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COMPOSITES THEORY AND PRACTICE

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THERMOCLINCHING - A NOVEL JOINING PROCESS FOR LIGHTWEIGHT STRUCTURES IN MULTI-MATERIAL DESIGN

In the scope of reduced resource consumption and CO_2 emissions, lightweight structures in multi-material-design offer a high potential for use in aviation or automotive applications. Though, to take advantage of the specific structural and functional properties of the different materials of hybrid structures, it is necessary to provide adapted manufacturing and joining technologies. This article presents the development of a new thermoclinching joining process to produce hybrid structures with continuous fiber reinforced thermoplastic composites and metallic components. Based on the principles of staking and the classical clinching process, thermoclinching technology ensures element free and form-closed joints by plastic deformation of the reinforced thermoplastic component. To approve the technological concept of the thermoclinching process, prototypic joints with both reinforced and non-reinforced thermoplastics were produced and experimentally tested, revealing up to 50% higher failure loads of the reinforced joints. In order to understand the generated fiber reorientation during the thermoclinching process and its optimization, the produced joints were analyzed using non-destructive and destructive testing methods such as computed tomography scans and micrograph analysis. It was shown that parts of the textile reinforcement were purposefully relocated into the neck and head area of the joint and thus considerably contribute to the load carrying capacity of the joint. Process simulations are performed to predict the plastic deformation and the resulting fiber orientation during the joining process. Even now, it can be stated that without the necessity to apply any additional joining elements, the developed thermoclinching technology projects a high lightweight potential for future composite structures.

Keywords: clinching, hybrid structure, multi-material, joint, thermoplastic composite material, textile composite

THERMOCLINCHING - NOWATORSKA METODA ŁĄCZENIA LEKKICH MATERIAŁÓW HYBRYDOWYCH

W celu zmniejszenia zużycia energii i emisji CO_2 coraz częściej projektuje się lekkie konstrukcje z wykorzystaniem materiałów z różnych grup, których potencjał predestynuje je do stosowania w przemyśle lotniczym i motoryzacyjnym. Jednak, aby wykorzystać wyjątkowe właściwości materiałów hybrydowych, konieczne jest zapewnienie odpowiednio zaprojektowanych metod wytwarzania i łączenia. W niniejszej pracy przedstawiono opracowanie nowego procesu łączenia materiałów pochodzących z różnych grup, np. tworzyw termoplastycznych wzmacnianych włóknami ciągłymi i metali. W oparciu o zasady spęczania i klasycznego procesu zaciskania technologia „thermoclinching" została opracowana w taki sposób, że zapewnia zamkniętą postać połączenia, wykorzystując odkształcenie plastyczne tworzywa termoplastycznego. W celu zweryfikowania koncepcji procesu „thermoclinching" wykonano złącza z tworzyw termoplastycznych zarówno wzmocnionych, jak i niewzmocnionych włóknami ciągłymi. W przypadku materiału wzmocnionego zaobserwowano o ponad 50% wzrost wartości obciążeń, potrzebnych do zniszczenia takiego połączenia, w porównaniu do termoplastu niewzmocnionego. W celu określenia sposobu przemieszczania się włókien podczas procesu „thermoclinching" wykonane złącza przebadano za pomocą zarówno niszczących, jak i nieniszczących metod badania materiałów, m.in. tomografii komputerowej i mikroskopii świetlnej. W pracy pokazano, że część wzmocnienia została celowo przesunięta do środkowej i dolnej części połączenia, przyczyniając się tym samym do zwiększenia nośności połączenia. Wykonano również symulacje komputerowe w celu przewidzenia odkształcenia plastycznego oraz przesunięcia wzmocnienia w trakcie procesu łączenia. Na podstawie przeprowadzonych badań można stwierdzić, że opracowana technologia „thermoclinching" pozwala na łączenie lekkich materiałów kompozytowych bez konieczności stosowania dodatkowych elementów łączących oraz ma wysoki potencjał aplikacyjny w perspektywie przyszłych zastosowań w technologiach materiałów kompozytowych.

