博士学位论文

激光与机械复合精密修整凹形青铜金刚石砂轮理论与试验研究

学位申请人姓名

培　养　单　位

导师姓名及职称

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Theoretical and experimental study on precision dressing of concave bronze diamond grinding wheel by laser and mechanical method

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摘 要

硬质合金、陶瓷、光学玻璃、半导体等高硬脆性难加工材料，因其高强度、高硬度等特点在航空航天、能源、半导体、光电子等领域运用越来越广泛，而这些领域对于复杂、高性能零部件的精密加工要求高且需求迫切，这类材料的成形加工采用传统的切削、铣削等加工方式难以甚至无法成形，因此，成形磨削加工仍然是当下高精高效高质的加工工艺。凸形面轮廓的成形磨削需要高精度的凹形面成形砂轮，而这类砂轮一般为粗粒度的青铜结合剂金刚石砂轮/滚轮，是世界上最硬的金刚石与金属烧结而成的复合材料，砂轮轮廓中微槽和底部小圆弧加工难度很大！目前对于粗粒度凹形面青铜结合剂金刚石砂轮的整形还存在修整精度低甚至难以完成、修整效率很低和修整表面质量差等世界性难题，亟待寻找一种新的方法实现凹形面砂轮的高精度高质量修整。针对此世界性难题，本文提出了一种激光粗修整、偏转激光半精修整和滚轮机械精整形的原创修整新方法，特别是首次提出的偏转激光修整新技术在精度提高上起到关键作用。综合了激光修整方法的高效且无刀具损耗和机械修整方法高精度的优点。然而，由于激光本身的聚焦特性，此前激光修整成形砂轮存在较大的轮廓误差，因为激光加工属于一种在焦点处加工能力最强的热加工方式，且没有明确的“刀尖”，导致加工精度从原理上无法进一步提高，遇到了精度提升的瓶颈！本文深入研究了激光在材料加工中的作用机制，无明确“刀尖”的加工特性，以及类似“车削”成形面的原理和特点；此外，还探索了视觉检测技术和算法、工艺和试验研究，以及修整后磨削对比试验等方面。主要研究内容如下：

1. 首次发现了造成激光修整成形砂轮轮廓误差的激光遮蔽效应和斜面分散效应，并建立了两种效应的数学模型。阐明了精确控制激光修整余量，减小机械磨损是激光与机械复合修整工艺设计的准则。仿真分析了纳秒激光功率和离焦量对烧蚀温度和烧蚀深度的影响规律，揭示了切向和径向修整的原理，阐述了切向修整表面平整的关键是作用于结合剂与金刚石的离焦量改变。理论建模分析了修整凹矩形轮廓出现斜面轮廓角度误差的原因，提出了影响激光聚焦加工能量大小的激光遮蔽效应和斜面分散效应理论模型，分析了两种效应的形成机理和影响因素；揭示了激光遮蔽效应是最外层旋转面和剩余材料对激光遮挡共同作用影响的，斜面分散效应是斜边轮廓角度对激光光斑的面积分散和反射率改变影响的结果。针对两种效应影响程度不同，阐明了不同角度大小轮廓砂轮角度误差形成机理是激光能量密度变化的结果，为后续修整奠定理论基础。

2. 建立了一套直接监测和间接检测的视觉系统，并改进了直线和圆弧检测算

法，实现了加工全过程的精度调控。搭建了一套激光与机械复合精密修整工艺装备，针对激光与机械复合加工过程无反馈造成的修整困难和效率低的问题，提出了一种直接监测加工过程和间接检测加工精度相结合的检测方案，搭建了一套视觉检测系统，针对间接检测过程中砂轮轮廓中的直线和圆弧轮廓特征，优化改进了轮廓边缘检测算法。结果表明，改进后的边缘检测算法相较于 Devernal 方法和 Rafael 方法的直线轮廓检测精度提高 86.5%和 60.1%，圆度误差检测精度提高 26.1%和 12%。

3. 首次提出一种偏转激光修整成形轮廓青铜金刚石砂轮的方法，攻克了砂轮激光修整存在的轮廓误差大的难题。分析总结了不同激光周向重叠比 O_C 和轴向重叠比 O_A 对修整砂轮表面和亚表面的影响规律，最终获得较优的加工参数为 O_C = 30%，O_A= 80.8%。针对斜面分散效应影响较小的较平缓小凹圆弧轮廓的修整，深入分析了修整过程中修整误差的变化，阐明了修整过程圆弧半径误差的原因是周向进给量的不足。通过提出的基于增大进给量的误差逼近补偿方法有效减小了修整轮廓误差。完成了斜面分散效应影响的 11°斜边直线轮廓砂轮的修整试验，证明了提出的偏转激光修整方法的有效性，结果表明在偏转角度 1°的条件下就可实现 11°轮廓的精确整形，直线度误差可达 6 μm 以内。试验了偏转激光对两种效应共同影响的凹矩形轮廓的修整，结果表明，在偏转角度为 5°的条件下可实现凹矩形轮廓的整形。

