

## 外界应力对熔石英激光损伤性能的影响研究

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**摘要** 高功率激光系统的熔石英真空隔窗作为分隔大气环境和真空环境的重要窗口, 因其两侧气压差而承受一个大气压的压力。为了研究外界应力对熔石英真空隔窗的激光损伤性能的影响, 通过 1-on-1 方法测试了不同压强 (10~50 MPa) 下熔石英 351 nm 激光损伤产生阈值和初始损伤点尺寸, 通过 R-on-1 的方法测试了有、无外界应力时的损伤增长阈值。研究发现, 0~50 MPa 的张应力不影响熔石英损伤产生阈值和初始损伤点尺寸, 有、无应力下损伤产生阈值的差值不及最小值的 4.1%, 初始损伤尺寸的平均值的差值不及最小值的 5.5%; 0~50 MPa 的张应力也不影响损伤增长阈值, 有、无应力下损伤增长阈值的平均值的差值不及最小值的 1%。研究结果为解决高功率激光装置中真空隔窗的激光损伤问题提供了重要的实验支撑。

**关键词** 激光技术; 激光损伤; 熔石英; 机械应力; 损伤产生阈值; 损伤增长阈值

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## 1 引言

光学元件的激光损伤严重限制了高功率激光装置的输出能力和运行能力, 尤其是紫外激光诱导的光学元件损伤<sup>[1-3]</sup>。在高通量紫外激光辐照下, 熔石英元件表面出现尺寸为数微米至数十微米不等的点状损伤 (即损伤产生); 在后续发次的激光辐照下, 损伤点随激光发次的累计而不断扩大 (即损伤增长), 在一定发次内, 尺寸为微米级的初始损伤点将扩大到毫米量级, 导致元件无法继续使用。熔石英元件损伤产生和损伤增长制约了元件的使用寿命, 限制了激光装置的运行能力<sup>[4-5]</sup>。学术界对熔石英损伤产生和损伤增长开展了大量研究, 也已认识清楚各类缺陷, 如加工产生的亚表面缺陷、元件表面污染等诱导的元件损伤<sup>[6-8]</sup>, 并采取了先进延缓处理工艺来消除缺陷<sup>[9]</sup>, 大幅提高了熔石英元件的损伤性能。

但是, 高功率激光装置有一类特殊的熔石英元件——真空窗口, 其负载能力显著低于其他熔石英元件, 如美国国家点火设施 (NIF) 装置上的熔石英真空窗口, 其使用寿命是熔石英楔形透镜的  $1/3$ <sup>[10]</sup>。在相同的加工工艺和后处理工艺下, 真空窗口和楔形透镜使用寿命的差异说明存在其他影响损伤性能的因素, 其中一个可能的因素是外界压力。真空窗口作为隔绝靶室内部真空环境和外部大气环境的窗口, 承受着一个大气压的压力, 其后表面承受了数十 MPa 的张应力, 可能影响元件的损伤产生和损伤增长特性<sup>[11]</sup>。

尽管目前对熔石英激光损伤的机理已有了广泛的

研究<sup>[12-15]</sup>, 但关于应力对其影响的研究却相对较少。应力分为两种类型: 一是宏观应力, 即通过机械方式对元件整体施加张应力或压应力; 二是微观应力, 主要指元件微观裂纹形成的局域应力 (如裂纹尖端的局部应力), 以及元件键长键角变化产生的微观应力。这两类应力对激光损伤的影响不同, 目前认为微观应力对元件损伤性能存在影响, 但是缺少直接的实验证据。而宏观应力对元件损伤的影响, 不同文献的研究结果不完全相同。如 1999 年, Dahmani 等<sup>[16]</sup>在熔石英两侧施加相对的 6 psi (约 0.04 MPa) 以内的外界应力, 测得其激光损伤阈值大幅提升。2013 年, 陈庆红等<sup>[17]</sup>发现, 对熔石英后表面施加 0~50 MPa 压应力后, 其激光损伤阈值有逐渐上升的趋势, 损伤增长阈值则有逐渐下降的趋势。2018 年, Gingreau 等<sup>[18]</sup>的实验表明, 在 1~30 MPa 的外界机械应力作用下, 熔石英的激光诱导损伤初始阈值没有受到明显影响, 但学者没有研究外界应力对熔石英损伤增长阈值的影响。2016 年, 蒋勇等<sup>[19]</sup>研究了熔石英损伤修复后残余局部内应力对损伤性能的影响, 发现损伤修复点残余局部内应力不会导致修复区的损伤阈值低于基底的损伤阈值, 但会加剧损伤<sup>[20]</sup>。为了探究高功率激光装置中真空隔窗损伤性能下降的因素, 本文针对外界应力对熔石英抗激光损伤性能的影响, 研究了不同应力给熔石英损伤产生阈值、损伤尺寸以及损伤增长阈值带来的变化。

