# 无涂层激光冲击强化对40CrNiMo结构钢摩擦磨损性能的影响

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**摘要：目的** 采用无涂层激光冲击强化技术诱导残余压应力和细化晶粒，提高40CrNiMo结构钢的显微硬度及耐磨性。**方法** 采用高功率激光束对40CrNiMo结构钢表面进行激光冲击强化处理，通过显微组织观察、XRD检测、显微硬度测试、残余应力测试、摩擦磨损实验及磨损形貌观察，对比分析未处理试样、有涂层激光冲击强化处理试样和无涂层激光冲击强化处理试样的显微组织、显微硬度、残余应力和摩擦磨损性能。**结果** 在有/无铝箔涂层、去离子水约束层作用下分别对40CrNiMo结构钢试样进行有涂层/无涂层激光冲击强化处理，诱导产生残余压应力和晶粒细化，试样表面显微硬度分别提高至313.5HV和336.9HV，提高了约13.5%和21.9%，表面最大残余压应力达到–405.3 MPa和–326.6 MPa；有涂层激光冲击强化处理试样的摩擦因数较稳定，降低了约14.1%，而无涂层激光冲击强化处理试样的摩擦因数出现较大波动，在摩擦磨损前期，摩擦因数降低了22.9%；在摩擦磨损中后期，摩擦因数降低了7.9%。未处理试样的磨损量为13 mg，有涂层激光冲击强化处理试样和无涂层激光冲击强化处理试样的磨损量分别为6 mg和8 mg，减少了约53.8%和38.5%。**结论** 与有涂层激光冲击强化相比，无涂层激光冲击强化对40CrNiMo结构钢耐磨性能的强化效果较差。由于无涂层激光冲击强化无需涂覆涂层就能够进行激光冲击强化处理，因此可以有效提高加工效率、节省涂层成本，同时在一定程度上也提高了40CrNiMo结构钢的显微硬度和耐磨性。

**关键词：**40CrNiMo结构钢；无涂层激光冲击强化；激光冲击强化；显微组织；显微硬度；残余压应力；耐磨性

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# Effect of Laser Shock Peening without Coating on Friction and Wear Properties of 40CrNiMo Structural Steel

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**ABSTRACT:** 40CrNiMo structural steel has excellent mechanical properties and is widely used in key components such as turbine shafts, gear shafts and large ring gears. In view of the problems of fatigue and fracture of these mechanical parts in harsh working conditions, the surface of 40CrNiMo structural steel is subject to laser shock peening (LSP) treatment by high-power laser beam. The work aims to improve the microhardness and wear resistance of 40CrNiMo structural steel by inducing residual compressive stress and refining grains through laser shock peening without coating. By means of metallographic microscope, XRD test, microhardness tester, residual stress tester, friction tester and laser scanning confocal microscope, the microstructure, microhardness, residual stress and friction and wear properties of the untreated sample, the LSP sample (with coating) and the LSPwC sample were compared and analyzed. The 40CrNiMo structural steel samples were subject to LSP treatment with/without coating under the action of aluminum foil coating/no-coating and deionized water confinement layer, respectively, which induced residual compressive stress and grain refinement. The diffraction peaks of the samples were all shifted, and the average grain size of the samples treated with LSP (with coating) and LSPwC decreased by 6.0% and 9.6%, the surface microhardness of the samples increased to 313.5HV and 336.9HV, an increase of 13.5% and 21.9%, and the maximum residual compressive stress on the surface could reach –405.3 MPa and –326.6 MPa. After the LSP treatment, the wear surface of the samples was less worn and the number of pits and furrows was reduced, but the width of the furrows varied. The friction coefficient of the LSP (with coating) sample was relatively stable, decreasing by about 14.1%. The friction coefficient of the LSPwC sample was staged relatively. In the early stage of friction and wear, the friction coefficient was reduced by 22.9% compared with that of the untreated sample and 3.2% lower than that of the LSP sample. The main reason was that in the LSPwC process, the laser was in direct contact with the surface of the sample, which induced thermal effects and plastic deformation, thus increasing the number of austenite nucleation. At the same time, the dispersed carbides prevented the growth of austenite grains, and the distribution was uniform, which improved the wear resistance of the sample surface, so that the friction coefficient of the outer layer was the lowest and the wear resistance was the best. In the middle and late stages of friction and wear, compared with that of untreated sample, the friction coefficient decreased by 7.9%, but increased by 4.8% compared with that of LSP sample. Compared to the LSP (with coating) sample, the LSPwC sample show an increased number of pits and oxides on the surface and the presence of larger furrows. As the depth increased, the thermal effect of LSPwC decreased rapidly, and because there was no coating in the LSPwC process, the absorption rate of laser energy was reduced, resulting in a smaller shock wave energy. Thus, the plastic deformation effect was weakened, and the wear resistance was also reduced. The wear amount of the untreated sample was 13 mg and those of the LSP (with coating) sample and the LSPwC sample were 6 mg and 8 mg, respectively, which decreased by 53.8% and 38.5%. On the whole, compared with LSP (with coating), LSPwC has a poorer effect on the wear resistance of 40CrNiMo structural steel, but LSPwC can be directly applied to complex working conditions and structures with complex structures, because LSPwC can be carried out under the condition of no coating, thereby effectively improving the processing efficiency and saving the cost of the coating. At the same time, the microhardness and wear resistance of 40CrNiMo structural steel are also improved to a certain extent.

