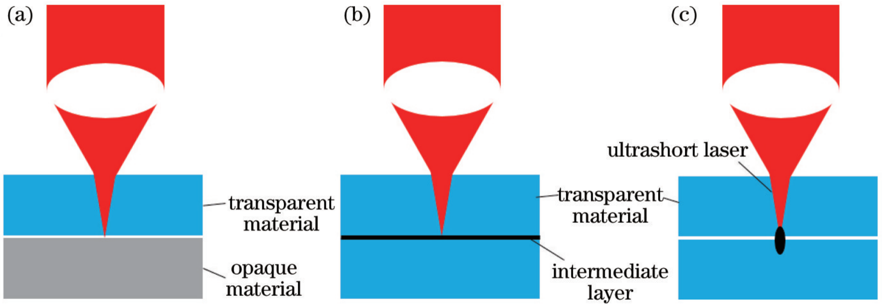

图 2 不同激光微焊接方法。(a) 不透明材料线性吸收；(b) 插入中间层的线性吸收；
(c) 超短脉冲激光作用透明材料的非线性吸收

Fig.2 Different methods of laser microwelding. (a) Linear absorption of opaque material; (b) linear absorption of the intermediate layer; (c) non-linear absorption of transparent material by using ultrashort laser

2 超短脉冲激光微焊接玻璃研究进展

2.1 超短脉冲激光微焊接玻璃原理

对玻璃等透明固体介质来说，超短脉冲激光在介质中传播会出现非线性吸收[11,14-15]、熔化损伤[12]、等离子体形成[16-17]、烧蚀[18-19]、光丝传播[20]等多种现象。图 3 为不同功率密度及时间尺度下，超短脉冲激光与固体材料相互作用发生的各种现象。

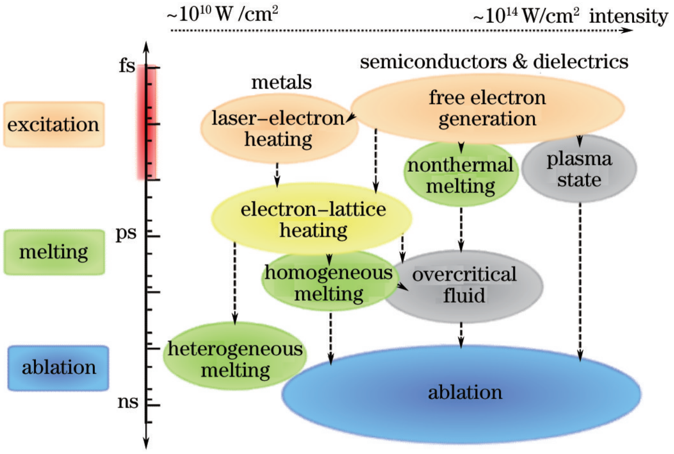

图 3 不同功率密度及时间尺度下，超短脉冲激光与固体材料相互作用现象分类[21]

Fig.3 Classification of phenomena of different timescales and intensity ranges during and after irradiation of a solid materials with a ultrashort laser pulse[21]

强度较大的超短脉冲激光辐照透明材料时，非线性过程如多光子吸收、隧道电离或雪崩电离是材料内自由载流子形成的主要机制[12,22]，多光子吸收或隧道电离把自由电子从价带激发到导带，种子电子进一步通过逆韧致辐射加速，如果这些种子电子动能足够大，可通过雪崩电离使电子数进一步快速增加。Linde 等[16]使用 120 fs 脉冲激光辐照熔融石英，当激光的功率密度约为 10^{13} W/cm^{2}时，材料发生损伤解离，形成等离子体和液体池，激光功率密度由低到高增强，致使形成的等离子体密度超过临界密度，等离子体形成镜面屏蔽，材料对能量的吸收达到饱和，液相的熔融材料最终固化。Kudriašov 等[20]用 130 fs 激光脉冲辐照熔融石英，在实验上观测到光丝的形成和光丝对材料折射率的永久改性，增加飞秒激光功率到自聚焦临界功率若干倍时，发现了多光丝效应。图 4 为超短脉冲激光微焊接玻璃过程。首先聚焦在两玻璃交界面处的超短脉冲激光使玻璃材料发生光电离，界面处玻璃受热熔化，最终熔融体凝固实现玻璃的焊接。