## 2 实验系统和方法

实验采用的样品为 Corning-7980 熔石英, 样品尺

寸为 100 mm × 50 mm × 5 mm, 表面粗糙度小于 0.5 nm。样品放入图 1 所示的夹持结构的插槽内, 通过拧紧底座中间的旋钉来推压插槽绕两侧的轴偏移, 以此对样品施加均匀的外界应力。同时, 使用激光位移传感器测量熔石英样品的表面位移, 其精度为 0.25 μm。以一维步进电机驱动, 每隔 2 mm 对样品中间 60 mm × 50 mm 范围内的表面位移进行一次采样。并利用 ANSYS 软件进行有限元模拟, 推导出表面应力。因为变形发生在弹性区域, 熔石英样品中心部分的最大表面应力与其表面位移呈现线性关系, 其应力位移关系如图 2 所示。

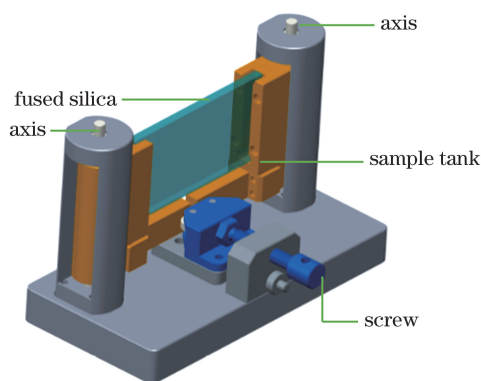


图 1 对熔石英样品施加机械应力的框架结构

Fig. 1 Frame structure for applying mechanical stress to fused silica samples

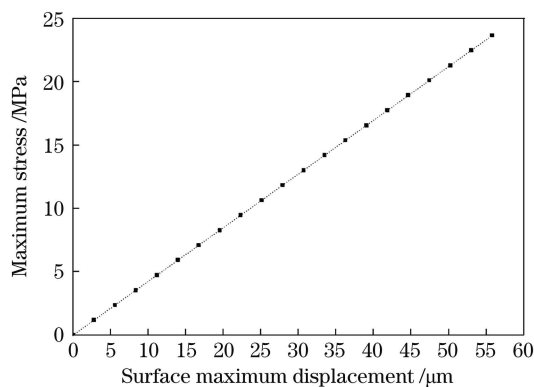


图 2 熔石英样品所受最大应力和表面最大位移的关系

Fig. 2 Relationship between maximum stress and surface maximum displacement of fused silica samples

由于处于真空环境的真空窗口表面承受张应力的作用, 因此实验中将承受张应力的样品表面作为后表面, 并选择表面平坦、应力均匀的样品中心区段进行激光损伤测试。实验采用 Nd:YAG 激光器, 激光波长为 351 nm, 脉冲为高斯型, 脉冲宽度为 5 ns (半峰全宽), 靶面光斑直径为 1.4 mm, 调制度为 2.0。实验使用 1-on-1 方式来测试激光损伤产生阈值, 使用 R-on-1 方式来测试产生初始损伤点的增长阈值。在 1-on-1 测试程序中, 每个通量下进行 20 次辐照测试, 总共测试 100~120 个点, 以获取足够的数据来得到激光损伤概率。实验先粗测得到对应 0 和 100% 损伤的上下限通量, 确定通量台阶为 ~1 J/cm<sup>2</sup>。对于每个样品, 首先

