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经编鞋面增材印花机理研究及工艺参数优化

RESEARCH ON THE MECHANISM AND OPTIMIZATION OF PROCESS PARAMETERS IN ADDITIVE PRINTING OF WARP - KNITTED VAMP

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摘 要

21 世纪是一个大健康时代，随着全民健身上升为国家战略，运动消费伴随着民众健康意识的提高成为新的消费热点。作为穿戴领域中最引人注目的品类之一，经编鞋面印花运动鞋产品因其特殊的织物结构和印花特色，在舒适度和外观上兼具优势，具有广阔的消费市场和发展前景。经编鞋面增材印花是以丝网印花为基础，在三层经编间隔织物上经过数十次叠印、套印成型厚度 0.8mm 以上复杂立体图案的制造工艺，该技术几乎是通过工程经验评估发展的，当前以人工操作为主，针对产业劳动密集生产现状，提升经编鞋面增材印花的自动化水平已被列入鞋服行业绿色智能制造的科技攻关规划。

本论文是国家重点研发计划（2018YFB1308800）的部分内容。为理解经编鞋面增材印花浆料转移机理，更好地开发出智能印花装备和工艺，提升行业自动化水平，本文围绕影响丝网印刷的要素分别研究浆料流变性、刮刀力学特性、网版变形与渗透特性，基于以上研究对三者构成的流场进行流固耦合分析，得到浆料转移机理，开发增材印花装备和配套工艺，生产出增材印花产品。论文主要研究工作如下。

（1）研究印花浆料的理化性质与流变性及对印花过程的影响。利用傅立叶变换红外光谱（Fourier Transform Infrared Spectroscopy，FTIR）、动态光散射（Dynamic Light Scattering，DLS）及多普勒电泳（Laser Doppler Electrophoresis，LDE）技术对高固含水性聚氨酯分散液印花浆料的理化特性进行表征，得到浆料的主体成份、粒径大小及分布、表面电荷及 Zeta 电位。针对印花过程中的黏性流动和动态震荡，通过稳态剪切实验和动态震荡剪切实验研究浆料的流变特性，分析浆料黏度随剪切速率、温度和固含量的变化规律，黏弹特性随应变与震荡频率的变化规律，可知浆料呈现弱凝胶结构，是具有剪切变稀特性的假塑性非牛顿流体。基于 Arrhenius 公式和 Carreau 方程构造浆料多因素影响下的黏度相关性模型，推导并优化三元件分数阶导数 Zener 模型和分数阶导数 Poynting-Thomson 模型，对浆料的线性黏弹特性进行回归分析。基于上述本构方程，得到印花过程中浆料受剪切、应变、震荡的理论边界值。

（2）构造考虑浆料流变性、刮刀形态与印花速度的印花流场数学模型，研究流场分布特点。从弹性力学理论出发，提出求解楔形变截面刮刀形态变化的解析

方法，对楔形变截面超弹性刮刀进行平面应变问题的力学分析，得到楔形变截面刮刀的应力、应变和位移分布，进一步得到刮刀在印花流场中的变形方程。基于刮刀形态变化方程和浆料的本构关系，将润滑理论应用于印花流场的数学建模，得到无量纲速度和动压积分表达式，采用 Romberg 数值积分算法得到流场的动压分布。随后使用扩展傅立叶振幅灵敏度测试（Extended Fourier Amplitude Sensitivity Test，EFAST）方法对印花力、印花角度和印花速度进行全局灵敏度分析，得到一阶灵敏度指数和总灵敏度指数。为验证上述数学模型的有效性，提出考虑浆料牛顿特性和非牛顿特性的计算流体动力学（Computational Fluid Dynamics，CFD）模型，对印花流场仿真，证实理论分析的有效性。

（3）分析并计算网版形态与印花协调条件，研究网版反弹过程中浆料的流变分裂。通过计算得到印花图案变形与网版尺寸、网距、图案位置、印花力的数学表达式。基于 Poiseuille 流动，由运动学协调条件得到印花速度与网版目数、网版厚度、网纱丝径、浆料黏度的协调关系，得到印花过程中网版的反弹速度与网版尺寸、网距和印花速度的关系。基于胡克定律和牛顿内摩擦定律，由网版反弹的力学协调条件，得到网版尺寸、刮刀尺寸、网距、网版力学参数、网纱规格等实现印花应满足的数学关系。借助表面润湿过程和界面重构技术分析网版反弹过程中浆料的流变分裂，分析分裂过程和影响因素，可知表面自由能和线径对浆料的流变分裂有重要影响。

