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授　　与　　学　　位　博士（工学）
学 位 授 与 年 月 日　令和６年３月２２日
学位授与の根拠法規　学位規則第４条第１項
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博士後期課程総合システム科学専攻
学 位 論 文 題 目　Evaluation of Injection Welding Performance and Interface Structure Analysis of CFRTP
（CFRTP の射出溶着特性および界面構造解析）
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論 文 内 容 要 旨

A thermoplastic polymer injection molding welding technique was proposed, discussing the enhanced interlaminar shear strength of injection welding with the addition of short carbon fibers (CF). The effectiveness of this welding method was confirmed through the evaluation of homogeneous polyamide 6 (PA6) polymers. To address the challenge of low welding strength in carbon fiber-reinforced thermoplastic (CFRTP) composites, the polymer welding interface structure and the distribution of short carbon fibers at the interface were thoroughly discussed, resulting in optimal carbon fiber content and welding parameters. Tensile and thermal tests were conducted to study their physical and welding properties. Additionally, the interface structure was observed using optical microscopy and scanning electron microscopy. Fourier infrared spectroscopy and differential scanning calorimetry were used to analyze the crystalline behavior at the interface. The relationship between welding strength and interface structure was analyzed, and the welding process was discussed from the perspective of interface structure.

In chapter 1, the research backgrounds and the construction of this thesis are described. The purpose of this

study is to explore the relationship between the injection welding interface structure and strength, and to address the issue of low welding strength in CFRTP by altering welding parameters.

In chapter 2, the properties of experiment materials, as well as experimental methods and characterizations are presented.

In chapter 3, secondary injection molding was utilized to weld polyamide 6 (PA6). The welded samples were evaluated for the welding strength via a shear tensile test. Three process parameters of mold temperature, injection temperature, and injection speed were varied to determine the optimal conditions for welding. A polarizing microscope analysis of the welding interface revealed formation of a shish kebab layer (SKL) structure, which significantly contributed to the welding strength. A differential scanning calorimetry analysis of the welded samples showed that changes in the crystallinity at the interface were closely related to the welding strength under different injection molding conditions. To analyze the crystal phase of the interface after welding, we propose the use of Fourier-transform infrared spectroscopy area scanning to obtain the relationship between the phase transformation and welding strength. Additionally, microhardness testing is proposed as a means of evaluation of the welding effect. Overall, this study highlights the importance of optimization of process parameters in secondary injection molding to achieve strong welds in PA6, where the SKL structure and crystallinity changes at the interface have crucial roles.

In chapter 4, carbon fiber was added to the commonly used resin reinforcing material, polyamide (PA6, nylon), to create a carbon fiber reinforced thermoplastic composite (PA6/CF) that was welded using injection molding. This study not only investigates the impact of different welding conditions on shear strength, but also discusses the sequence of welding. Attaining 85% of the shear strength of the PA6 base material under optimal conditions. The carbon fibers distribution and reinforcement mechanism were analyzed by observing the connection interface and cross-section by polarizing microscope and scanning electron microscope. When PA6/CF was used as the secondary molded body, the welding results were better. The addition of carbon fiber had a significant strengthening effect on the strength of the Polyamide 6 injection welding.

In chapter 5, CFRTP with varying carbon fiber contents were prepared to explore the impact of carbon fibers on shear strength. PA6/CF composites with CF contents of 10wt% and 30wt% were subjected to injection over-molding for the first and second molding cycles, respectively. It was observed that the reinforcement effects varied considerably depending on the combinations studied. Under the optimal combination and process parameters, the weld shear strength of PA6/CF composites reached 63MPa, equivalent to 90% of the shear strength (70MPa) of the original PA6/CF material. Polarized light microscopy and scanning electron microscopy were utilized to analyze the distribution of carbon fibers at the interface and the reinforcing mechanism during tensile fracture. The significance of maintaining uniform CF content during the welding process of PA6/CF composites was emphasized.

In chapter 6, the relationship between the angle of entry into the interface during injection welding and the strength was analyzed after the addition of short carbon fibers. The interweaving effect between carbon fibers was also elucidated at high carbon fiber content.

In chapter 7, the conclusions of main results are remarked.

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論文審査結果要旨

本論文では、射出溶着技術を用いてポリアミド樹脂（PA6）およびその炭素繊維（CF）強化熱可塑性複合材料（CFRTP 或は PA6/CF）を溶着させ、その溶着特性と界面構造を調査することにより、CFRTP の接合強度を向上させることを目的としている。本論文は全 7 章で構成されている。

第 1 章は緒論として、CFRTP の接合に関する既存の研究から本研究の背景を述べ、本研究の目的を示している。第 2 章では材料および試験方法として、PA6/CF の作製方法および射出溶着特性の評価方法について説明している。第 3 章では、PA6 を溶着するために二次射出成形法を用いて、溶着加工を行った。溶着体のせん断溶着強度に及ぼす射出温度、射出速度および金型温度の影響を検討し、最適な溶着条件を明らかにしている。また、溶着界面に形成されたマイクロ構造が溶着強度に大きな影響を与えることが認められている。第 4 章では、PA6 に CF を添加し、射出成形法により PA6/CF 溶着体を作製した。PA6/CF 溶着体のせん断溶着強度は CF の添加により向上し、また、CF 含有量にも依存することを示している。第 5 章では、PA6/CF 溶着体のせん断溶着強度に及ぼす CF 添加量および溶着加工方法の影響を調べるために、10wt%および 30wt%CF 含有量の PA6/CF 複合材料をそれぞれ一次成形体および二次成形体として溶着体を作製した。それぞれの組み合わせによって、溶着強度が異なるが、最適な組み合わせ条件が存在していることがわかった。特に、金型温度 120℃、射出温度 380℃、射出速度 30mm/s の下では 63MPa の最大接合強度が得られた。第 6 章では、PA6/CF 複合材料の溶着界面における CF の強化メカニズムについて分析し、高い溶着強度を得るには CF が溶着界面を渡ることが非常に重要であることが認められている。第 7 章は結論であり、研究結果をまとめている。

本論文の成果は、CFRTP の接合に関する理論と技術の確立において重要な学術的貢献を果たすだけでなく、その高い溶着特性により優れた工学的価値を持っている。また、研究業績として、査読付学術論文 4 編、国際会議 1 件、国内会議 3 件を公表している。

よって、本論文は博士（工学）の学位論文として合格と認める。