在有外界应力的条件下进行损伤测试, 然后去除应力进行进一步的测试。为了观测每个给定通量下的损伤现象, 使用 CCD 相机监测每一次激光辐射后是否产生损伤, 使用分辨率为 6 μm 的光学显微镜对损伤点尺寸进行离线测量。

### 3 实验结果

为了评估外界应力对熔石英损伤产生阈值的影响, 实验选择 5 块样品, 分别施加 11.2、21.0、30.8、46.2、46.2 MPa 的张应力。由于熔石英抗张强度为 55 MPa, 因此实验中对样品施加的外界张应力控制在 50 MPa 以下。为了排除样品加工工艺对实验结果的影响, 5 块样品由同一供应商采用相同的加工工艺制备。其中 4 号样品进行了动态化学蚀刻处理, 提高了样品损伤性能, 目的是判断样品在不同的抗损伤水平下, 应力对熔石英损伤性能的影响是否相同。

为了避免样品发生严重损伤, 实验使用无应力下样品损伤概率为 50% 时的通量为基准“阈值”, 测试得到的不同应力下的阈值变化情况如图 3 所示。可以看出, 在 10~50 MPa 的外界应力范围内, 有应力和无应力两种情况下样品损伤产生阈值相差甚微, 相差均在 0.5 J/cm<sup>2</sup> 以内, 该差值不及最小值的 4.1%, 说明外界应力对熔石英初始损伤阈值无影响。另外, 图 3 中 4 号样品和 5 号样品施加了相同的张应力, 虽然 5 号样品的损伤阈值整体高于 4 号样品 (这与样品处理工艺有关), 但是两块样品在有应力和无应力条件下的损伤阈值基本相同, 说明即使采用动态蚀刻处理提升了样品的抗损伤水平, 但是外界应力仍然对样品损伤阈值无影响。

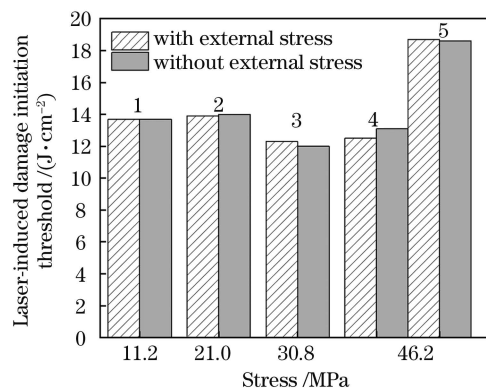


图 3 不同条件下熔石英样品的激光诱导损伤产生阈值

Fig. 3 Laser-induced damage initiation thresholds of fused silica samples under different conditions

采用光学显微镜观察有应力和无应力两种情况下的损伤坑形貌, 如图 4 所示。损伤坑为典型熔石英紫外激光损伤形貌, 呈不规则形状, 并表现出材料剥落的特征, 伴随有向四周延伸的裂纹, 损伤坑中央存在熔融状物质, 损伤坑形貌表明损伤过程中出现高温高压的状态<sup>[8]</sup>。有应力 [图 4(a)] 和无应力 [图 4(b)] 两种情况下的损伤坑无明显区别, 这是因为熔石英损伤坑形