**KEY WORDS:** 40CrNiMo structural steel; LSPwC; LSP; microstructure; microhardness; residual compressive stress; wear resistance

激光冲击强化作为一种先进的表面改性技术，利用激光在处理材料表面产生的高强度冲击波压力，通过细化晶粒和产生残余压应力来改善材料的性能，已经成功应用于多个领域[1-5]。激光冲击强化是在纳秒时间内发出高能激光脉冲，并作用于试样表面，产生等离子体冲击波，从而使试样表面发生塑性变形[6-9]。通常会在试样表面采用水等透明的约束层来限制等离子体向外扩散，有时还会在试样表面涂覆保护涂层，增加激光能量的吸收率，避免产生热效应。目前，在激光冲击强化的研究中，有涂层的激光冲击强化最普遍[10-16]。

需要注意的是，从工程应用的角度来看，无涂层激光冲击强化（LSPwC）比有涂层激光冲击强化（LSP）更有利。因为 LSPwC 无需覆涂层就能进行喷丸处理，提高了加工效率，节省了涂层成本[17]。如果待加工的零部件在水下工作（如核反应堆部件的维护），则进行多次冲击较困难。因为在触发激光进行第 1 轮激光冲击强化加工后，激光脉冲会干扰或损坏涂层，所以需要更换涂层后才能进行第 2 轮的激光冲击强化加工。由于更换涂层的过程非常困难，甚至不可行，且待加工的样品处于水下环境，因此在激光触发时更换涂层极其危险。此外，如果零部件的形状较复杂，则涂覆涂层非常困难。这些现状促进了 LSP 处理的一个新分支的发展，称为无涂层激光冲击强化[18-20]。自从 Sano 等[21]首次提出 LSPwC 的概念并应用于核反应堆后，很多学者对 LSPwC 进行了深入研究。Binod 等[22]研究了 LSPwC 对 7075–T6 铝合金的力学性能和微观结构的影响，结果表明，试样的显微硬度增加了约 25%，加工硬化层超过 1 000 μm，最大压缩残余应力达到–227 MPa。这主要是因 LSPwC 引起的塑性变形、压缩残余应力，实现了晶界偏析和晶粒细化。Spadaro 等[23]报道，LSPwC 的热效应使超铁素体不锈钢发生了晶粒间腐蚀，导致早期疲劳裂纹成核。从这个意义上说，必须考虑在无涂层激光冲击过程中发生的激光直接与物质间的相互作用，而这种相互作用结果在材料之间是不同的。

40CrNiMo 结构钢具有优异的力学性能，如淬透性、高强度和高韧性，已广泛应用于涡轮轴、齿轮轴和大型齿圈等高强度、大截面的关键部件[24-27]。由于这些机械部件通常在恶劣环境中使用，容易出现疲劳、断裂等失效现象，因此将严重影响零部件的使用寿命[28-29]。Chen 等[30]研究了多次激光冲击强化对 40CrNiMo 钢力学性能和组织演变的影响。结果表明，多次喷丸对 40CrNiMo 钢的显微硬度、残余应力和显微组织有着显著影响，表面粗糙度和凹坑深度随着冲击次数的增加而增加。同时，在表层也诱发了亚晶粒、碳化物析出和位错等。Li 等[31]研究了低温激光冲击强化对 40CrNiMo 结构钢高温磨损性能和组织响应的影响。实验结果表明，激光冲击强化产生了大量的孪晶、高密度的位错结构和超细颗粒，有效提高了显微硬度，磨损质量损失显著降低，改善了其高温耐磨性。目前，关于 LSPwC 对材料耐磨性的研究未见报道，因此，文中将探讨无涂层激光冲击强化对 40CrNiMo 结构钢摩擦磨损性能的影响，对比激光冲击强化前后样品的显微组织、显微硬度、残余应力和摩擦磨损性能，并对其强化机理进行分析与讨论。