超短脉冲激光以脉冲宽度是否大于焦体积内的热扩散所需时间可分为低重复频率和高重复频率两种情况[23]。通常认为重复频率在 1~200 kHz 的脉冲为低重频，高于 200 kHz 为高重频。2005 年，日本大阪大学 Tamaki 等[24]首次在不插入光吸收中间层的情况下，使用 1 kHz 低重频脉冲将相同的两块熔融石英玻璃成功微焊接，2006 年又实现了硼硅酸盐玻璃和熔融石英之间不同玻璃的微焊接[13]。焊接过程中激光在透明介质内部形成 20~30 μm 由等离子体衍射和克尔效应自聚焦平衡产生的光丝，聚焦区域因为光丝沿着光轴

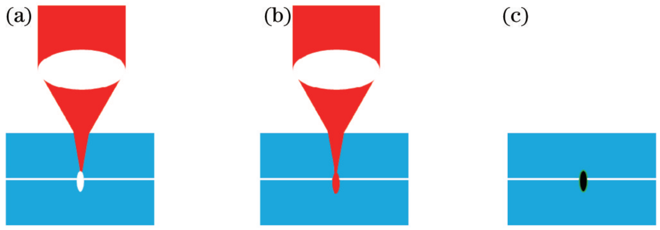

图4 超短脉冲激光微焊接玻璃过程。(a) 超短脉冲激光在焦点处产生光电离; (b) 界面玻璃熔化和凝固; (c) 再凝固实现微焊接

Fig.4 Schematic diagram of the process of the ultrashort laser pulses microwelding glasses. (a) Laser is focused at the interface of two glasses, and optical ionization is initiated by nonlinear optical absorption only around the focal volume; (b) glass of interface melts and resolidificates; (c) resolidification of the materials results in microjoining

拉长,高强度光丝引发非线性吸收场电离(多光子吸收、隧道电离)和雪崩电离。这种非线性吸收导致焦体积内的电子电离产生等离子体,材料熔化形成液体池,在界面处填充材料间的间隙之后再凝固将两材料连接起来。这样通过在垂直光轴的二维平面光丝扫描使得材料在宏观上被连接在一起。在熔融石英的荧光光谱分析中发现,等离子体形成过程中Si—O键断裂,导致缺陷形成并生成了非桥氧空穴中心。图5显示为1 kHz低重频飞秒激光连接硼硅酸盐玻璃的显微图像。

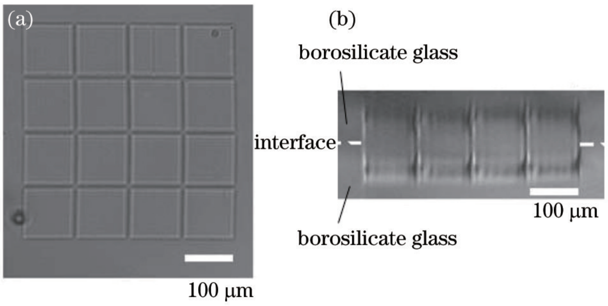

图5 1 kHz低重频飞秒激光微焊接硼硅酸盐玻璃显微图像。 (a) 俯视图; (b) 侧视图[25]

Fig.5 Microscopic optical image of femtosecond laser microjoining borosilicate glasses. (a) Top view; (b) side view at 1 kHz[25]

另一方面,使用高重频飞秒激光因为多脉冲之间间隔可与热扩散时间间隔相比拟甚至比热扩散时间短,脉冲能量来不及扩散而累积在焦体积处,相比低重频脉冲激光具有更强的局部热效应,更容易将透明介质熔化实现焊接,而且焊接处理的速度也可以大幅提高。如图6所示,当低重频(如1 kHz)脉冲作用材料时,脉冲能量在下一个脉冲到达前已经扩散出焦体积外,不发生热累积;而当高重频(如1 MHz)作用材料时,脉冲能量在还未热扩散出焦体积前,之后的脉冲又相继到达,产生热累积效应,使用高重频脉冲作用材料能得到更高的温度。

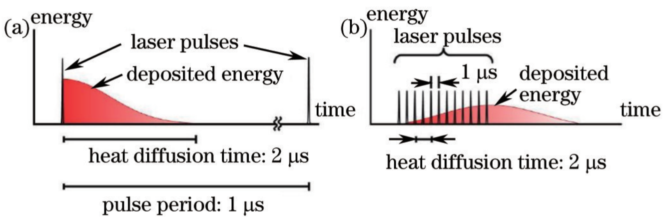

图6 脉冲重复频率和能量沉积关系。(a) 低重频 (如1 kHz) 脉冲能量在下一个脉冲到达前已经扩散出焦体积外; (b) 高重频 (如1 MHz) 时单脉冲能量在还未热扩散出焦体积前又有脉冲到达,能取得更高温度[26]

