Kurzfassung

Die Gewichtsreduktion im Strukturbereich stellt einen zentralen Optimierungsansatz in der Luftfahrtindustrie dar, der vor allem durch adäquate Fügetechnologien genutzt werden kann. Ausgehend vom aktuellen Stand der Technik im Helikopterbau, dem Nieten, gilt es durch die Verwendung einer innovativen Fügetechnologie das volle technologische Leistungsvermögen hinsichtlich Performance, Qualität und Kosten zu nutzen. Dazu wurde das Induktionsschweißen als die potentialreichste Fügetechnologie für den Helikopterbau bewertet. Um dieses identifizierte Potential für eine Luftfahrtfertigungstechnologie nutzbar zu machen, ist es unerlässlich, das Induktionsschweißen an die Luftfahrtanforderungen anzupassen. Vor allem in den Bereichen Nachweisbarkeit, Leistungsfähigkeit und Kosten wurden daher Fragestellungen identifiziert deren Beantwortung den Kern dieser Arbeit darstellt.

Beim Induktionsschweißen werden faserverstärkte Thermoplaste durch ein Aufschmelzen der Matrix und ein anschließendes Abkühlen unter Druck gefügt. Die Erwärmung des sich in einem alternierenden elektromagnetischen Feld (EMF) befindlichen Laminats erfolgt dabei durch die Einkopplung eines elektrischen Stroms in die Fasern.

Das zentrale Element zur Erreichung der geforderten Leistungsfähigkeit stellt die interlaminare Temperaturverteilung dar, welche es nachzuweisen gilt. Dieser Nachweis wurde durch ein umfassendes analytisches Modell realisiert, das eine höchstpräzise interlaminare Temperaturberechnung ermöglicht. Die Kernaussagen, welche aus dem Modell abgeleitet werden, sind die dickenabhängige Erwärmung des Laminats, die EMF-Semipermeabilität der Laminatoberflächen und der nicht exponentielle Abfall sowie der nicht lineare Verlauf der Temperatur in Dickenrichtung. Die Validierung der analytischen Modellierung gelang nur durch die Identifikation einer EMF-toleranten, hochdynamischen Temperaturmesstechnologie, welche mit hoher Auflösung interlaminar eingesetzt werden kann.

Auf Grundlage der Modellergebnisse wurden die optimalen Schweißparameter definiert, auf deren Basis die Leistungsfähigkeit der Induktionsschweißtechnologie mit circa 36 MPa Scherfestigkeit bestätigt wurde. Durch eine Sensibilitätsanalyse konnte weiterhin der Einfluss der Parameter Generatorleistung, Kühlvolumen, Anpressdruck, Induktorabstand, Fehlereinschlüsse und Geschwindigkeit bestimmt

werden. Aufgrund der im aktuellen Anlagenaufbau nicht vorhanden Parameterüberwachung und aufgrund des hohen Prozesseinflusses erwies sich dabei der Induktorabstand als der kritischste Faktor.
Etwaige dadurch auftretende qualitative Mängel können durch den schlanken, maßgeschneiderten Einsatz einer Kombination aus der Ultraschalluntersuchung, einer in der Luftfahrt standardmäßig eingesetzten Qualitätssicherungsmethode und eines progressiven Inline-Prozesskontrollansatzes detektiert werden.
Parallel zur mechanischen Leistungsfähigkeit der Technologie stand der Einfluss der Temperaturverteilung auf die Oberflächenqualität im Fokus. Durch die umfangreiche theoretische und experimentelle Analyse bereits bekannter und neu entwickelter Temperaturoptimierungsmethoden konnte mit der Kühlung der Oberfläche mit temperatur- und volumenvariablen Druckluftströmen eine effiziente Methode zur zielführenden Lösung der bestehenden Problemstellung ermittelt werden.
Die Anwendbarkeit der Induktionsschweißtechnologie konnte auch durch eine Kostenrechnung am Beispiel eines helikopterspezifischen Musterbauteils bestätigt werden.

Abstract

Aerospace companies are focused on the maintenance and extension of their competitiveness, by an increase of the product performance while reducing costs at the same time. One of the main optimization approaches is the reduction of structural weight. In particular, in the field of joining technologies rivetless joining processes offer a high potential. Furthermore, the waiver of cost-intensive joining additives like rivets and the increase of the automation degree lead to a reduction of joining costs. Thereby, the traceability of the successfully performed joining must always be available.

In accordance with these requirements the induction welding was evaluated by the analysis of the specialist literature as the joining technology with the highest potential for aerospace manufacturing. None of the technologies described in literature is in accordance to the aerospace requirements. Therefore the objective of this research is to adapt the induction welding to the aerospace requirements.