## 1 试验

采用的材料为 40CrNiMo 结构钢，其化学成分见表 1。

表 1 40CrNiMo 结构钢的化学成分

**Tab.1 Chemical composition of 40CrNiMo structural steel**

| Composition | Cr | Ni | Mo | C | Si | Mn | S | P | Cu | Fe |
|---|---|---|---|---|---|---|---|---|---|---|
| Mass fraction/% | 0.79 | 1.58 | 0.23 | 0.4 | 0.25 | 0.64 | 0.017 | 0.012 | 0.19 | bal. |

将试样切割成 20 mm×10 mm×5 mm 的块状，用粗细砂纸逐级对试样表面打磨至 2000 目，并进行抛光处理。采用 SIA–LSP–51 激光冲击波加工系统进行激光冲击强化（包括有涂层和无涂层）实验，激光能量为 6 J，光斑直径为 3 mm，搭接率为 50%，约束层为厚度 2 mm 的水，涂层为铝箔。

采用 LXRD 型残余应力仪测试试样表面的残余应力分布情况，在平行于激光扫描方向的激光冲击强化区域中选择相同距离的测量点，如图 1 所示。通过电解抛光对试样进行剥层，每个测试点检测 3 次，取其平均值。

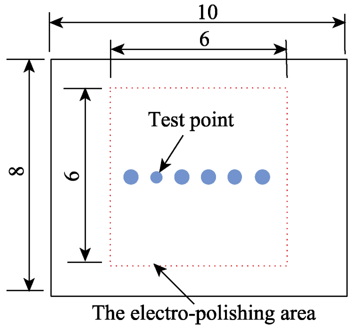


图 1 电解抛光区和测试点

Fig.1 Electro-polishing area and test points

采用 HXD–1000TM/LCD 型数显式显微硬度计测定激光冲击强化处理前后试样的表面显微硬度，采用 OLS4100 3D 激光扫描共聚焦显微镜来分析测定激光冲击强化处理前后试样的表面形貌和表面粗糙度。此外，还利用 BX53M 光学显微镜分析观察了不同处理下试样的显微组织。使用往复式摩擦试验机进行摩擦磨损试验，采用的对磨球为硬度 63HRC、直径 3 mm 的 E52100，试验负荷选择 9 N，往复速率为 500 r/min，试验时间为 30 min。

## 2　结果及分析

### 2.1　宏观形貌分析

不同处理 40CrNiMo 结构钢的宏观形貌如图 2 所示。未处理试样的表面粗糙度为 0.326 μm。由于 LSP 试验将铝箔作为涂层，以吸收激光能量，同时使试样表面免受激光带来的损伤，故加工后试样表面无明显变化，表面粗糙度为 0.458 μm；在 LSPwC 试验过程中，由于无保护涂层，激光直接与试样表面接触，导致试样表层受到一定的损伤，形成了均匀的微小凹凸不平的表面结构，使得试样的表面粗糙度增至 3.074 μm，与未处理试样相比，增加了近 10 倍。

### 2.2　显微组织分析

从图 3 可以看到，经过激光冲击强化（包括有涂层和无涂层）后，试样并未产生新的衍射峰，但材料衍射峰的强度出现了宽化，未处理试样的（110）平面峰的半高宽值为 0.262，LSP 和 LSPwC 处理试样的半高宽值分别为 0.280 和 0.270，提高了约 6.9%和 3.1%，说明激光冲击强化使得试样表面发生了明显的塑性变形。经 LSP 和 LSPwC 处理后峰值发生了位移，这表明 2 种处理都会诱导晶格应变。此外，LSPwC 处理试样的（200）平面峰的半高宽值的增幅最大，由 0.367 增至 0.408，提高了约 11.2%。根据谢乐公式[32]计算出未处理试样的平均晶粒尺寸为 29.83 nm，经 LSP 和 LSPwC 处理后试样的平均晶粒尺寸分别为 28.05 nm 和 26.96 nm，经 LSPwC 处理后试样的表面平均晶粒尺寸最小。