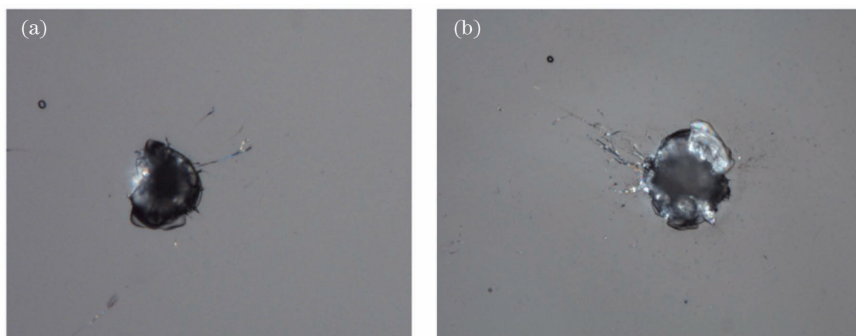


图 4 不同条件下的损伤坑形貌图。(a)无外界应力;(b)有外界应力

Fig. 4 Morphologies of damage pits under different conditions. (a) Without external stress; (b) with external stress

貌主要由损伤过程中的高温高压状态决定,损伤产生的冲击波高达数十 GPa,远大于施加给元件的数十 MPa 的机械应力。

有应力(11.2 MPa)和无应力两种情况下的损伤点尺寸如图 5 所示,共测量了 50 个损伤点,这里使用损伤点的等效圆直径来表示损伤点的大小<sup>[21]</sup>。图 5 中实线和虚线分别表示有应力和无应力两种情况下的损伤点直径,损伤点直径在 50~250  $\mu\text{m}$  之间。两种情况下的损伤点直径分布均呈近似正态分布,且平均尺寸分别为 134  $\mu\text{m}$ (有应力)和 127  $\mu\text{m}$ (无应力),两种情况下的损伤点直径基本一致,其他三种应力(21.0、30.8、46.2 MPa)条件下的损伤点直径也基本一致,说明应力对损伤点尺寸无明显影响。

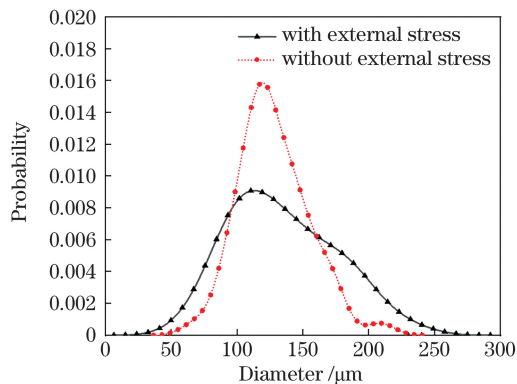


图 5 不同条件下的熔石英样品损伤尺寸分布

Fig. 5 Damage size distributions of fused silica samples under different conditions

为了判断应力是否影响熔石英的损伤增长阈值,在有应力(11.2 MPa)和无应力情况下采用 R-on-1 方式测量了 10 组损伤点的损伤增长阈值,实验结果如图 6 所示。这里仍使用无应力下样品损伤点增长概率为 50%的通量来代表样品的损伤增长阈值。从图 6 可以看出,同一组损伤点,有应力和无应力情况下的损伤增长阈值基本相同,两种情况下损伤增长阈值的平均值分别为 3.84  $\text{J}/\text{cm}^2$  和 3.88  $\text{J}/\text{cm}^2$ ,基本一致,说明外界张应力不影响熔石英的损伤增长阈值。此外,在图 6 中,10 组损伤增长阈值存在一定差别,且分布在 3.0~5.5  $\text{J}/\text{cm}^2$  区间,这可能与初始损伤点的尺寸和形态有关。

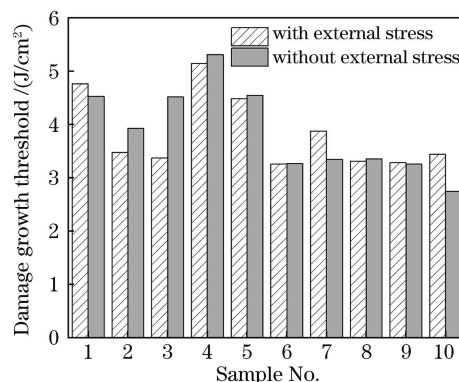


图 6 不同条件下的熔石英样品激光损伤增长阈值

Fig. 6 Laser-induced damage growth thresholds of fused silica samples under different conditions