Induction welding is a technology for joining carbon fiber reinforced thermoplastics (thermoplastic composite - TPC) by melting the thermoplastic matrix material causing fusion, by subsequent cooling under pressure. The heating of the TPC situated in an alternating electromagnetic field (EMF) is performed by induction of the current into the carbon fibers.

According to the traceability of the successfully performed joining, the relevant process parameters have to be predicted or measured during the welding process. This is possible for every parameter influencing the process expect for the interlaminar temperature distribution. A measurement of the interlaminar temperature during the subsequent industrial application is not possible, consequently an analytical temperature model was developed. The model was validated with practical studies, by researching the process influencing parameters laminate thickness, generator power, coil-laminate distance, time and speed.

For the conduction of process studies, an experimental rig was built. This computer controlled test bench was designed to enable both continuous and spot welds with full parameter control, measurement of all parameters and maximum reproducibility of the induction heating and the welding operations. The basic investigations have been conducted with laminates made of carbon fiber (fabric and unidirectional tapes) reinforced polyetheretherketone (PEEK).

The model and the practical studies have shown that the temperature is mainly influenced by the specimen thickness and the related skin depth ratio. By an increase of the ratio, meaning thicker laminates, the temperature through the whole thickness decreases and converges to the temperature distribution for infinite thick specimens. Independently of the specimen thickness the highest temperature in the laminate is reached between the first plies near to the surface facing the inductor and not directly at the surface. This is because of cooling by natural convection.

For an optimization of the interlaminar temperature distribution eight different theoretical approaches were identified. Most of them were contrary to the defined aerospace requirements, only the use of multiple inductors or the use of parabolic mirrors to focus the EMF in a line or a plane and the cooling of the surface with a fluid comply with the requirements. A theoretical discussion demonstrated that a focusing of the EMF is not possible, accordingly only the cooling of the surface was implemented in the analytical model and practically researched, which leads to the following results. When cooling the surface with an air jet, the maximum temperature can be shifted inward. The temperature was successfully reduced up to the interfaces between the second and third respectively the third and the fourth ply by increasing the air jet volume up to 500 l/min. By a decrease of the temperature of the air jet a further reduction of the temperature in the first plies was shown. In comparison to the cooling with pressurized air by room temperature the cooling of the air jet by cyclone tubes (reduced air temperature) does not increase the efficiency of the process.

For the validation of the model an EMF-tolerant temperature measurement method was identified and validated. It was shown that during the induction welding and heating process, type E thermocouples show the lowest self heating effect in the field. Due to the higher surface-volume-ratio and the corresponding higher heat conduction, the thinnest wire diameter should be used. During the tests, the thermal radiation of the coil influenced the heating studies. The measurement of the heat distribution in thickness direction with thermocouples is not influenced by inductor's heat radiation because the thermocouples are embedded into the material and not influenced by heat radiation. Between room temperature and 350 °C the temperature increase decreases from 10.6 °C to 8.0 °C. An adaption of the measurement during the heating process effected by non-linear heating behavior is not necessary. All assumptions were derived by theoretical means and empirically proven. A significant reduction of inaccuracy in measurement can be reached by the use of thermocouples type E with a peak radius of 0.1 mm and 0.18 mm (approx. 0.1 mm wire diameter). With a reference measurement the influence of the induction generator power can be calculated and the measured temperature can be adjusted. In comparison to the previously used measurements the maximum error can be reduced from 80 °C to 12 °C, which can be precalculated and eliminated.

With the validated model for the calculation of the temperature distribution in thickness direction an optimal process window for the used CF/PEEK material was identified. For an 8-layer $[(0°/90°)4]_s$ the parameters were determined with 25 % generator power, 300 l/min cooling volume, 20 °C cooling fluid temperature, 2 mm coil-laminated distance, 0,1 m/min welding speed and 1 kN pressing force and confirmed by a high mechanical strength. The welded specimens achieved a lap shear strength up to 36 MPa.

Furthermore, the applicability of the state of the art quality assurance methods was confirmed. With the ultrasonic technology (C-scan) an insufficient adhesion can be identified, which may be caused by various process deviations like inclusions, deviations of the power, the pressure and welding speed. Also their influence to the joining strength was shown. Another element for the realization of a cost efficient joining process is the use of lean surface treatment technologies. The highest lap shear strength was reached with the surface treatment grinding and cleaning with acetone.

With regards to the cost efficiency of the induction welding technology, it was demonstrated by cost engineering that the process costs are even superior to the state of the art processes.

Within the investigations the potential of the technology for the helicopter manufacturing was confirmed and all the objectives were reached.