未处理试样、LSP 处理试样和 LSPwC 处理试样的表面显微组织如图 4 所示。从图 4a、d 可以看出，碳化物呈团絮状且分布不均匀，主要为铁素体和珠光体组织。经 LSP 处理后，试样表面晶粒更细化，且碳化物分布较均匀，显微组织并未发生改变，如图 4b、e 所示。结合 Hall–Petch[33]公式可知，材料的抗塑性变形能力与晶粒尺寸成反比，因此试样发生晶粒细化会提高材料的强度和硬度，从而提高试样的耐磨性。从图 4c、f 可以看到，LSPwC 处理试样表面的显微组织也未发生改变，虽然在 LSPwC 过程中，激光直接与试样表面接触，产生了热效应，但并未达到相变点，无法发生相变。同时，因产生了相变驱动力，使得奥氏体的形核数目增加，弥散分布的碳化物阻止了奥氏体晶粒的生长，且分布均匀，提高了试样表面的抗磨损能力。

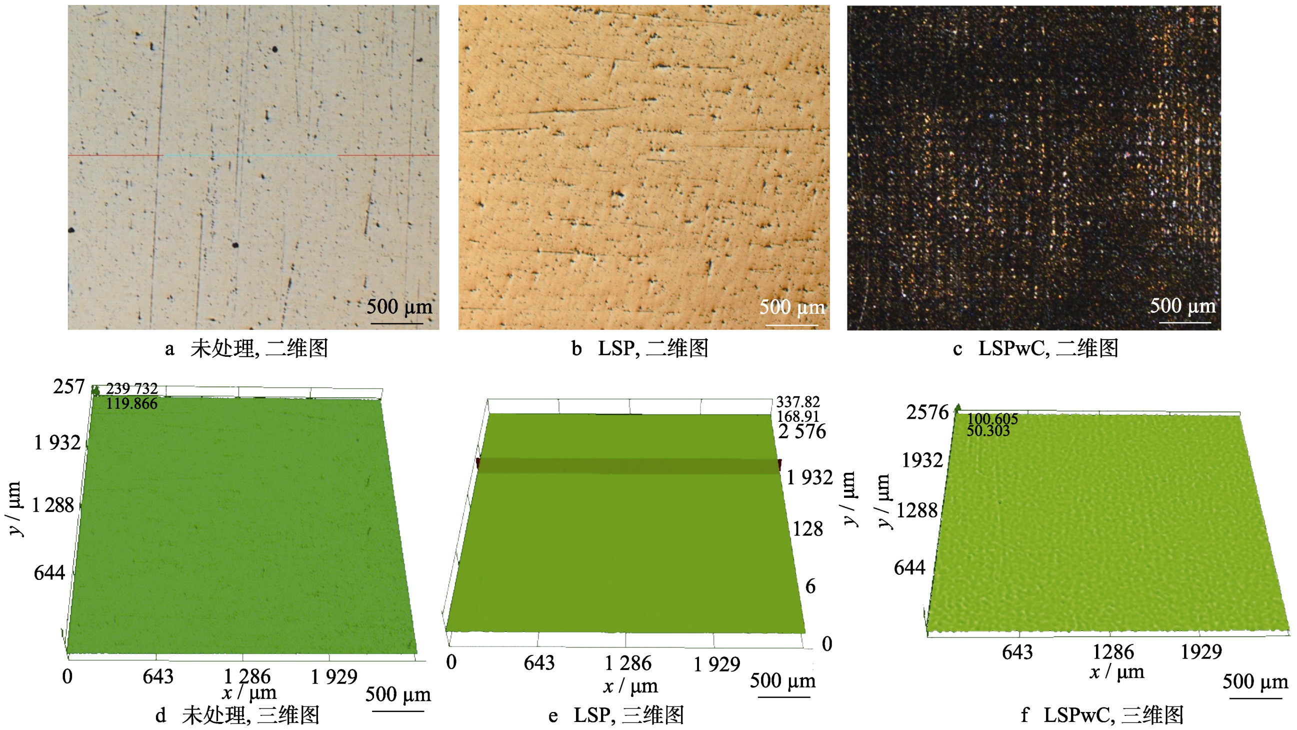


图 2　不同处理 40CrNiMo 结构钢的宏观形貌

Fig.2 Macroscopic morphologies of 40CrNiMo structural steel under different treatments: a) untreated, 2D map; b) LSP, 2D map; c) LSPwC, 2D map; d) untreated, 3D map; e) LSP, 3D map; f) LSPwC, 3D map

