ANALYSIS OF LASER-CLADDING REPAIR PERFORMANCE OF WORN UNIVERSAL JOINT SURFACES IN AGRICULTURAL VEHICLES / 农用车十字轴磨损表面的激光熔覆修复性能分析

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Abstract: *In order to solve the remanufacturing and repairing of universal joint in agricultural vehicles against surface peeling and evident indentation, laser cladding technology was applied to prepare Fe 314 alloy cladding layer on the journal surface of the universal joint. Metallographic structure of the cladding layer was observed with metalloscope and its hardness was tested by Vickers hardness tester. Moreover, a finite element model of the universal joint load in agricultural vehicles was established. After load and boundary constraint were applied, the cloud chart of displacement changes before and after the cladding was concluded. The universal joint repaired through laser cladding was installed onto agricultural vehicles, presenting no surface peeling and cracking more than eight months later. Test results demonstrated that the cladding layer combines with the substrate well and the hardness of the universal joint improves from 170HV0.025 to 560HV0.025. Abrasive resistance of the cladding position is improved significantly and the displacement decreases by 10.8% compared to that before cladding. Laser cladding could improve performances of the universal joint and prolong its service life.*

Keywords: *agricultural vehicles, universal joint, journal, laser cladding, hardness, performance analysis*

摘要: *为了解决农用车十字轴表面剥落和压痕明显现象的再制造修复问题，采用了激光熔覆技术在十字轴轴颈表面制备 Fe314 合金熔覆层。利用金相显微镜和维氏硬度计进行了十字轴样品的熔覆层金相组织观察和硬度测试，并建立农用车十字轴载荷的有限元模型，施加载荷及边界约束后，得到了熔覆前和熔覆后位移的变化云图。激光熔覆修复后的十字轴装配在农用车上，从事日常工作 8 个多月未出现表面脱落、开裂等问题。试验结果表明：熔覆层和基体结合良好，硬度由 170HV0.025 提高到 560HV0.025，熔覆部位耐磨性得到明显提高，位移量比熔覆前减小了 10.8%，达到了改善十字轴性能并延长十字轴使用寿命的目的。*

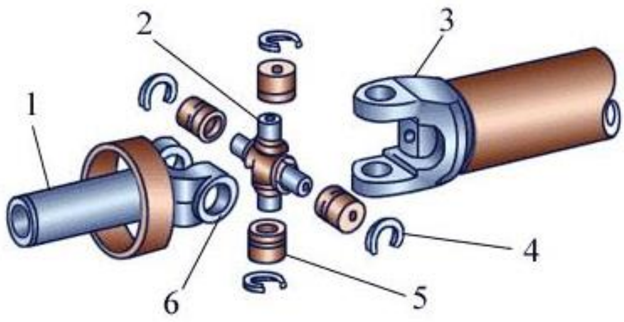
关键词: *农用车，十字轴，轴颈，激光熔覆，硬度，性能分析*

INTRODUCTION

As one of the most important equipment in agricultural production, agricultural vehicles mainly serve in farmlands and rural regions with poorer road conditions than urban areas. Furthermore, they bear heavy freight volume. Therefore, the universal joint in the drive system of agricultural vehicles suffer transient impact loads and huge pressure frequently, thus showing surface peeling and evident indentation failures after being used for 1.5-2 years. Both surface peeling and indentation will enlarge space of the universal joint, thus easy to cause fracture failure at the journal and increasing impact on the main drive system, and even threatening operation safety of the main driving equipment and the whole agricultural vehicle. The installation position and working principle of universal joint in agricultural vehicles are shown in Fig.1.

引言

农用车作为现在农业生产中最重要的设备之一，主要工作在田间和路面质量不及城市的农村地区，路况差，环境恶劣，再加上农用车承载运输量较大，其传动系统中的十字轴频繁承受瞬时冲击载荷和极大的压力，一般使用 1.5-2 年表面就会出现剥落和压痕明显的失效情况。剥落和压痕使十字轴承的间隙增大，进而在轴颈处极易发生断裂失效，更加重主传动系统的冲击，甚至危及主传动设备和整个农用车行车安全。图 1 为农用车十字轴的安装位置和工作原理。



1, 3: universal joint yoke; 2: universal joint; 4: spacer; 5: bearing; 6: holes above the universal joint yoke

Fig.1- Installation position and working principle of universal joint in agricultural vehicles