4. 提出了一种激光粗修整、偏转激光半精修整和滚轮机械精整形的复合修整方法，有效实现了复杂凹形面青铜金刚石砂轮的高效高质成形。首先完成了大切深激光粗修整；基于滚轮磨刃切削机理，设计了一种新型滚轮，并完成了其精密整形理论和试验研究。为获得机械修整控制的余量，探究分析了在纯激光、纯机械、激光+5 μm 机械和激光+10 μm 机械修整条件下的金刚石石墨化程度和材料成分变化，使用维氏硬度检测和结合剂亚表面电镜检测探究了结合剂的结合能力和热影响层的变化规律，将最终机械法的修整余量控制在 10 μm。分析了纯机械和激光+10 μm 机械修整方式的修整效率和刀具磨损，结果表明了激光+10 μm 机械修整的优势性。分析了粗修整的误差并完成了偏转激光半精修整试验，探究了试验参数对修整精度的影响。最后，使用滚轮完成了机械精整形试验，最终轮廓误差均可控制在 15 μm 以内，直线度误差可达 3 μm 以内。但表面磨粒平整无突出，需进行修锐才能发挥最优磨削性能。

5. 探究了激光和机械复合修整的磨削性能，并应用于实际硬质合金刀具生产，证明了修整的可行性。使用改进的 U-Net 神经网络完成了激光修锐表面磨粒的分割，使用最优高度比值为依据评价激光修锐效果，并获得最优的激光修锐参数为平均功率 15 W，重复频率 100 kHz，扫描速度 3 mm/min。对比分析了最优参数下四种修整方法得到的砂轮磨削力和磨削表面质量随磨削深度和磨削速度的变化规

律，结果表明，机械法相较于激光法磨削力有所增大，但磨削工件表面质量提高，且激光+10 μm 机械修整获得最优的磨削工件表面质量。最后，完成了复杂凹形面轮廓青铜金刚石砂轮的激光修锐并实现了磨削硬质合金刀具的应用，得到的刀具轮廓满足轮廓精度 20 μm 和线性度 4 μm 以内的要求。

关键词：金刚石砂轮；偏转激光；滚轮机械精整形；复合修整；斜面分散效应；复杂凹形面轮廓；轮廓误差；磨削性能

Abstract

Hard and brittle materials that are difficult to process such as cemented carbide, ceramics, optical glass, semiconductor and so on are more and more widely used in aerospace, energy, semiconductor, optoelectronics and other fields because of their high strength, high hardness and other characteristics, and these fields have high and urgent requirements for precision machining of complex and high-performance parts and components. The forming process of such materials is difficult or even impossible to form using traditional tool cutting, milling and other processing methods, so the forming grinding process is still a high-precision, high-efficiency and high-quality processing technology at present. High precision concave contour grinding wheels are needed for the form grinding of convex profile workpiece, and this kind of grinding wheel is generally coarse-grained bronze-bonded diamond grinding wheel or roller tool, which is the world's hardest diamond and metal sintered composite material, and it is extremely difficult to process micro-grooves and small arcs at the bottom of the grinding wheel profile! At present, there are still some global problems in the shaping of coarse-grained concave surface bronze-bonded diamond wheel, such as low dressing precision or even difficult to complete, extremely low dressing efficiency and poor dressing surface quality. It is urgent to find a new method to achieve high precision and high quality dressing of concave surface grinding wheel. In order to solve the worldwide problem, the paper proposes an original innovative method of laser rough dressing, deflection laser semi-finishing and mechanical fine shaping using roller tool. In particular, the new deflection laser dressing technology proposed for the first time plays a key role in improving the accuracy. The advantages of high efficiency and no tool loss of laser dressing method and high precision of mechanical dressing method are combined. However, due to the focusing characteristics of the laser itself, there is a large profile error of the laser dressing forming wheel before, because the laser processing is a hot processing method with the strongest processing ability at the focus, and there is no clear "knife tip", resulting in processing accuracy from the principle can not be further improved, and the bottleneck of accuracy improvement has been encountered! In the paper, the mechanism of laser in material processing is deeply studied, and the processing characteristics of "knife tip" are not

clearly defined, as well as the principle and characteristics of similar "turning" forming surface; In addition, the visual inspection technology and algorithm, process and experimental research, and grinding comparative test after dressing were carried out in-depth research, the main research contents are as follows:

1. The laser shielding effect and the bevel dispersion effect which cause the contour error of laser dressing forming wheel were discovered for the first time, and the mathematical models of the two effects were established. It is stated that precisely controlling the laser dressing allowance and reducing mechanical wear are the criteria for the design of laser and mechanical composite dressing process. The influence laws of nanosecond laser power and defocusing amount on ablation temperature and depth was analyzed by simulation. The principle of tangential and radial dressing was revealed. The key of tangential dressing surface being flat was the change of defocusing amount between the bond and diamond materials. The causes of the angle error of the beveled surface of the dressed concave rectangular contour were analyzed. The theoretical models of the laser shielding effect and the bevel dispersion effect, which affect the energy of laser focusing, were put forward, and the formation mechanism and influencing factors of the two effects were analyzed. It is revealed that the laser shielding effect is the joint effect of the outermost rotating surface and the residual material on the laser shielding effect, and the bevel dispersion effect is the result of the influence of the bevel contour angle on the area dispersion and the reflectivity of the laser spot. According to the different degree of influence of the two effects, the formation mechanism of the angle error of the grinding wheel with different angle sizes was explained as the result of the change of laser energy density, which laied a theoretical foundation for the subsequent dressing.