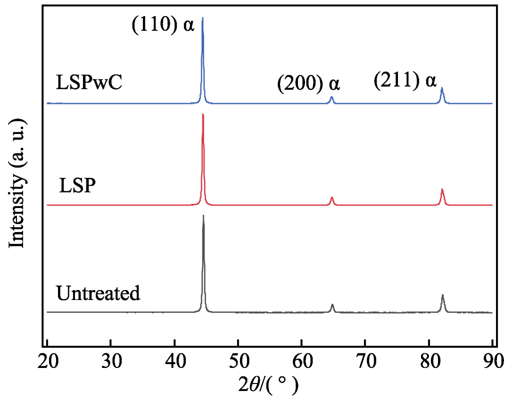


图 3 不同处理 40CrNiMo 结构钢的 XRD 图谱
Fig.3 XRD patterns of 40CrNiMo structural steel under different treatments

## 2.3 显微硬度与残余应力分析

3 组不同试样表面显微硬度如图 5 所示。从图 5 中可以看到，未经处理的试样表面显微硬度为 276.3HV，而经 LSP 和 LSPwC 处理后试样的表面显微硬度分别为 313.5HV 和 336.9HV，其显微硬度分别提高了约 13.5%和 21.9%。显然，LSPwC 处理对试样表面显微硬度的影响更大，较 LSP 处理试样提高了约 7.5%。根据 Archard 经验公式，试样的显微硬度增大，其耐磨性也会相应增加。

3 组试样的残余应力分布如图 6 所示。经激光冲击强化（包括有涂层和无涂层）处理后，由于冲击波的作用，材料发生了剧烈的塑性变形，试样表面的拉应力转变为压应力，LSP 处理试样和 LSPwC 处理试

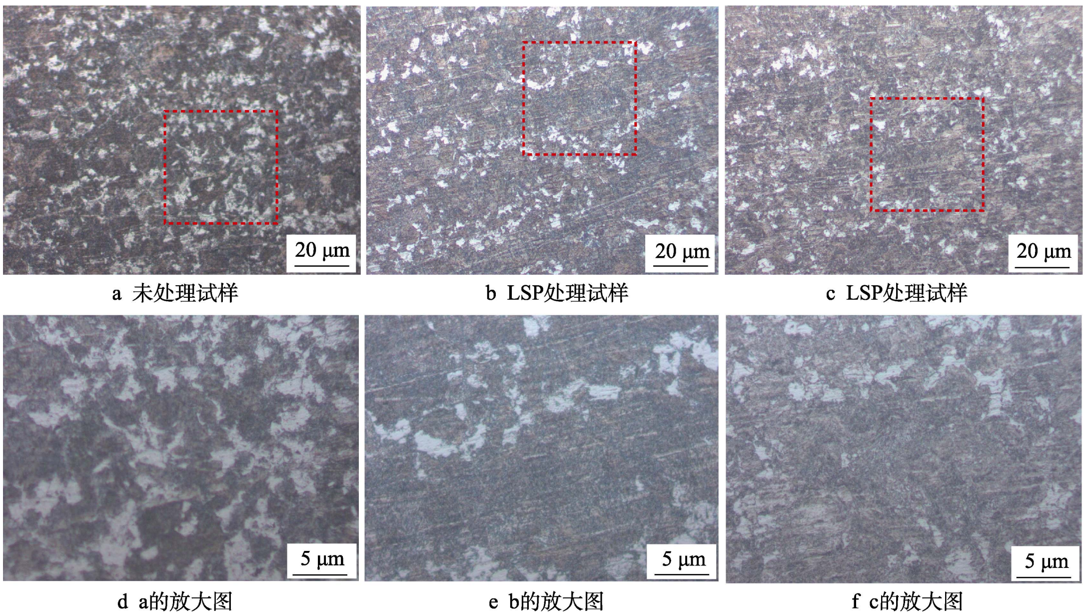


图 4 不同处理 40CrNiMo 结构钢表面显微组织
Fig.4 Surface microstructure of 40CrNiMo structural steel under different treatments: a) untreated sample; b) LSP sample; c) LSPwC sample; d) enlarged map of a; e) enlarged map of b; f) enlarged map of c