Many studies have been conducted on the surface peeling and indentation failure of universal joints in recent years. Jin et al. [3] made a digital simulation of a universal joint by using DEFORM software. Although this simulation shortens the development period to a certain extent, it fails to improve the performance of the universal joint. Liu et al. [7] believed that the surface peeling of the universal joint is related to material properties. They suggested the use of imported and more advanced alloy-carburizing steel. However, this approach will increase costs and goes against popularization. Wu et al. [10] reported that although increasing the space between the end faces of the universal joint and the bearing cap can reduce friction heat, this method can easily cause the surface peeling of the universal joint. Tian et al. [9] indicated that optimizing the circular transition at the journal root can improve the performance of the universal joint to a certain extent but not significantly. Liao [5] declared that the simple mechanical re-processing of a surface-peeled universal joint can recover its surface hardness and roughness and prolong the service life of the universal joint. However, this method only fixes the damage and does not address the cause.

Laser cladding is a flexible, advanced manufacturing technology that can create high-performance surfaces on low-cost substrates [6]. In laser cladding, coating materials are placed on the substrate surface simultaneously or in advance. The coating materials are then melted with the substrate surface simultaneously through irradiation of high-energy density laser beams. Thereafter, a cladding layer with compact metallurgical bonding is solidified quickly, thus significantly improving the hardness, wear resistance, and corrosion resistance of the substrate material surface. Laser cladding can repair damaged positions directly and quickly to realize the size and shape reproduction and high-performance repair of damaged parts. Laser cladding is superior to other remanufacturing technologies because of its characteristics of quick cooling, low-rate coating dilution, resource saving, small thermal deformation of the substrate, availability of high-performance metallurgical bonding coating, automatic process, and few follow-ups of mechanical processing cuttings. Yao et al. [11], Feng et al. [2], and Cheng [1] reproduced surface-damaged bent axles and gear thrust surfaces by laser cladding and achieved good results. Ma et al. [8] and Lei et al. [4] made simulation studies on the temperature field and dynamics of laser cladding and achieved some progress.

A simulation analysis and experimental verification of laser cladding were implemented on the basis of universal joints with surface peeling and evident indentation in agricultural vehicles. The microstructure and hardness of the cladding layer were observed and tested. Stress-induced deformation was calculated by using the finite element method.

近年来，众多学者对十字轴表面剥落和压痕失效处理进行了大量的研究工作。金广柱等[3]应用 DEFORM 软件对十字轴进行了数字模拟，一定程度上缩短了开发周期，但并没有提高十字轴的性能。刘雪燕等[7]认为，十字轴表面剥落和选材不当有关，应该选用进口的更高级别的合金渗碳钢，但是成本增加，不利于推广。吴石等[10]认为增大十字轴端面和轴承盖之间的间隙，这样虽然可以降低摩擦发热量，但是很容易因为间隙增大而脱落。田辉等[9]认为优化轴颈根部的圆角过渡处，这样可以起到一定的作用，但是效果不明显。廖永锋[5]认为重新简单的机械加工表面剥落的十字轴，恢复其表面硬度和粗糙度，可以延长十字轴的使用寿命，这本身就是一种治标不治本的方法。

激光熔覆是一种柔性化的先进制造技术，可以在低成本基体上制成高性能表面的表面工程技术[6]。激光熔覆就是在基体表面同步或预置涂层材料，经高能量密度激光束辐照，使涂层材料和基体表面同时熔化，并快速凝固形成具有致密冶金结合的熔覆层，从而显著改善基体材料表面的硬度、耐磨、耐腐蚀等性能，可根据受损部位的形状直接进行快速修复，最终实现受损零件外形尺寸重现和高性能修复。相对于其他再制造技术，激光熔覆具有冷却速度快、涂层稀释率低、节约资源、基体热变形较小、可获得高性能冶金结合涂层、工艺过程易于实现自动化、后续机加工切削量少等优点。姚成武等[11]、封慧等[2]、成凯华[1]对表面损伤的曲轴、齿轮推力面进行了激光熔覆再制造，获得了良好的效果。马琳等[8]、Lei Yiwen 等[4]对激光熔覆温度场、动力学进行了仿真研究，取得了一定进展。

利用激光熔覆的方法对表面剥落和压痕明显的农用车十字轴进行了仿真分析和实验验证。观察熔覆后的熔覆层的显微组织和硬度，用有限元的方法对受力产生的变形量做了计算。

MATERIAL AND METHOD

Laser cladding of the universal joint sample and universal joint

The laser-cladding test used a YLS-4000-S2 fiber laser, a Siasun XSL-PF-01B-2 double-bin negative pressure powder feeder, and a KR30HA robot made by KUKA (Germany). The cladding parameters include 2200 W laser power, 600 mm/min scanning speed, 3.4 mm spot diameter; 28.5 g/min powder feeding rate, and 1.7 mm multiple welding landing.