Słowa kluczowe: klinowanie, struktura hybrydowa, połączenie, termoplastyczne materiały kompozytowe, kompozyty

INTRODUCTION

In the scope of energy-efficient and resource sustaining product development, lightweight structures in multi-material design have proven to be very efficient. Thereby, hybrid structures made of textile reinforced thermoplastics in combination with metallic materials are gaining increasing relevance for high-volume applications particularly in the transportation industry. This results from both, their ability of effective and reproducible manufacture in short cycle times using pressing technology and their adjustable high level mechanical properties. In order to take advantage of the specific structural and functional properties of the different materials and to fully exploit the bearing capacity of such structures, it is necessary to provide distinct processing and joining technologies.

As classical joining technologies like bonding or riveting are common and proven joint systems for composite materials with thermoset matrices, their efficient integration into the manufacturing process of thermoplastic composites is not always transferable. The adhesive bonding of most thermoplastic composites is problematic due to their low surface polarity and lacking surface wettability, resulting in extensive surface pretreatment of the joining partners, which extend the process [1]. Riveted connections are common joining methods for aviation applications due to their fast joining processes and high reproducibility [2-4]. Nonetheless, the riveted joining area is structurally weakened due to local delamination and fiber interruption, since the holes which are needed for these connections are usually produced by drilling [5, 6]. As shown by Blaga et al. [7], adaption of the riveting process for a non-destructive joining method with thermoplastic composites and metallic parts is highly complex, increases the process time and therefore is not very efficient in the scope of high-volume applications. In contrast to metallic joining partners, thermoplastic materials have the advantage of low thermal conductivity in combination with low melting temperature offering an easy and repeatable local forming ability by temperature assisted plastic deformation. State-of-the-art joining techniques for short and long fiber reinforced hybrid joints considering thermoplastic matrices are for example injection clinching joining or ultrasonic staking [8, 9]. On the contrary, textile reinforced thermoplastic composites only provide a limited plastic deformation range, restricting the adaption of established joining technologies for short and long fiber reinforced thermoplastics.

In this study, a novel joining process is introduced to produce hybrid components with textile reinforced thermoplastic composites and metallic joining partners. Based on thermoplastic staking and the metallic clinching process, the first prototypic joints were produced, demonstrating the capability of the developed joining technology. Furthermore, the thermoclinching joints were analyzed by means of experimental, analytical, and numerical methods.

DEVELOPMENT AND DESCRIPTION OF THERMOCLINCHING PROCESS

The new joining technology of thermoclinching is based on process sequences from thermoplastic staking and the metallic clinching process, which are established methods to join double- or multi-layered structures by plastic deformation. The principles of the staking process are displayed in Figure 1 for the hot staking variant [10]. Thereby, a heated punch is used for softening/melting a thermoplastic stake normally integrated in the polymeric component and passing through a perforated metallic part. After heating, the punch plastically deforms the stake building a form-closed joint between the metallic and thermoplastic joining partners.

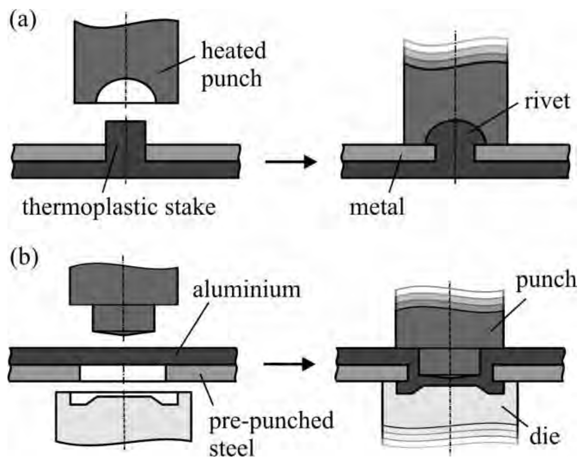


Fig. 1. Schematic illustrations: a) thermoplastic staking process and b) single-staged clinching process with a pre-punched pilot hole