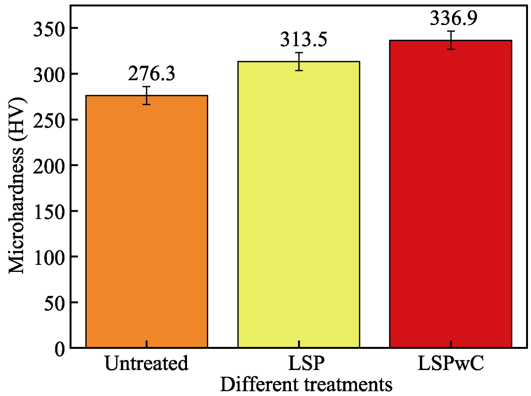


图 5 不同处理 40CrNiMo 结构钢的表面显微硬度
Fig.5 Surface microhardness of 40CrNiMo structural steel under different treatments

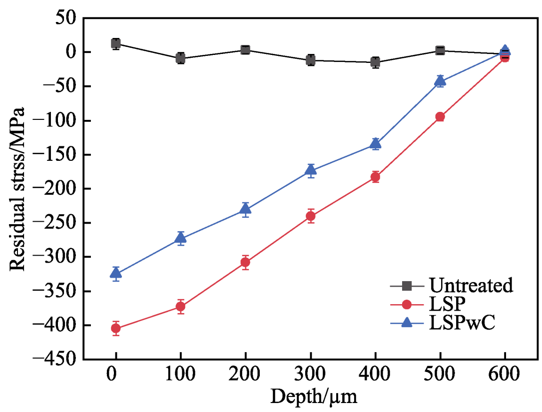


图 6 不同处理 40CrNiMo 结构钢的残余应力
Fig.6 Residual stress of 40CrNiMo structural steel under different treatments

样的表面最大残余压应力分别达到−405.3 MPa 和−326.6 MPa，提高了材料的力学性能。从图 6 可以看到，LSPwC 处理试样的残余压应力低于 LSP 处理试样的残余压应力。这是由于在 LSPwC 过程中，激光与材料表面直接接触，发生了热效应，导致残余拉应力的产生，抵消了部分塑性变形产生的残余压应力，因此激光冲击（包括有涂层和无涂层）在试样表面诱导残余压应力，提高了 40CrNiMo 结构钢的耐磨性。

## 2.4　摩擦磨损性能分析

3 组不同试样的摩擦磨损表面形貌如图 7 所示。从图 7 可以观察到，激光冲击强化（包括有涂层和无涂层）处理前后试样表面存在平行于磨损方向的磨损轨迹。同时，在所有的磨损轨迹上都观察到大量的犁槽，但其犁沟宽度不同。在相同的磨损试验参数下，经激光冲击强化（包括有涂层和无涂层）处理后犁沟宽度减小。从图 7a 可以看到，未处理试样表面存在很多大凹坑和较多的黑色块状氧化物。经 LSP 处理后试样表面的凹坑较少，氧化物细小且分布较均匀，如图 7b 所示。LSPwC 处理试样表面的凹坑和氧化物数量较 LSP 试样有所增加，且存在较大的犁沟。

从图 8 可以看到，经激光冲击强化（包括有涂层和无涂层）处理后，试样的摩擦因数均小于未处理试样的摩擦因数，说明激光冲击强化改善了试样的摩擦磨损性能。在激光冲击强化过程中产生了极大的冲击波，诱导了残余压应力和晶粒细化，提高了试样的耐磨性[34-35]。其中，LSP 的耐磨性最好。在摩擦磨损前期，LSPwC 处理试样的摩擦因数最低，比 LSP 处理试样的摩擦因数降低了约 3.2%。这是由于在 LSPwC 过程中激光与试样表面直接接触，发生了热效应与塑性变形的协同作用，在试样最外表层上热效应的影响较大，产生了相变驱动力，使得奥氏体的形核数目增加。同时，弥散分布的碳化物阻止了奥氏体晶粒的生长，且分布均匀，提高了试样表面的抗磨损能力，使得外表层的摩擦因数最低、耐磨性最好。