Hardening and tempering 45# steel with the same material as the universal joint was used, and the components of this steel are listed in Table 1. The cladding material will have good wettability because of the similar coefficient of thermal expansion and melting point between the cladding material and substrate metal. Considering the requirement on hardness of the cladding layer, Fe314 alloy was used as cladding material; its chemical composition is shown in Table 2. Before the experiment, the sample surface was polished by sandpaper, and then the rust, oxide film and greasy dirt on the sample surface should be eliminated by using acetone and high-purity ethyl alcohol. Samples were preheated to 250 °C for 2 h before laser cladding.

材料与方法

对十字轴样品和十字轴进行激光熔覆

激光熔覆试验采用 YLS-4000-S2 型光纤激光器，新松 XSL-PF-01B-2 双料仓负压式送粉器，德国 KUKA 公司 KR30HA 机器人。熔覆时采用的参数：激光功率为 2200W，扫描速度为 600mm/min，光斑直径为 3.4mm，送粉量为 28.5g/min，采用多道搭接，搭接度为 1.7mm。

用与十字轴材料相同的，经过调质的 45#号钢，成分如表 1。根据熔覆材料与基体金属热膨胀系数和熔点相近原则，熔覆材料应当具有良好的润湿性，以及对于熔覆层硬度的要求，选择熔覆材料 Fe314 合金，其化学成分见表 2 。试验前，先用砂纸将样品表面打磨，然后采用丙酮和高纯酒精进行清洗，将表面的铁锈、氧化膜和油污去除干净，并预热到 250℃，保温两小时后激光熔覆。

Table 1

Composition of substrate material (mass fraction/%)

Elements	C	Si	Mn	P	S	Cr	Ni	Cu	Fe
45#	0.42-0.50	0.17-0.37	0.50-0.80	≤0.035	≤0.035	≤0.25	≤0.25	≤0.25	Bal.

Table 2

Composition of cladding powder material (mass fraction/%)

Elements	Cr	Ni	Si	B	C	Fe
Fe314	14.82-15.24	9.22-11.12	0.93-1.14	0.92-1.14	0.09-0.11	Bal.

Fig. 2 presents a universal joint journal with surface peeling and indentation deeper than 0.1 mm. However, this universal joint journal cannot be used normally. In this paper, this universal joint was mechanically cleaned to remove the coating and fatigue layers, and it was laser cladded by using the same equipment and method as stated above. To obtain a good cladding layer, the distance from the laser head to the universal joint journal surface should be fixed, the traveling speed of laser spot relative to the universal joint journal should be constant, and the laser beam should be kept at the top of the universal joint journal. The inconsistent matching between the laser beam and universal joint journal will change the laser power, thus influencing the morphology of the cladding layer. Fig. 3 shows the laser cladding to the universal joint with surface peeling and evident indentation. The cladding layer on the universal joint journal after cladding is shown in Fig. 4.

图 2 为表面剥落和压痕深度超过 0.1 mm 的十字轴轴颈，该十字轴已不能正常使用。对其进行机械清理，去除镀层和疲劳层，并采用与上述相同的激光熔覆设备和熔覆方法对该十字轴进行激光熔覆。熔覆过程中，为获得良好的熔覆层必须满足以下条件：激光头到十字轴轴颈表面的距离不变，激光光斑与十字轴轴颈相对运行速度恒定，激光束要始终处于十字轴轴颈的最上端。若激光束和十字轴轴颈的运行速度没有匹配好，会引起激光功率的改变，从而影响熔覆层的形貌。图 3 为对表面剥落和压痕明显的十字轴进行激光熔覆，熔覆后的轴颈表面的熔覆层如图 4 所示