Rys. 1. Schemat: a) proces kołkowania termoplastycznego oraz b) jednoetapowy proces zaciskania z otworem pilotażowym

Similar to the staking process but without the necessity to position a stake through a metallic joining partner, the clinching process can also be applied to build form-locking joints with thermoplastic and metallic components by plastic deformation [11]. During classical clinching, the fixed joining partners are partially interspersed by a punch and afterwards compressed using a die, whereby a positive-locking undercut is created by cold forming alone [12]. However, the classical clinching process is limited by the thickness and formability of the joining partners. This led to developments such as single-staged clinching with a pre-punched pilot hole, also known as CONFIX clinching [13]. For this technique, the non-ductile material is pre-punched, arranged at the die side and interspersed from the ductile joining partner (cf. Fig. 1).

To join the metallic components with the textile reinforced thermoplastic structures, the new joining technology of “thermoclinching” demonstrates a plastic deformation process similar to CONFIX-clinching and the staking process. The principle procedure of the novel thermoclinching process is shown in Figure 2. In particular, the process starts with aligning and positioning of the joining partners inside the mould. The following heating process (Fig. 2a) enables the tapered pin to permeate the joining zone by increasing the plastic deformation ability of the thermoplastic composite. After closing the mould, the pin is shifted forward into the composite, shifting the thermoplastic matrix and parts of the textile structure through the pre-punched hole of the metallic joining partner (Fig. 2b). Subsequently, the passed-through material is recompressed by the ring shaped die, forming out the form-closed head of the joint (Fig. 2c). After cooling and solidification, the mould is opened and the geometrically defined joint is removed (Fig. 2d). Without the necessity of additional joining elements and by compiling a defined fiber orientation of the composite in the neck and head area of the joint, the high lightweight potential of the thermoclinching joint can be achieved.

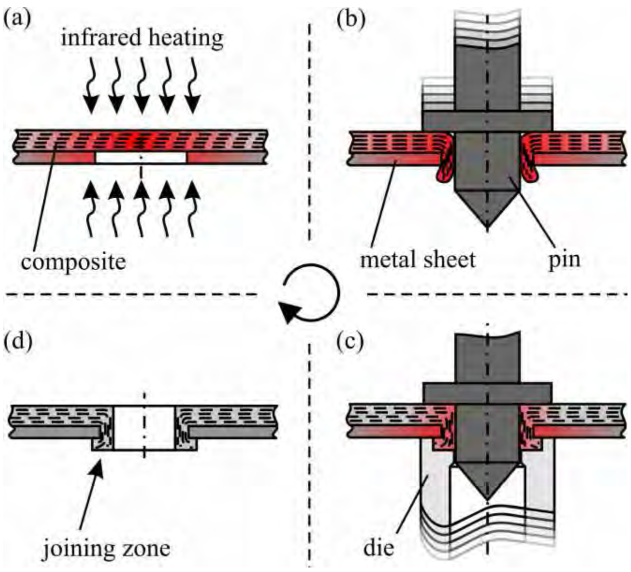


Fig. 2. Schematic illustration of novel thermoclinching process

Rys. 2. Schemat nowoczesnego procesu "thermoclinching"