随着摩擦时间的延长，处理 6 min 后 LSPwC 试样的摩擦因数逐渐上升。这是由于随着深度的增加，LSPwC 产生的热效应极速减小。直到 12 min 后，其摩擦因数逐渐稳定在未处理试样与 LSP 处理试样的摩擦因数之间。由于 LSPwC 过程无涂层，使得激光能量的吸收率减小，形成的冲击波能量较小，导致塑性变形效应减弱，其摩擦因数比 LSP 提高了约 4.8%，耐磨性也有所降低。与未处理试样相比，经 LSPwC 处理后试样的摩擦因数降低了约 9.7%，说明耐磨性得到了一定提升。与未处理试样相比，LSP 处理试样的摩擦因数降低了约 14.1%，对试样的强化效果最好。同时，从图 9 可以看到，未处理试样的磨损量为 13 mg，经过激光冲击强化（包括有涂层和无涂层）处理后，试样的磨损量均有所减小，LSP 处理试样和 LSPwC 处理试样的磨损量分别为 6 mg 和 8 mg，分别减少了约 53.8%和 38.5%，其中，LSP 处理试样的磨损量最少、耐磨性最佳。

激光冲击强化（包括有涂层和无涂层）处理可诱导产生残余压应力和晶粒细化，提高了材料的表面硬度和耐磨性。其中，在 40CrNiMo 结构钢的上表层，

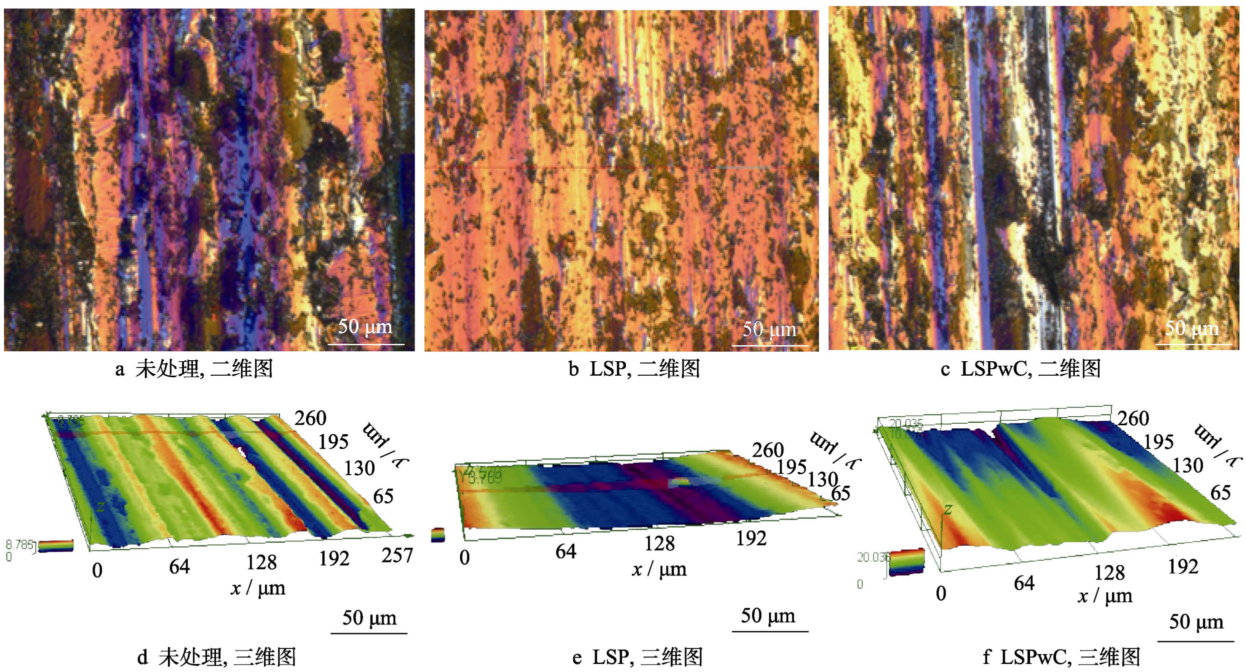


图 7　不同处理后 40CrNiMo 结构钢的磨损形貌

Fig.7 Wear morphologies of 40CrNiMo structural steel under different treatments: a) untreated, 2D map; b) LSP, 2D map; c) LSPwC, 2D map; d) untreated, 3D map; e) LSP, 3D map; f) LSPwC, 3D map