Fig.2- Universal joint journal with surface peeling and evident indentation

Fig.3- Laser-cladding process

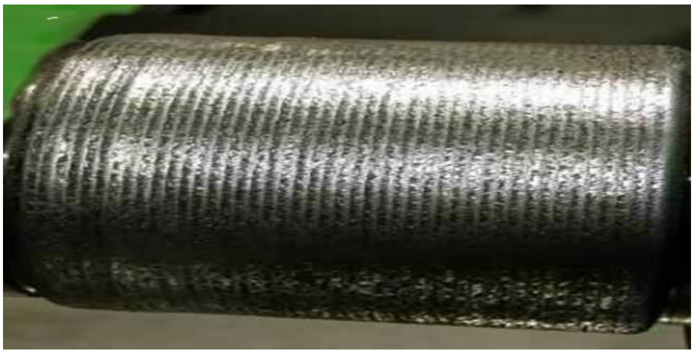


Fig.4- Universal joint journal surface after cladding

RESULTS ANALYSIS

Cladding layer microstructure of the universal joint sample

Fig. 5 shows the universal joint sample after laser cladding. The sample was cut into 60 mm × 60 mm × 30 mm pieces and then polished to make metallographic samples. The microstructure of the cladding layer was observed by using an optical microscope. The cross-section morphology of the cladding layer is displayed in Fig. 6. The cross-section is divided into three parts, namely, cladding layer, interface layer, and substrate. The cladding layer has a compact and uniform structure without cracks and pores. Furthermore, the cladding layer forms a suitable metallurgical bonding with the substrate.

结果分析

十字轴样品熔覆层显微组织

图 5 为激光熔覆后的十字轴样品。把熔覆后的十字轴样品切割成 60mm×60mm×30mm，并对其进行研磨抛光，制作成金相样品。采用光学显微镜观察样品熔覆层的显微组织。图 6 为熔覆层的横截面形貌，从图中可以看出，横截面分为 3 部分，即熔覆层、结合区和基体。熔覆层组织致密、均匀，未出现裂纹、气孔等缺陷，熔覆层与基体实现了良好的冶金结合。