Fig.6 Relation between repetition rate and energy deposition. (a) At low repetition rate (e.g. 1 kHz), the energy deposited by each laser pulse diffuses out of the focal volume before the next pulse arrives; (b) at high repetition rate (e.g. 1 MHz), energy accumulates in the focal volume making it possible to achieve higher temperatures around the focal volume[26]

日本理化所的Sugioka等[27-29]研究了双脉冲之间延迟时间对热影响区和连接强度的影响。他们使用抽运-探测技术分析超快脉冲诱导的瞬时吸收来解释双脉冲微焊接的物理机制。他们使用360 fs、200 kHz延迟时间为10 ps的双脉冲微焊接Foturan玻璃实现了22.9 MPa的连接强度,比单脉冲焊接实现的连接强度高22%。他们在对不同延迟的双脉冲的非线性吸收机制进行分析后,得到两种情况,其中双脉冲延迟时间小于

30 ps情况下自由电子的激发和弛豫分别是0.98、20.4 ps,第二个光脉冲自由电子的单光子吸收为主要过程,导致较高连接强度,而延迟时间大于30 ps情况下的导带-局域态和局域态-价带时间分别为104.2、714.3 ps,局域态电子通过单光子吸收第二个脉冲46%的能量(功率为155 mW时)形成受激-局域态,由于局域态电子通过单光子吸收比自由电子能更高效激发,所以相比单脉冲焊接有更高的连接强度。

大阪大学Miyamoto等建立的理论模型[15,30-34]显示超短脉冲激光作用透明材料内部的改性区增加并不是因为热累积,而是由于非线性吸收的增加。当超短脉冲激光聚焦到透明材料中时,激光能量被光电离吸收而产生雪崩电离,被等离子体吸收的脉冲能量被转移到晶格形成温度场。因为被自由电子吸收的激光能量转移到晶格的时间快于热扩散,所以将激光能量视为即时热源。由热传导模型得出超短脉冲激光作用如硼硅酸盐玻璃的透明介质时会出现内外双层结构,模型所得的结论和实验结果符合较好。高重复频率脉冲激光在透明介质内形成双结构过程首先是超短脉冲激光紧聚焦到材料内部,激光能量通过多光子电离被吸收,接着在焦体积内通过雪崩电离产生等离子体,随着脉冲数增加,被吸收区顶部雪崩电离吸收激光能量逐渐累积,激光吸收区域朝着光源方向扩展产生等离子体柱状区,形成自由电子密度高达$10^{19}/\mathrm{cm}^3$的内层结构,而熔融区相应形成外层结构,双层结构如图7所示。

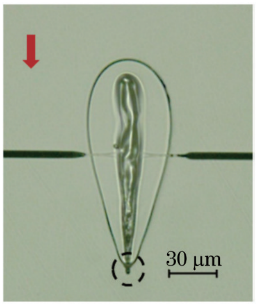

图7 1 MHz的10 ps脉冲激光微焊接D263玻璃SEM图像,红色箭头为激光入射方向,虚线圆为熔融区域底部[35]

Fig.7 Exemplary SEM image of a weld seam generated between two D263 glass plates with 10 ps pulse width at 1 MHz repetition rate. The red arrow is the laser beam direction and the dashed circle points to the bottom tip of the molten zone[35]

2.2 超短脉冲激光微焊接玻璃研究进展

Tamaki等[35-37]用500 kHz的高重频飞秒光纤激光系统实现非碱玻璃和硅片的焊接,并得到了3.74 MPa的连接强度,而非碱铝硅酸盐玻璃之间的连接强度达到9.87 MPa。Lacroix等[2,38-40]使用70 fs/55 fs、250 kHz脉冲激光的光丝效应用于增强光学连接熔融石英、BK7玻璃,得到的连接具有耐热冲击的特点,同时熔融石