PRODUCTION AND TESTING OF THERMOCLINCHED JOINTS

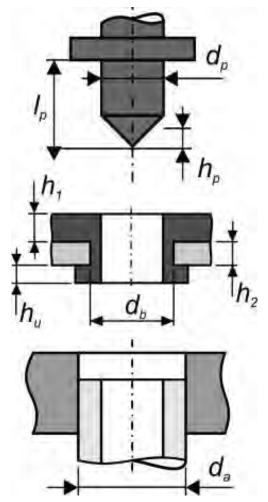
To approve the technological concept of the developed process, first prototypic joints were produced using a laboratory scaled experimental installation with defined mould, pin and die geometry (Table 1). As summarized in Table 1, the manufacturing trials were conducted on pre-punched steel sheets in combination with thermoplastic composite sheets made of glass fiber reinforced polypropylene (GF/PP) known as TWINTEX [14]. However, alternative thermoplastics and reinforcement structures such as carbon fibers and thermoplastic laminates with different fiber volume contents are expected to also be suitable for the thermoclinching process. Their adapted transmission into processing is intended for further investigations once the thermoclinching process is sufficiently investigated concerning an adjustable and reliable process operation.

Due to the high deformation degree of the textile reinforcement structure during the thermoclinching process, the composite was locally cut crosswise in the space of the joining zone to improve the drapability of the fibers (Fig. 3c). The cut was applied using a rotary tool with a precision cutting disc whereby the cutting length was adjusted to the diameter of pilot hole d_b inside the metallic joining partner. To ensure reproducible joint quality, the joining partners were further prepared by degreasing.

TABLE 1. **Semi-finished part properties and tool dimensions for manufacturing trials**

TABELA 1. **Własności półfabrykatów oraz wymiary narzędzi dla prób wytwarzania**

fabric	TWINTEX TPP 60 745
weave	Twill 2/2
laminate structure	$[(0°/90°)]_4$
fiber volume content	0.35
laminate thickness h_1	4 mm
steel sheet thickness h_2	1 mm
pilot hole diameter d_b	15 mm
pin length l_p	35 mm
pin diameter d_p	12 mm
die diameter d_a	22 mm
pin point length h_p	10 mm



In order to determine an adequate process temperature, thermal analyses such as differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) were conducted on the chosen composite material. Based on these analyses the process temperature was defined at 200°C. At this temperature the composite is sufficiently softened to deform and relocate the material in the joining zone without damaging it. Furthermore, the process temperature is sufficiently low to keep a thermo-oxidative degradation at a minimum level.

The ensuing joining process was started by warming up the composite with infrared heaters until the process temperature of 200°C was reached. Having transferred the thermoplastic composite sheet into the mould and after closing it, the joining process lasts 0.5 s. To avoid rapid cooling down of the heated area during the joining process, the mould had a temperature of 80°C. After final shaping and compression of the plastically deformed composite by the die, the mould was cooled for 35 s. The geometry of the produced thermoclinching joining zone is displayed in Figure 3, whereby a form-closed and geometrically defined head of the joint was generated with a height of h_u = 1.5 mm and an outside diameter of d_a = 22 mm.

In order to obtain a statement concerning the joint strength of the thermoclinching joints, first loading tests were performed on single-lap specimens with general dimensions based on quasistatic testing standard ISO 14273 (Table 2). As the load bearing capacity of metallic clinching joints is basically specified through their main structural attributes, it is assumed that varying the geometrical dimensions of the thermoclinching joints will provoke different load bearing capacities as well. Thus, thermoclinched specimens with both reinforced and un-reinforced thermoplastic joining partners were produced and tested with different geometrical joint dimensions such as head height t_u, head extent l_u and neck thickness t_n (Fig. 4).