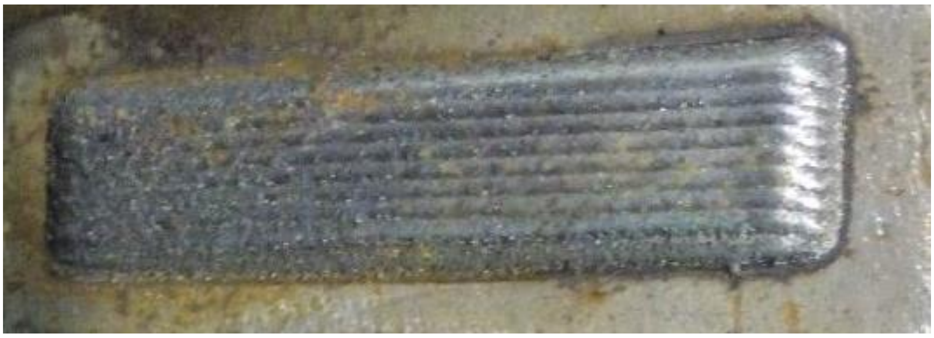


Fig.5- Laser-cladding sample

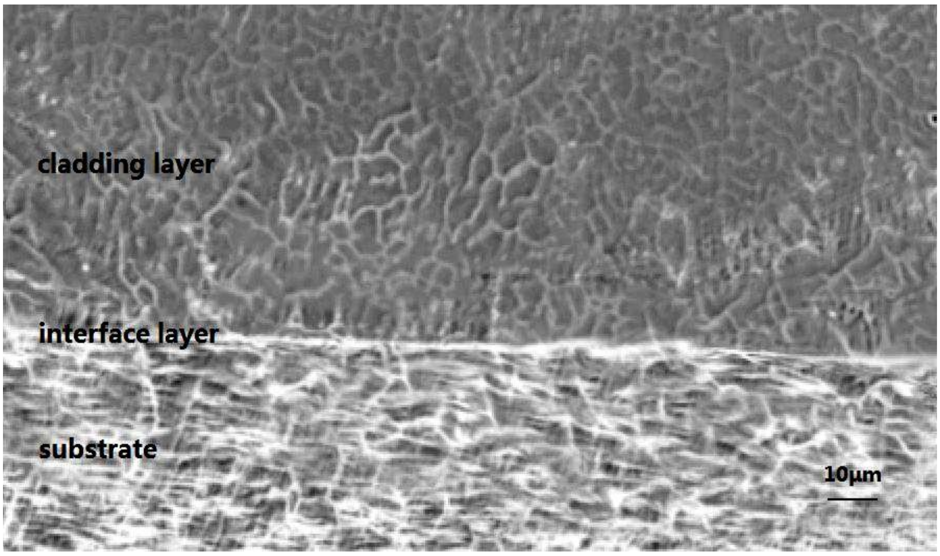


Fig.6- Cross-section morphology of the cladding layer

Hardness of the cladding layer of the universal joint

The micro-hardness of the cladding layer and substrate of the universal joint sample were measured by using a DHV-1000 Vickers hardness tester under a 0.245 N load (25 gf) and 10 s loading time. Each sample was measured at least five times and the mean measured value was taken as the final value. Fig. 7 is the variation curve of the cross-section hardness of the specimen. The horizontal axis is the vertical distance from the measuring point to the cladding layer surface, and the vertical axis is the hardness of the measuring point.

十字轴样品熔覆层硬度

使用 DHV-1000 维氏硬度计测量十字轴样品熔覆层和基体的显微硬度，所加载荷为 0.245N（即 25gf），加载时间为 10s，测量至少 5 次，取平均值。图 7 为试样块横截面硬度的变化曲线。横坐标为被测点到熔覆层表面的垂直距离，纵坐标为被测点的硬度值。

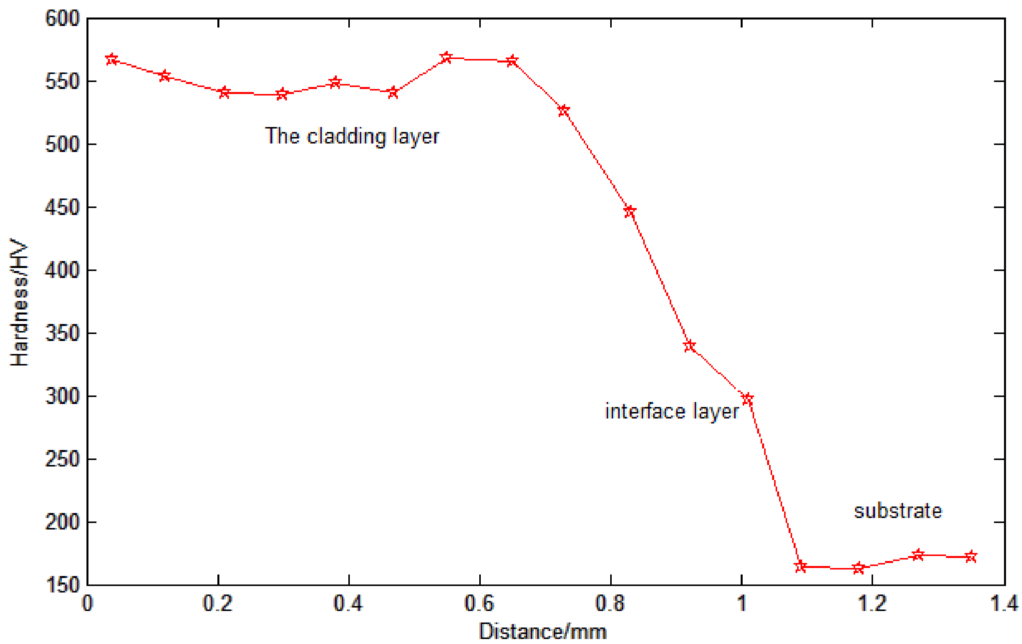


Fig.7- Hardness of the cladding layer, interface layer, and substrate cross-section

In Fig. 7, the hardness of the cladding layer increases from approximately 170HV0.025 of the substrate to approximately 560HV0.025. This increase is mainly caused by the quick solidification of the molten pool and

从图 7 中可以看出，熔覆层的硬度由基体的 170HV0.025 左右提高到 560HV0.025 左右，这主要是因

the refinement of the grains of the cladding layer during laser cladding, thus, compacting the structure and enhancing the grain boundary well. Furthermore, the wear resistance of the cladding position is improved significantly.

为激光熔覆过程中熔池快速凝固使熔覆层的晶粒细化，组织致密，起到了很好的晶界强化作用，熔覆部位耐磨性亦得到明显提高。

Stress analysis of the cladding layer

Stress analysis of the universal joint

The tolerable rated moment of the universal join installed on the Shifeng SF354 agricultural vehicles is expressed as follows:

熔覆层的应力分析

十字轴的受力分析

对安装在时风 SF354 型号农用车上的十字轴，所能承受的额定力矩为：

$$T = 9549 \times \frac{P}{n} = 322.91\text{Nm} \quad (1)$$

where P=25.7kW, and the engine power of the agricultural vehicle n=760 r/min is the rated speed.