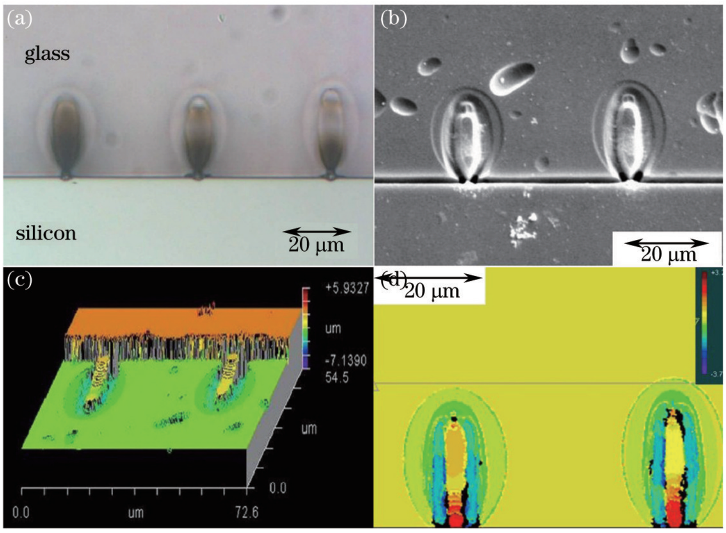

图8 350 fs超短脉冲激光微焊接玻璃-硅。(a) 玻璃内横截面光学显微图;(b) SEM图;(c)、(d) 玻璃-硅浸蚀后的横截面图像[44]

Fig.8 Microwelding glass and silicon plates by using 350 fs ultrashort laser. (a) Cross-section of glass-silicon welding seams with focal position in the glass detected by light microscopy; (b) SEM; (c), (d) cross-section of glass-silicon welding seams after etching[44]

英焊接得到的剪切应力是光学接触连接的3倍而光透射率不发生改变。他们还使用Weibull拟合来评估方法的可靠性。Richter等[41-42]使用450 fs、9.4 MHz高重频飞秒激光成功实现熔融石英、硼硅酸盐玻璃、Zerodur、BK7和ULE等玻璃之间的相互微焊接，另外还将高重频飞秒脉冲激光经声光调制得到的相邻时间间隔约10 ms的脉冲群(Burst)作用熔融石英，相比连续脉冲得到的熔化结构更大，还有效减少了激光诱导的应力，通过优化脉冲群频率和重复频率后焊接的最大破坏应力相当于材料本身强度的96%。Horn等[43]使用350 fs、0.7 MHz脉冲激光焊接硼硅酸盐玻璃和硅并研究了焊缝形态和折射率的改变。图8(a)、(b)为350 fs超短脉冲激光微焊接玻璃-硅的横截面光学显微图和扫面电镜图(功率为250 mW，移动速度30 mm/min)，图8(c)、(d)为玻璃-硅浸蚀后的横截面图像。

美国PolarOnyx公司使用飞秒光纤激光器的750 fs，1 MHz高重复频率脉冲直写单线/多线熔融石英，实现玻璃的焊接和它们中间的密封[45]，如图9所示，其中LED为发光二极管。

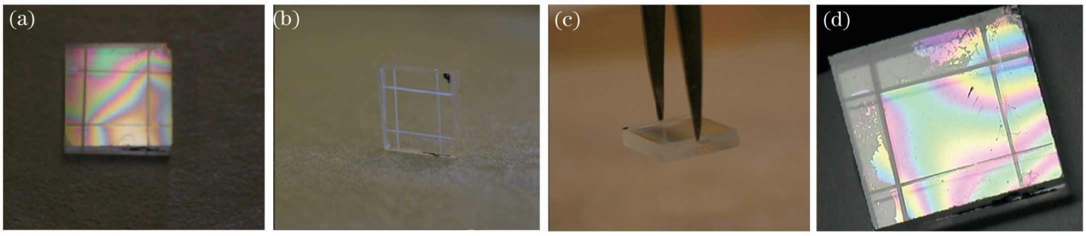

图9　超短脉冲激光密封熔融石英。(a) 超短脉冲激光多线微焊接顶视图，密封区域没有干涉边缘；(b) LED背光照明通过4条焊缝的透射图；(c) 镊子夹着焊接后密封好的玻璃顶部；(d) 浸水后四边密封后的中间区域没有水渗入[45]

Fig.9 Sealing two fused silica glasses by ultrashort pulse laser. (a) Top view with no interference fringe seen for the sealing seams; (b) transmission view of the 4 welding seams with LED backlight illumination; (c) holding the top glass sample by tweezers after ultrashort laser microwelding; (d) water immersion can not penetrate into the center region well sealed by ultrashort pulse laser[45]

超短脉冲激光在介质内能量分布和热传导过程可以通过模型进行模拟[15,30-34,46-49]。Kongsuwan等[48]使用130 fs，1 kHz激光脉冲透射焊接两硼酸盐玻璃，在考虑时空特性和光束的传播特性情况下，建立的数值模型研究了脉冲能量和数值孔径对吸收体积尺寸和形状的影响，预测了其泪滴状结构的吸收体积，其理论宽度和实验结果相吻合，意味着可以通过控制脉冲的能量和数值孔径大小来获得玻璃理想的吸收体积以改进焊接性能，另外他们还通过空间分辨的微压痕研究了焊缝的力学特性的改变。