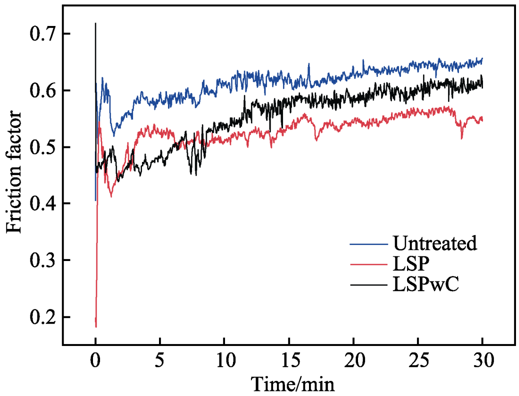


图 8 不同处理后 40CrNiMo 结构钢的摩擦因数
Fig.8 Friction coefficient of 40CrNiMo structural steel after different treatments

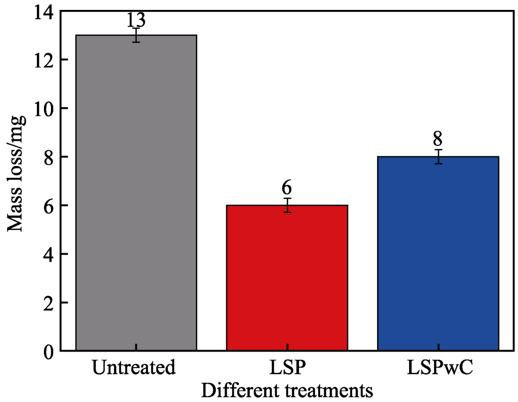


图 9 不同处理后 40CrNiMo 结构钢的磨损量
Fig.9 Wear amount of 40CrNiMo structural steel after different treatments

LSPwC 对材料的耐磨性强化效果较好，其摩擦因数比 LSP 处理试样降低了约 3.2%。从整体上看，LSP 处理试样的摩擦因数比 LSPwC 处理试样降低了约 4.8%，磨损量降低了约 25%，说明 LSP 对 40CrNiMo 结构钢耐磨性的强化效果最佳。在工程应用上，如果待加工的零部件在水下工作或零部件的结构形状复杂，LSPwC 无需涂覆涂层就能够进行激光冲击处理，可以有效提高加工效率和节省涂层成本，而且在一定程度上，无涂层激光冲击强化有效提高了 40CrNiMo 结构钢的显微硬度及耐磨性。

## 3 结论

1）通过激光冲击强化（包括有涂层和无涂层）处理 40CrNiMo 结构钢，能够有效提高试样的显微硬度和耐磨性能。

2）激光冲击强化处理试样诱导了晶格应变和晶粒细化，试样峰值都发生了位移，LSP 和 LSPwC 处理试样的平均晶粒尺寸分别减少了约 6.0%和 9.6%，LSPwC 处理试样的表面平均晶粒尺寸最小。

3）与未处理试样相比，经 LSP 和 LSPwC 处理后试样的表面显微硬度分别提高了约 13.5%和 21.9%，残余压应力分别达到−405.3 MPa 和−325.6 MPa。

4）经激光冲击强化（包括有涂层和无涂层）处理后，试样表面犁沟的宽度减小。未处理试样表面存在很多大凹坑和较多的黑色块状氧化物，经 LSP 处理后试样表面的凹坑较少，氧化物细小且分布较均匀，而经 LSPwC 处理后试样表面的凹坑和氧化物数量较 LSP 试样有所增加，且存在较大的犁沟。

5）经激光冲击强化（包括有涂层和无涂层）处理后，试样的磨损量和摩擦因数均有所降低。与未处理试样相比，LSP 处理试样和 LSPwC 处理试样的磨损量分别减少了约 53.8%和 38.5%。在摩擦磨损前期，LSPwC 处理试样的摩擦因数最低，比 LSP 处理试样的摩擦因数降低了约 3.2%，其耐磨性最好。随着摩擦时间的延长，LSPwC 处理试样的摩擦因数逐渐上升，逐渐稳定在未处理试样与 LSP 处理试样的摩擦因数之间，比 LSP 的摩擦因数提高了约 4.8%，但与未处理试样相比，LSPwC 处理试样的摩擦因数降低了约 9.7%，说明试样的耐磨性得到了一定的提升。

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