The driving force acts on the middle cylindrical surface of the driving shaft neck of the universal joint. The resultant force on the shaft neck F is then expressed as follows:

其中：P=25.7kW，为农用车发动机功率；

n=760 r/min，为额定转速。

传动力作用于十字轴主动轴轴颈的圆柱面上，取轴颈的中间位置施加作用力，则轴颈所受到的合力 F 为：

$$F = \frac{T}{L} = 10091\text{N} \quad (2)$$

where L is the straight-line distance from the F acting point to the geometric center of the universal joint, and L = 0.032 m.

The dynamic model of universal joint is shown in Fig. 8.

其中：L— F 作用点到十字轴几何中心的直线距离，L =0.032m。

十字轴受力模型如图 8 所示。

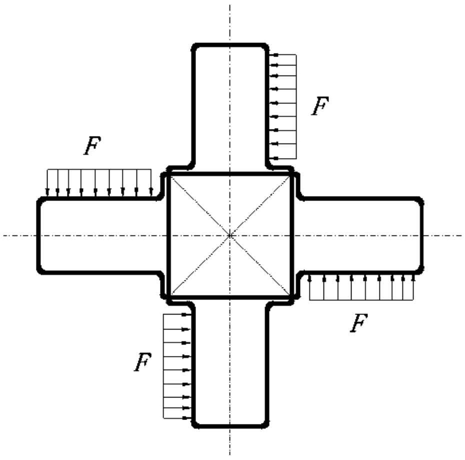


Fig.8 - Dynamic model of uniformly distributed load on the universal joint

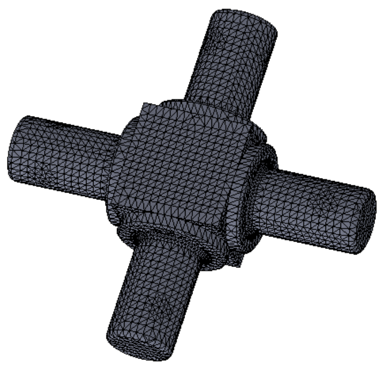


Fig.9 - Gridding result of the universal joint

Finite element simulation of the universal joint

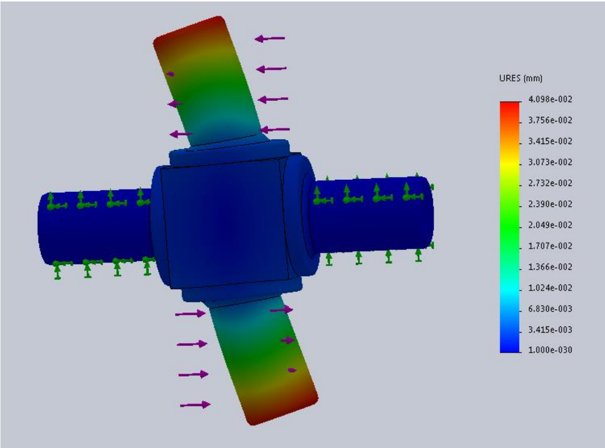
The universal joint model was established in SolidWorks and then entered into SolidWorks Simulation for gridding and simulation analysis. The universal joint model has a complicated structure and cannot be gridded by using default technology. This model has to cut parts before gridding. According to the stress analysis of the universal joint, the universal joint was divided into two symmetric parts. A total of 68,957 units were divided through the free gridding technique, including 100,050 nodes. The gridding result of the universal joint is shown in Fig. 9.

对十字轴有限元仿真

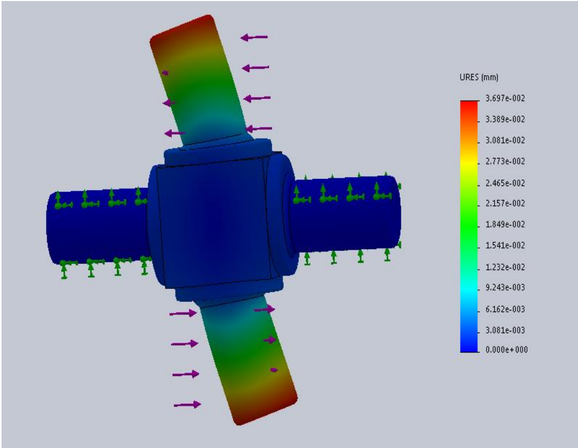
在 SolidWorks 中创建十字轴模型，并将其导入 SolidWorks Simulation中进行网格划分和仿真分析。十字轴模型结构复杂，无法采用默认技术划分网格，需要对部件进行分割，再划分网格。根据十字轴的受力分析，将十字轴分割为对称的两部分。采用自由网格划分技术，共划分有68957个单元，100050个节点。十字轴网格划分效果如图9所示。