Miyamoto等[33]给出的热传导模型在移动速度为1~100 mm/s范围内的计算值和实验结果符合较好，模型显示重复频率通过影响雪崩电离，进而影响飞秒激光脉冲非线性吸收的效率，即给定能量，增加重复频率，热激发自由电子密度增大，雪崩电离增强，非线性吸收增加；而平均激光功率给定，非线性吸收率随重复频率减小。他们给出了10 ps脉冲激光同玻璃(Schott D263、Foturan等)相互作用模型和热传导模型[15,32,35,50-51]，并采用三点弯曲测试评估了连接的机械强度和剪切强度。他们在研究超短脉冲激光对裂纹产生影响时发现重频超过200 kHz，焊接材料内部熔化没有裂纹产生，于是可以微焊接具有较大热胀系数的透明材料如硼硅酸盐玻璃和Foturan玻璃等，而连续激光仅能焊接如熔融石英等热胀系数小的玻璃。另外他们还发现在改变重复频率时，因为没有玻璃网络修饰离子，熔融石英的微焊接不会出现内层结构，而硼硅酸盐玻璃会在高重频时出现内外双层结构，该双层结构又多为无裂纹区域。Miyamoto等认为这是因为在低重频(如50~100 kHz)时没有热激发电子，光电离产生自由电子引发雪崩电离，而高重频热激发的自由电子引发雪崩电离。

京都大学的Shimizu等[49,52]使用70 fs、250 kHz脉冲作用钠钙硅玻璃研究分析了玻璃内部的三维温度分布和双结构改性形成机理。由玻璃内部的温度分布评估得到的光吸收率约为80%，比透射损失测量得到的值小3.5%。而根据温度和应力分布，他们认为改性区外层是由粘弹性形变造成，改性区域的内层则是因为玻璃材料的流动形成。另外，还有Utsumi等[53]深入研究了100、500 kHz的10 ps脉冲激光焊接玻璃球和玻片。Carter等[54]使用皮秒脉冲激光实现了玻璃和铝、铜、硅、不锈钢等各种金属或半导体的微焊接。表1为Sugioka等总结的近年在超短脉冲激光微焊接玻璃领域的研究进展[55]。

表1 超短脉冲激光微焊接各种玻璃的研究进展[55]

Table 1 Research progress on ultrafast laser welding for various of glass materials[55]

Bonded materials	Laser			Remarks	References
	Pulse width	Wavelength	Repetition rate		
Fused silica	130 fs	800 nm	1 kHz	First demonstration of glass welding by ultrafast laser	[24]
	550 fs	515 nm	9.4 MHz	Welding by femtosecond laser bursts	[42]
	750 fs	1030 nm	up to 1MHz	Complete four edge sealing by multiline scanning	[45]
	550 fs	515 nm	9.4 MHz	Breaking stress up to 75% of bulk fused silica	[56]
Fused silica borosilicate glass	85 fs	800 nm	1 kHz	Characterization of joint strength	[25]
Borosilicate glass	10 ps 16 ps		up to 500 kHz 1 kHz	Superiority of ps laser in glass welding as compared with fs laser	[34]
	406 fs 325 fs	1045 nm 1045 nm	1MHz 100 kHz	Dependence of repetition rate, thermal conduction model	[33]
	10 ps	1064 nm	50 kHz~ 1 MHz	Simulation by thermal conduction model	[57]
	10 ps	1064 nm	1 MHz	Defect-free welding by prebonding the samples by optical contact	[58]
	350 fs	1045 nm	0.7 MHz	Dependence of dimension and geometry of welding seam on scan speed, repetition rate and pulse energy	[59]
	350 fs	1045 nm	up to 1 MHz	Geometry of welding seam	[43]
Soda-lime glass	10 ps	1064 nm	up to 8.2 MHz	Measurements of shear strength and bonding energy for different experimental conditions	[35]
Non-alkali alumino silicate glass	360 fs	1558 nm	500 kHz	Localized heat accumulation effect	[36]
Photosensitive (Foturan) glass	360 fs	1045 nm	200 kHz	Double-pulse irradiation	[29]
	360 fs	1045 nm	200 kHz	Double-pulse irradiation, characterization, mechanism	[28]
	360 fs	1045 nm	200 kHz	Double-pulse irradiation, mechanism	[27]
	10 ps	1064 nm	50 kHz to 8.2 MHz	Relation of mechanical strength on the averaged absorbed laser power	[15]
Glass slide	10 ps	1064 nm	1 MHz	Dependence of hear force and shear strength on focal displacement from the joining surface	[51]
Fused silica fused silica/borosilicate glass	70 fs	787 nm	10~300 kHz	Filamentation based ultrafast laser welding	[40]
	70 fs	790 nm	250 kHz	Bonding of dissimilar materials	[39]
Fused silica/ borosilicate glass	85 fs	800 nm	1 kHz	Welding of dissimilar materials	[13]
	10 ps	1064 nm	0.5~2 MHz	Mechanical properties of welded seams	[60]
Fused silica/ borosilicate glass/ ULE/zerodur	550 fs	515 nm	9.4 MHz	Welding various combination of dissimilar glass materials	[41]