## 4 分析讨论

实验结果表明,10~50 MPa 的张应力不影响熔石英损伤产生阈值,且有外界应力和无外界应力两种条件下初始损伤点的尺寸也基本相同,说明外界应力不影响熔石英的初始损伤性能。按照熔石英激光损伤的失控吸收理论,缺陷吸收激光能量,温度升高,并将热量扩散至周围的熔石英基底,当温度超过 2000 K 后,熔石英吸收系数增大,进一步加剧激光能量的吸收以及温度和压力的升高,达到某一临界状态时,发生局部的“微爆炸”,从而诱发损伤的产生。决定激光损伤产生过程的关键因素是缺陷的吸收系数和局部温度,而外部施加的张应力对缺陷吸收热量及热量扩散均不会产生明显影响。因此 10~50 MPa 应力下的熔石英损伤产生阈值与无应力情况下的相当。而初始损伤点的尺寸主要受微爆炸的影响,微爆炸产生的冲击波压强高达 30 GPa,实验中施加的外部应力则不超过 50 MPa,后者显著低于前者,因此实验中有应力和无应力两种情况下的损伤点尺寸基本相同。

实验结果同时表明,10~50 MPa 的张应力不影响熔石英的损伤增长阈值。这是因为熔石英发生初始损伤后,形成紫罗兰型损伤坑<sup>[22]</sup>。在后续激光辐照下,损伤坑中心的致密层吸收激光能量,温度升高,达到一定条件后,再次发生微爆炸。微爆炸形成的冲击波从损伤坑中心区域传播至损伤坑边缘的裂纹区域,

使裂纹沿着其尖端扩展,从而导致损伤坑的扩大。冲击波以声纵波和声横波的形式传播,传播速度可达数 km/s,20 GPa 以下的应力不影响声波的传播速度。实验中施加的外部应力小于 50 MPa,显著低于对声波传播速度产生影响的应力,因此,实验结果显示外界应力不影响熔石英的损伤增长阈值。

需要说明的是,应力对熔石英损伤的影响与实验条件有一定关系,主要是激光辐照条件和应力作用方式。如 1999 年,Dahmani 等<sup>[16]</sup>的实验表明,6 psi(约 0.04 MPa)左右的张应力或压应力可以使元件损伤阈值大幅提升(提升约 70%)。该结果是利用脉宽为 500 ps 的激光脉冲开展的,损伤坑直径小于 1  $\mu\text{m}$ ,且损伤坑纵向深度与损伤坑直径相当,甚至略大,这与纳秒紫外损伤形貌有所不同。2013 年,陈庆红等<sup>[17]</sup>的实验显示,56 MPa 的应力可以使损伤阈值小幅提升(提升 9.1%),该结果是通过在元件施加局部单点应力而获得的。2018 年,Gingreau 等<sup>[18]</sup>采用与本文相似的应力作用方式,发现 1~30 MPa 的机械应力对熔石英损伤初始阈值无明显影响。本文采用与装置中真空隔窗相同的应力作用方式,所得结果对解决装置中真空隔窗的损伤问题有参考价值。

## 5 结 论

实验研究了对熔石英施加 10~50 MPa 的外界张应力时,损伤产生阈值和损伤增长阈值的变化。实验结果显示,熔石英在有应力和无应力两种情况下的损伤产生阈值的差值不及最小值的 4.1%,且初始损伤点尺寸的平均值的差值不及最小值的 5.5%,这说明外界张应力不影响熔石英的损伤产生阈值和初始损伤点尺寸。熔石英在有应力和无应力两种情况下的损伤增长阈值的平均值分别为 3.84 J/cm<sup>2</sup> 和 3.88 J/cm<sup>2</sup>,基本一致,说明外界应力不影响熔石英的损伤增长阈值。从损伤产生阈值和损伤增长阈值两方面研究和评估了外界应力对熔石英损伤性能的影响,研究结果为解决高功率激光装置中真空隔窗的损伤问题提供了重要的实验支撑。