The displacement effect after a 10091 N force and boundary constraint that were applied to the original universal joint neck, is exhibited in Fig. 10(a). The displacement effect after a 10091 N force and boundary constraint which was applied to the cladding universal joint is shown in Fig. 10(b). Figs. 10(a) and 10(b) show that after the load and boundary constraints were applied, the maximum deformation before cladding is 4.098 × 10^{-2} mm but decreases by 10.8% to 3.697 × 10^{-2} mm after cladding. The performance and service life of the universal joint are improved and prolonged.

对原十字轴的轴颈施加 10091 N 的力及边界约束条件后，显示位移效果如图 10（a）所示。对激光熔覆后的十字轴同样施加 10091 N 的力及边界约束条件后，显示变形量效果如图 10（b）。从图 10（a）中可以看出，熔覆前施加载荷和边界约束条件后十字轴最大变形量为 4.098×10^{-2}mm，从图 10（b）中可以看出，熔覆后施加载荷及边界约束条件后十字轴最大变形量减小为 3.697×10^{-2}mm，减小了 10.8%，达到了改善十字轴性能并延长十字轴使用寿命的目的。



(a) Universal joint before cladding



(b) Universal joint after cladding

Fig.10- Cloud chart of universal joint deformation

The cladding universal joint was repeatedly polished to the aimed request of the original size and then installed on a Shifeng SF354 agricultural vehicle in Sandaoba Town, Midong District, Urumqi Municipality, Xinjiang, on May 12, 2014. The agricultural vehicle was used in daily farmland work and the transportation of agricultural products. Fig. 11 shows the testing agricultural vehicle with the cladding universal joint. The universal joint disassembled from this agricultural vehicle on January 20, 2015, is shown in Fig. 12. No peeling and cracks were observed, thus indicating that laser cladding is a feasible repair method for universal joints in agricultural vehicles.

熔覆后的十字轴颈经过反复机械修整，达到其原始尺寸精度后，于 2014 年 5 月 12 日装配在新疆乌鲁木齐市米东区三道坝镇的时风 SF354 型号农用车上，从事日常的田间地头劳作和农产品的运输工作。图 11 为装配熔覆后十字轴的试验农用车。图 12 为 2015 年 1 月 20 日，从装配该熔覆后十字轴的试验农用车上拆卸下来的十字轴。对该十字轴进行仔细检查，并未出现脱落、开裂等现象，说明此方法对农用车十字轴修复是可行的。

Fig.11- Testing agricultural vehicle with the cladding universal joint

Fig.12- Disassembled universal joint

CONCLUSIONS

(1) A laser-cladding test is conducted on the universal joint samples of the same material and shows a good metallurgical bonding between the cladding layer and substrate.

(2) The microstructure of the cladding layer is compact without defects. Hardness is improved from 170HV0.025 to 560HV0.025. The wear resistance of the cladding position is significantly improved.

(3) A finite element simulation on universal joint before and after cladding is implemented, concluding that deformation after cladding is 10.8% less than that before cladding.

(4) A universal joint with surface peeling is processed with laser cladding and grinding and is used in a Shifeng SF354 agricultural vehicle for more than eight months, thus confirming the feasibility of laser cladding in repairing surface-worn universal joints.

结论

（1） 对十字轴的同材质的样品进行了激光熔覆试验。试验表明：熔覆层和基体之间形成了良好的冶金结合。

（2） 样品熔覆层的显微组织致密无缺陷，硬度由170HV0.025 提高到 560HV0.025，熔覆部位耐磨性得到明显提高。

（3） 对十字轴熔覆前和熔覆后分别进行了有限元仿真，得到熔覆后的变形量比熔覆前减小了 10.8%。

（4） 对表面剥落的十字轴激光熔覆后，经过磨削加工，装配在时风 SF354 农用车上，正常运行 8 个多月，验证了此方法对修复表面磨损十字轴的可行性。

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