2. A set of direct monitoring and indirect detection vision system was set up, the linear and circular arc detection algorithm was improved, and the precision control of the whole process was achieved. A set of laser and mechanical composite precision dressing technology equipment was set up. Aiming at the problems of dressing difficulty and low efficiency caused by no feedback in laser and mechanical composite machining process, a detection scheme combining direct monitoring of machining process and indirect detection of machining accuracy was proposed, and a set of visual detection system was built. The contour edge detection algorithm was optimized and improved according to the straight line and circular arc contour features in the grinding wheel contour during indirect detection. The results showed that compared with Devernal method and Rafael method, the improved edge detection

algorithm improved the detection accuracy of straight line contour by 86.5% and 60.1%, and the roundness error by 26.1% and 12%.

3. A deflection laser dressing method for forming contour bronze diamond grinding wheel was proposed for the first time, overcoming the problem of large contour error in laser dressing of grinding wheel. The influence of different laser circumferential overlap ratio (O_C) and axial overlap ratio (O_A) on grinding wheel surface and sub-surface was analyzed and summarized. The optimal processing parameters were O_C= 30% and O_A= 80.8%. The dissertation analyzed the variation of the error in the dressing process of the relatively gentle small concave arc profile with little influence of the bevel dispersion effect, and explained that the error of the circular arc radius was caused by the insufficient circumferential feed. The error approximation compensation method based on increasing the feed rate was proposed to reduce the contour error effectively. The dressing test of 11° bevelled straight contour wheel affected by the bevelled dispersion effect was completed, and the effectiveness of the proposed deflection laser dressing method was proved. The results show that the 11° contour can be accurately shaped under the deflection Angle of 1°, and the straightness error can be less than 6 μm. The results show that the concave rectangle contour can be dressed under the deflection angle of 5°.

4. A composite dressing method of laser rough dressing, deflection laser semi-finishing and mechanical fine shaping using roller tool was proposed, which effectively realized efficient and high-quality dressing of complex concave surface contour grinding wheel. First, the large cut deep laser rough dressing was completed; Based on the cutting mechanism of roller grinding edge, a new type of roller was designed, and its precision shaping theory and experiment were studied. In order to obtain the controlled margin of mechanical dressing, the changes of diamond graphitization degree and material composition under the conditions of pure laser, pure mechanical, laser + 5 μm mechanical and laser + 10 μm mechanical dressing were investigated. Vickers hardness test and binder subsurface electron microscopy were used to investigate the binding ability of the binder and the changes of heat-affected layer. The final mechanical trim margin was controlled to 10 μm. The dressing efficiency and tool wear of pure mechanical dressing and laser +10 μm mechanical dressing were analyzed, and the results showed the superiority of laser +10 μm mechanical dressing. The error of rough dressing was analyzed and the semi-precision dressing test of deflection laser was completed, and the influence of test parameters on the dressing precision was explored. Finally, the mechanical fine

shaping test was completed by using a roller, and the final contour error could be controlled within 15 μm, and the straightness error could reach within 3 μm. However, the surface abrasive particles were flat and have no protrusion, so it needed to be sharpened to give full play to the optimal grinding performance.

5. The grinding properties of laser and mechanical dressing were investigated, and the feasibility of dressing was proved by its application in actual production of cemented carbide cutting tools. The improved U-Net neural network was used to segment the surface wear particles of the laser sharpening surface, and the optimal height ratio was used to evaluate the laser sharpening effect, and the optimal laser sharpening parameters were obtained as the average power of 15 W, the repetition rate of 100 kHz, and the scanning speed of 3 mm/min. The changes of grinding force and surface quality of grinding wheel obtained by four dressing methods with grinding depth and grinding speed under optimal parameters were compared and analyzed. The results showed that compared with laser grinding method, the grinding force of mechanical method increased, but the surface quality of grinding workpiece improved, and laser + 10 μm mechanical dressing obtained the optimal surface quality of grinding workpiece. Finally, the laser sharpening test of bronze diamond wheel with complex concave surface profile was completed and the application of grinding carbide tool was realized. The obtained tool profile meet the requirements of contour accuracy of 20 μm and linearity of 4 μm.

Key Words: Diamond wheel; Deflection laser; Mechanical fine shaping using roller tool; Composite dressing method; Bevel dispersion effect; Complex concave surface contour ; Contour error; Grinding performance