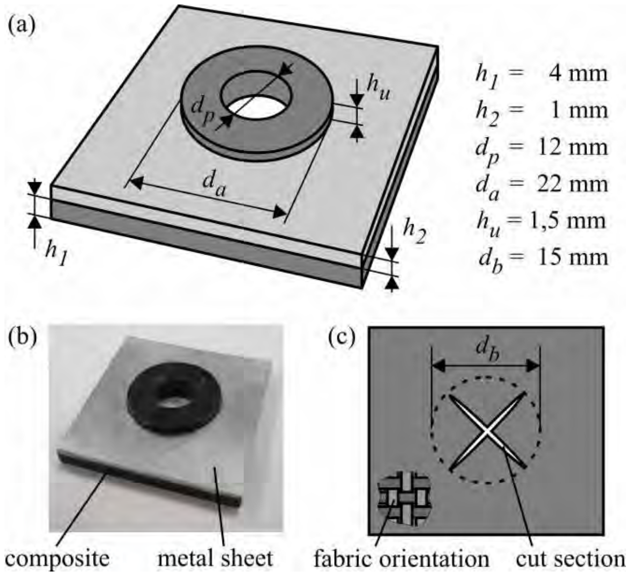
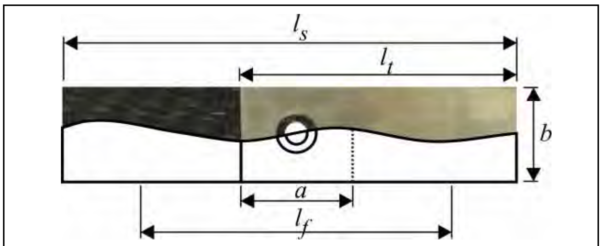


Fig. 3. Prototypic thermoclinching joint: a) schematic illustration and dimensions, b) sample specimen and c) schematic illustration of applied cut in composite joining zone

Rys. 3. Prototypowe połączenie metodą "thermoclinching": a) schemat oraz wymiary, b) przykład wykonania oraz c) schemat zastosowanego nacięcia w miejscu połączenia kompozytu

TABLE 2. **General dimensions of thermoclinching single-lap specimens for shear loading tests**

TABELA 2. **Główne wymiary próbek złączy pojedynczych do testów na ścinanie**



material	steel/ PP/ GFPP (cf. Tab. 1)
PP/ GFPP thickness h_1	4 mm
steel sheet thickness h_2	1 mm
single specimen length l_t	160 mm
specimen length l_s	260 mm
specimen width b	55 mm
clamping length l_f	120 mm
overlapping length a	60 mm

As displayed in Figure 4, the test results demonstrate the significant influence of the joining zone dimensions on the load bearing capacity of thermoclinching joints. It was observed that during shear loading of the joints, an extended width of the joint neck area increases the load bearing capacity, which can be tracked back to the higher material concentration in the load direction. Regarding this, maximum thickness in the neck area of the joining zone would be desirable. However, by extending the neck thickness, the head height of the joint decreases due to volume consistency and the joint resistance against pull-out failure is reduced. Aiming for an optimal load bearing capacity of the joint concerning the combined load cases, the joint dimensions have to be adapted taking into account each main geometrical parameter which influences the load bearing behavior.

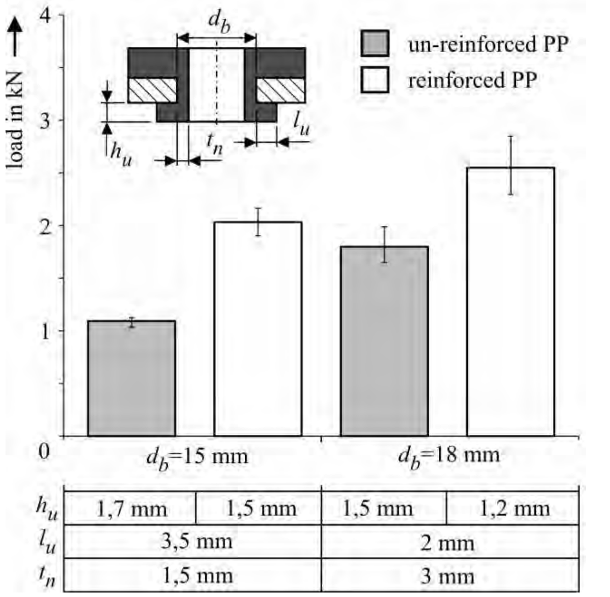


Fig. 4. Dependence of varying main joint dimensions on load bearing capacity of thermoclinching jonts with both un-reinforced and reinforced thermoplastic joining partners