续表1

Bonded materials	Laser			Remarks	References
	Pulse width	Wavelength	Repetition rate		
Optical fiber/glass slide	70 fs	787 nm	250 kHz	Assembling endcaps of optical fibers	[61]
Spherical glass bead/ float glass	10 ps		100 kHz/ 500 kHz	Sphere-to-plate welding	[62]
Sodium borate sodium borate/ borosilicate	180 fs	785 nm	1 kHz	Bonding of Sm3t and Cr3t doped glasses	[63]

2.3 超短脉冲激光微焊接玻璃的影响因素

影响超短脉冲微焊接玻璃的因素包括脉冲激光的脉宽、重复频率、脉冲能量等激光参数[15,30,56,64]，以及加工平台的移动速度[15,30,56,60]、材料种类[25]、材料准备[15,58]、焊线几何形状[15]等。

例如，Butkus等[65]通过200 kHz、280 fs微焊接钠钙玻璃得出结论为该玻璃的微焊接是一个比较精细敏感的过程，快速且成功的焊接仅存在一个相对较窄的脉冲能量和扫描速度的窗口，连接状态及强度如图10所示。Miyamoto等[15]使用皮秒脉冲微焊接FOTURAN玻璃结果表明其力学强度随着脉冲功率增加而减小，而随着重复频率和移动速度增大而增加，另外他们在对照了0.5 μJ、100 kHz下10 ps激光脉冲和325 fs激光脉冲辐照硼硅酸盐玻璃(Schott D263)[34]后总结得出在脉宽上，皮秒脉冲比飞秒脉冲有更强的非线性吸收，因而有更高的焊接效率。

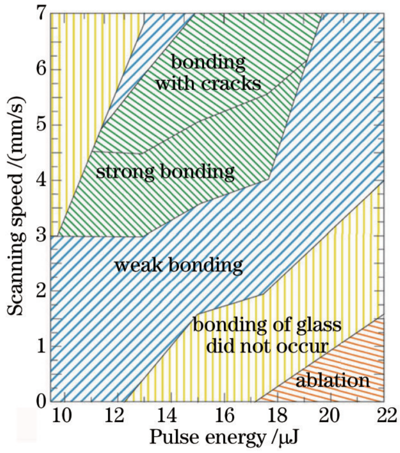

图10 280 fs脉冲激光不同脉冲能量和扫描速度下焊接钠钙玻璃效果，改变参数可导致强烧蚀和破裂[65]

Fig.10 Welding resulting diagram for soda-lime glass by using 280 fs ultrashort laser with differeent laser/pulse energies. Deviation from optimal parameter values may lead to strong ablation and cracking[65]

Watanase等[25-26]实验表明，玻璃的连接强度和透射率会因为加工平台的移动速度和脉冲能量发生变化。熔融石英和硼硅酸盐玻璃的透射率随着单脉冲能量增加而减少(他们认为这是焊接部分造成的散射损伤)，随着移动速度增加而增加，而连接强度随着单脉冲能量增加而增加，随着移动速度增加而减少，最大为15.3 MPa，而在阈值能流密度时为14.9 MPa。通过对比硼硅酸盐玻璃和熔融石英成功焊接的参数窗口后，他们发现玻璃材料的不同也会导致不同的焊接结果[25]，硼硅酸盐玻璃具有更大的实现窗口，比熔融石英更易实现微焊接，如图10所示。