（4）基于刚体动力学、多相流、多孔介质与动网格技术构造经编鞋面印花过程中浆料转移的流固耦合模型，研究流场变化与浆料转移机理。基于模型分析印花流场压力和速度的变化特点、印花过程中渗透区域与非渗透区域压力的变化。证实流场压力与浆料转移量的关系，并通过单因素变量实验分析印花力、印花角度、印花速度和网纱目数对浆料转移量的影响。通过仿真和实验结果总结经编鞋面增材印花浆料转移机理：刮刀与网版围成的楔形流场区域，满足黏性流体动压润滑的条件，在刮刀运动前端形成流体动力学泵，并在刮刀刀尖附近产生陡然升高的流体动压，使浆料填充到网孔，在刮刀压力作用下，网版与经编鞋面接触，形成液桥，随着刮刀继续刮印，网版动态反弹，接触线上移，液桥拉伸变细直至断裂，由于经编鞋面表面自由能大于网纱的表面自由能，大部分浆料转移到经编鞋面上。

（5）基于印花机理，分析经编鞋面增材印花流程，开发设计实现增材印花的关键机构。采用失效模式及其影响分析（Failure Mode and Effect Analysis，FMEA）方法分析增材印花系统可靠性，得到增材印花系统的故障模式和风险优先数，为设备优化和维护提供理论依据。在增材印花装备上开展七因素四水平的工艺参数

正交实验，对实验结果进行极差分析和方差分析。通过支持向量回归机和遗传算法构造工艺参数寻优模型，提出与增材印花装备相匹配的最优工艺参数。经测试，所开发增材印花装备和配套工艺生产的高品质印花产品均能满足拉力、耐挠及水解的物性测试要求。

在深入分析经编鞋面增材印花机理的基础上，开发增材印花装备，设计配套印花工艺，生产高品质经编鞋面印花产品，对于理解印花机理、提升行业自动化水平、提升经编鞋面印花产品竞争力和实现绿色智能制造具有重要意义。

关键词：经编鞋面；增材印花机理；工艺参数优化；流变特性；刮刀形态；网版形态；浆料转移

RESEARCH ON THE MECHANISM AND OPTIMIZATION OF PROCESS PARAMETERS IN ADDITIVE PRINTING OF WARP - KNITTED VAMP

ABSTRACT

With the rise of national fitness as a national strategy, sports consumption has gradually become a new hot spot in the 21st century, and sneakers have become one of the most eye-catching categories in the field of shoes and clothing. The sneakers with warp-knitted vamp printing have advantages in comfort and appearance due to its special fabric structure and printing characteristics. Therefore, it has broad market and development prospective. Screen printing is the technical basis of additive printing of warp-knitted vamp, which evolved almost purely through evaluation of engineering experience and is a manufacturing process forming the complex three-dimensional pattern with a thickness of 0.8mm or more through dozens of overprinting and overprinting on the warp-knitted spacer fabrics. At the moment, it is conducted by hands. In view of the labor-intensive characteristic of warp-knitted vamp printing, improving the automation level of additive printing of vamp has been listed in the technological plan of green and intelligent manufacturing in the field of shoes and clothing.

The work in this paper is a part of National Key Research and Development Program (2018YFB1308800). In order to understand the printing mechanism and develop intelligent printing equipment, theoretical analysis on paste rheology, mechanical property of squeegee, and the deformation and permeability characteristics of screen are carried out, based on which flow field simulation is done by the fluid-solid coupling method to obtain the printing mechanism. Then the automatic printing equipment is developed as well as corresponding process. The main contents and achievements of this paper are as follows:

(1) The physicochemical properties and rheological properties of printing paste as well as their effects on printing process are studied. The physicochemical characters of aqueous polyurethane dispersion (PUD) with high solid content, including main component, particle size distribution, surface charge and Zeta potential, are characterized using Fourier transform infrared spectroscopy, dynamic light scattering

and laser Doppler electrophoresis. The paste rheology is studied by steady and dynamic shear tests. The viscosity with shear rate, temperature and solid content as well as viscoelastic properties with strain and frequency were analyzed. It can be known that paste is pseudoplastic non-Newtonian fluid with weak gel structure and shear thinning characteristics. Based on Arrhenius formula and Carreau equation, the viscosity model of paste under the influence of multiple factors is constructed. Meanwhile, the fractional derivative Zener and Poynting-Thomson models are derived and optimized, based on which the linear viscoelastic properties of paste are analyzed by regression. Using the above constitutive equations, the theoretical boundary values of paste subjected to shear, strain and oscillation in printing were obtained.