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# Effect of External Stress on Laser Damage Properties of Fused Silica

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## Abstract

**Objective** Laser-induced damage to optical components seriously hinders the output ability and operation ability of high-power laser systems, particularly UV laser-induced damage. Various studies on the damage generation and growth of fused silica have been conducted, and it is recognized that laser damage is caused by several kinds of defects, including subsurface cracks, organic pollution on the optical component surface, and so on. Advanced mitigation processes are employed to eliminate the defects and considerably enhance the damage performance of fused silica components. However, the laser damage performances of vacuum windows which are a special kind of fused silica optical component employed in high-power laser systems, is substantially worse than those of other fused silica components. The rear surface of the vacuum window withstands tens of MPa tensile stress to isolate the internal vacuum environment in the target chamber from the external atmospheric environment outside the target chamber, which may influence the damage generation and growth characteristics of the vacuum window. To solve the damage problem of vacuum window in high-power laser systems, it is necessary to investigate the impact of external stress on damage generation and growth of fused silica.

**Methods** We employ the Nd:YAG laser delivering a Gaussian pulse width of 5 ns at 351 nm. Uncoated fused silica samples are investigated in the experiments. First, the sample is placed in a specially made clamping structure (Fig. 1) to apply uniform external stress to the sample. Simultaneously, the laser displacement sensor is employed to measure the surface displacement of fused silica sample. Driven by a one-dimensional stepper motor, the surface displacement in the middle area of the sample is sampled. The finite element simulation is conducted using ANSYS software, and the relationship between surface stress and surface displacement is deduced. Next, the 1-on-1 approach is employed to test the laser damage threshold, and the R-on-1 approach is employed to test the growth threshold of the initial damage. For each sample, the damage test is conducted under the condition of external stress, and then the stress is removed for further testing. Simultaneously, to observe the damage phenomenon under each given laser fluence, a CCD camera is employed to monitor the damage after each laser radiation, and an optical microscope with a resolution of 6  $\mu\text{m}$  is used to measure the size of the damage crater ex situ off-line.

**Results and Discussions** The experimental findings reveal that in the case of the tensile stress of 10–50 MPa, the difference in the damage threshold of fused silica with and without stress is less than 4.1% of the minimum (Fig. 3), and the average difference between the initial damage point sizes is less than 5.5% of the minimum (Fig. 5), indicating that the external tensile stress does not affect the damage threshold and the size of initial damage. The average damage growth threshold of fused silica with and without stress is 3.84 J/cm<sup>2</sup> and 3.88 J/cm<sup>2</sup>, respectively (Fig. 6), demonstrating that the external stress does not affect the damage growth threshold of fused silica. This is because the damage to fused silica under ultraviolet laser irradiation is primarily caused by the defect absorbing laser energy, causing the temperatures of the defect and its surrounding local area to rise, and finally resulting in “microexplosion”. The pressure of the shock wave produced by microexplosion can reach 30 GPa, while the external stress applied in the experiment is less than 50 MPa, making it difficult to influence the laser damage process of the material.

**Conclusions** Damage threshold and damage growth threshold of fused silica under the external tensile stress of 10–50 MPa are experimentally investigated. The findings reveal that the difference in the damage threshold of fused silica with and without stress is less than 4.1% of the minimum, and the average difference in the initial damage size is less than 5.5% of the minimum. In the experiments, no impact of stress on the damage threshold is observed. In addition, the average damage growth thresholds of fused silica with and without stress are 3.84 J/cm<sup>2</sup> and 3.88 J/cm<sup>2</sup>, respectively. No substantial effect of the stress on the damage growth threshold is found. In this study, the effect of external stress on the damage performance of fused silica is studied and the results rule out the effect of external stress on the damage performance of fused silica, providing crucial experimental support for solving the damage problem of vacuum window in high-power laser systems.

**Key words** laser technique; laser damage; fused silica; mechanical stress; damage initiation threshold; damage growth threshold