另外，微焊接玻璃需将两材料进行表面抛光处理，且处理后的材料表面间隙应小于四分之一波长[24](也有观点认为需要小于100 nm[58])，若超过这一临界间距则因为各自表面出现烧蚀而不能连接成功。而样品表面的预先准备，实现材料间隙小于100 nm的光学接触不仅可以有效防止样品破裂，还能增强连接能。实验结果表明，有效预连接后D263T玻璃的焊接剪切强度达到了55 MPa，BF33玻璃为92 MPa，接近材料本身的100~200 MPa。

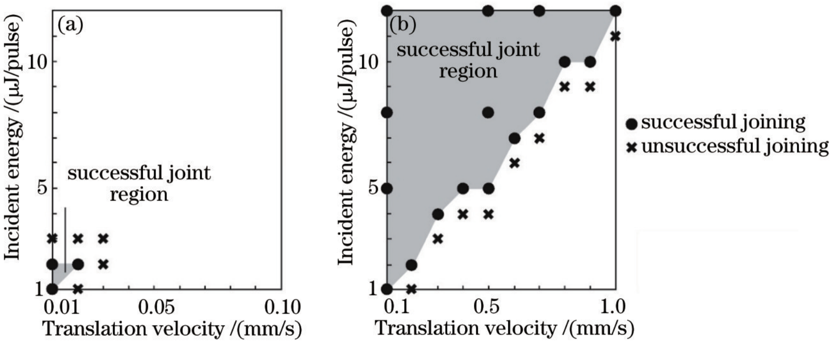

图11 不同脉冲能量和移动速度的微焊接结果。(a) 熔融石英; (b) 硼硅酸盐玻璃

Fig.11 Joining results for varying laser-pulse energy and translation velocity. (a) Fused silica; (b) borosilicate glass

3 超短脉冲激光微焊接玻璃的应用前景

正因为超短脉冲激光微焊接技术无需插入中间层、高效率、高精度、无宏观热效应以及微焊接处理后具有比较理想的力学、光学性能，其非常适合用于玻璃等透明材料的微焊接。

例如，Hélie等[61]使用70 fs、250 kHz脉冲成功为标准光纤和微结构光纤焊接端盖。光纤端盖可以起到增强组件的损伤阈值的保护或密封作用，还能减少光纤端面的菲涅耳反射，以及密封微结构光纤中产生超连续谱的空气孔，避免它们由于OH在玻璃内部扩散进一步降解。传统的方法是使用电弧放电、电阻丝或CO_2激光器实现局部加热来组装熔融连接一个无核的硅棒到硅的端面，再将硅棒拉细和打磨，通过激光烧蚀或化学蚀刻来改性其厚度和长度实现切割或塑形。在熔融连接的过程中会导致内核区域一定程度的变形，影响透射光质量。另外，在无核光子晶体激光器中，任意端面的加热都可能极大地改变光纤精密的周期结构和模式。其改进措施中需使用到的胶粘剂使用寿命有限且不耐高温。使用飞秒激光在标准硅光纤和微结构光纤顶端组装端盖的相互作用和热影响区主要集中在焦体积内，因此，在包层焊接不会对核心区和气孔区域产生影响。微焊接之后，还可以再使用相同脉冲激光对端面进行打磨。图11为使用70 fs、250 kHz飞秒脉冲将100 μm熔融石英端面微焊接到微结构光纤上的显微图像和说明示意图。

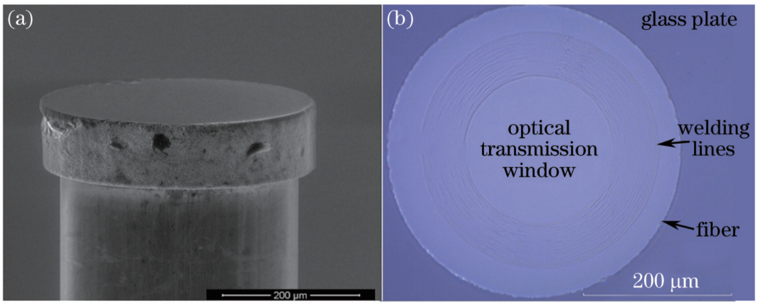

图12 使用70 fs、250 kHz飞秒脉冲微焊接到微结构光纤上的100 μm熔融石英端盖。
(a) 端盖侧视图; (b) 微结构光纤焊接顶视图[61]

Fig.12 A 100 μm thick fused silica endcap welded to a microstructured optical fiber by using 70 fs, 250 kHz femtosecond pulse laser. (a) Side view of the endcap; (b) top view of the microstructured optical fiber[61]