(2) A mathematical model of printing flow field considering rheological properties of paste, squeegee form and printing speed is constructed, and the distribution characteristics of flow field are studied. An analytical procedure is developed to solve the stress, strain, and displacement distribution of wedge squeegee with variable section based on elastic mechanics theory. As the plane strain problem, the mechanical characteristic of hyper elastic squeegee is conducted to obtain the deformation equation. Then the lubrication theory is applied to the mathematical modeling of additive printing, leading to non-dimensional velocity as well as the integral expression of hydrodynamic pressure that is solved by the Romberg integration algorithm. Then the extended Fourier amplitude sensitivity test is carried out to quantify the impacts of printing force, angle and velocity on hydrodynamic pressure. Finally, in order to verify the effectiveness of the mathematical model, a CFD model is developed to simulate the flow field of additive printing, taking into account Newtonian and non-Newtonian properties. And the simulation results are in good agreement with that in theoretical analysis.

(3) The screen form and printing coordination conditions are analyzed and calculated. In addition, the rheological splitting of paste during screen rebound is studied. By calculation, the deformation expressions of printing pattern with screen size, snap-off distance, pattern position and printing force is obtained. Based on Poiseuille flow, the relation between the printing velocity and mesh count, thickness, fiber diameter, viscosity is obtained through kinematics compatibility conditions. Meanwhile, the relationship between rebound velocity of screen and screen size, snap-off distance and printing velocity is also obtained. Based on Hooke's law and Newton's law of

internal friction, the mathematical equations for screen size, squeegee size, snap-off distance, mechanical parameters of screen and screen specification are proposed from the mechanical compatibility conditions of screen rebound. Using the surface wetting process and interface reconstruction technology, the rheological splitting of paste in the screen rebound is analyzed, through which it can be known that surface free energy and fiber diameter have important effects on the rheological splitting.

(4) Fluid-structure coupled model of paste transfer in printing is established, using the rigid body dynamics, multiphase flow, porous media and dynamic grid technologies, based on which the variation in flow field and transfer mechanism of paste are studied. The distribution of flow field is analyzed as well as the variation of pressure between permeable and impervious areas. Moreover, the relationship between transfer amount of paste and pressure is analyzed, which is verified by single factor experiment. The transfer mechanism of paste is summarized: the wedge flow field constructed from squeegee and screen meets the hydrodynamic lubrication, forming a hydrodynamic pump, and the steep increase in pressure near the squeegee tip inject the paste into the aperture of screen. Under the effect of printing force, the screen is in contact with the warp knitted vamp, forming a liquid bridge. As the squeegee moves on, the screen "peels off" dynamically from the warp knitted vamp at some distance behind the squeegee, and the contact line moves up. Meanwhile, the liquid bridge is stretched up to rupture. Since the surface free energy of the warp knitted vamp is greater than that of the screen, most of paste is transferred to the warp knitted vamp.

(5) The process of additive printing is analyzed to identify some special mechanisms. On the basis of transfer mechanism, additive printing equipment is researched and developed. Based on the fuzzy mathematics theory, the reliability of additive printing system is analyzed using failure mode and effect analysis to obtain the failure modes and risk priorities. Orthogonal experiment with seven factors and four levels is designed and performed on the additive printing equipment, then variance and range analysis are carried out. The optimizing model of process parameters is constructed by support vector machine for regression and genetic algorithm to obtain the optimum printing parameters. The high-quality printing products produced by the additive printing equipment can meet the requirements of tensile strength, flexometer and hydrolysis testes.

This paper develops additive printing equipment and design the corresponding process to produce high-quality printing products based on the in-depth analysis of transfer mechanism of paste. It has important theoretical significance and application value for understanding the mechanism of additive printing for warp knitted vamp, improving the automatic level of the industry, promoting competitiveness of products and achieving the green intelligent manufacturing.

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Key Words: warp-knitted vamp, additive printing mechanism, process parameter optimization, rheology, squeegee form, screen form, paste transfer