超短脉冲激光微焊接玻璃还可用于生产植入式芯片和传感器等电子、工程、医疗和科学研究设备。随着人们对超短脉冲激光微焊接玻璃技术的认识逐渐加深，其在生物医学应用中将大显身手。这是由玻璃材料本身的性质决定的。首先，玻璃对生物体而言可看作一种“中性”物质，将其植入人体内部时与人体体液组织的生物相容性较好，不会发生免疫排斥反应。其次，玻璃材料不像许多胶粘剂或其他焊接过程中使用的额外的基材那样会被体液腐蚀或自发降解，本身使用寿命长。而且，玻璃不会干扰电磁波，这有利于带信号的电磁波穿透玻璃封装的元件。如Jagannadh等[66]将使用飞秒激光加工后的熔融石英微流体集成到光流体成像系统中，利用玻璃优异的光学性能和生物兼容性成功实现红细胞(RBCs)和荧光微球成像，如图13所示。Sugioka等[67-70]还提出可以利用飞秒激光在玻璃内部三维制造微流体、微机械以用于集成生物芯片。因此，应用超短脉冲激光微焊接技术的玻璃装置可以协助体外诊断设备用于辅助检测疾病、生理状况等，甚至

未来可以为治疗脑损伤和记忆障碍的高科技大脑植入物提供解决方案[71-73]。

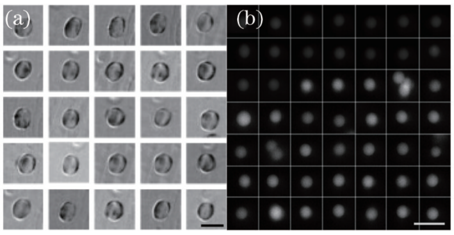

图13 红细胞 (a) 和荧光微球 (b) 通过飞秒激光微加工制造的微流体装置的成像。图中比例尺长度均为10 μm

Fig.13 Images of (a) RBCs and (b) fluorescent microspheres captured, while they are flowing through the femtosecond laser micromachined microfluidic devices. Length of scale bar is 10 μm

另外，因为玻璃封装的含有探测旋转、加速和压力等参数的微机电系统传感器的电子芯片在交通工具以及生物医学领域都有广泛应用，所以国内外已开展紫外或超短脉冲激光用于玻璃微机电系统的封装的相关研究[4,6,70,74-78]。由于超短脉冲激光微焊接产生的热影响区极小，能更安全地封装敏感材料，在整个封装过程中不会令敏感或有机元件受到高温或化学物质的影响，扩大了玻璃下方或内部封装易碎元件的应用范围，而且超短激光脉冲进行玻璃焊接整个过程中在基材上不需要中间层或胶粘剂，它需要的能量也远远少于阳极键合等一些传统的玻璃焊接技术，进而可以利用超短脉冲激光焊接后的焊缝出色的力学性能(高连接强度和在经受巨大的温度变化时能承受不同热胀系数带来的应力变化)应用到航空航天工业[2][包括像互补型金属氧化物半导体(CMOS)图像传感器的封装芯片器件等各种焊接的物体，需要在辐射损伤等最严酷的太空环境下保持高度的可靠性和气密性]。超短脉冲微焊接玻璃在电子产品行业也有潜在的应用。譬如可以使用超短脉冲激光在玻璃显示屏上焊接一层玻璃来保护显示屏或实现更多的功能，如抗反射特性等更多的功能[71]。

4 总结与展望

介绍了超短脉冲激光微焊接玻璃及其特点，然后阐述超短脉冲激光作用在玻璃中的非线性吸收、热传导机制以及加工影响因素，并介绍了超短脉冲激光的潜在应用。

目前，超短脉冲激光微焊接玻璃距离工业大规模应用还存在一些问题。例如实际生产需要高功率、高重复频率、体积紧凑而价格成本也能负担得起的飞秒或皮秒激光器(光源最有可能是带光纤放大器的半导体激光器)及加工平台，同时微焊接的玻璃材料需要经过表面准备以及表面压紧处理，另外目前微焊接的处理速度(Miyamoto等已经实现200 mm/s玻璃微焊接)、焊接后的机械强度、无破裂的成品率都还需要进一步改良以满足工业大规模生产加工的要求。

正是因为超短脉冲激光具有可加工几乎所有材料及其组合、热影响区小可有效减少破裂、连接强度高、不需加入中间层、可在透明材料内部空间选择性加工等突出优点，超短脉冲激光微焊接玻璃可用于晶片的连接和半导体传感器、微机电系统、太阳能电池等精密装置的密封。可以展望，超短脉冲激光微焊接玻璃将在植入式器件和传感器等电子、工程、医疗领域大有可为。

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