Rys. 4. Wpływ różnych wariantów wymiarowych na nośność połączenia wykonanego metodą "thermoclinching" dla niewzmocnionego i wzmocnionego termoplastycznego łączenia komponentów

In addition to the dependence of the joint dimensions, the load bearing capacity is further influenced by the reinforcement of the thermoplastic joining partner (Fig. 4). Although the textile reinforced joints show decreased head height t_u due to material discharge during the cut application in the joining zone to improve the local deformation capability of the textile structure, the reinforced joints bear up to 50% higher failure loads in comparison to the un-reinforced joints.

ANALYSIS OF PLASTICAL DEFORMATION BEHAVIOUR

For comprehension of the composite fiber orientation inside the generated joint and during the thermoclinching process, the microstructure of the joining zone has to be analyzed. Since a locally differentiated material structure with inhomogeneous three-dimensional fiber orientation and locally varying fiber content is generated in the joining zone during the forming process, detailed determination of the three-dimensional material configuration is necessary. Accordingly, non-destructive and destructive tests such as computed tomography scans and micrograph analyses were performed on the produced thermoclinching joints. As displayed in Figure 5, the received analyses of the thermoclinched joining zone show a relocation of the deformed textile reinforcement structure into the neck and head area of the joint, which considerably contributes to the load carrying capacity of the joint (cf. Fig. 4), even though largely undefined and not yet reproducible.

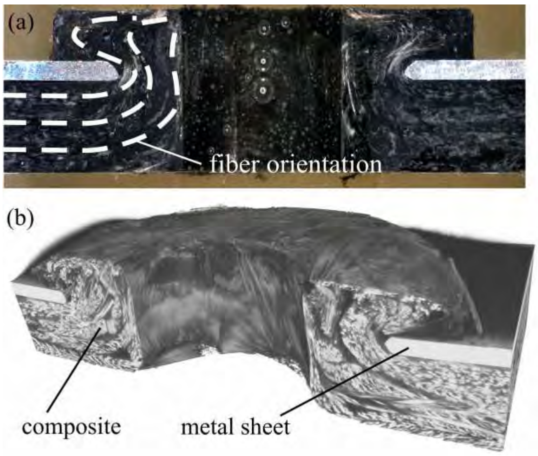


Fig. 5. Analyses of thermoclinched joint micro-structure by (a) micrograph analysis and (b) computed tomography

Rys. 5. Analiza mikrostruktury połączenia wykonanego metodą "thermoclinching" za pomocą (a) analizy mikroskopowej oraz (b) tomografii komputerowej

Efficient and detailed development of a reliable thermoclinching process considering accurate prediction of joint quality requires the application of adapted simulation tools that are not state of the current research. A process temperature near or above the melting point of the matrix locates the simulation problem in the transition area between solid continuum mechanics and fluid dynamics. Here, the estimation of material data in the viscous state is a challenging mission. Kaneko et al. [15] presented a rheological model for pure polypropylene for the generation of rate and temperature dependent stress-strain-curves. Extrapolation of the measured data gives a rough estimation of the material parameters in the viscous transition zone. Taking into account the effects of injection direction with Hill's yield potentials, the numerical pre-studies showed a good representation of the pure matrix indentation experiments. The texture of the pure matrix material as a result of its small injection molding dependent anisotropy contains information about the probable fiber orientation (Fig. 6). Hence, early studies allow estimation of the relation between the joint size and the local orientation field.

The observed high degrees of deformation, especially during the indentation phase, require advanced techniques to maintain the quality of the mesh throughout the analysis. Adaptive remeshing based on the Arbitrary Lagrangian-Eulerian (ALE) method effectively relocates the nodes with the drawback of concealing phenomena as folding or an interlaminar slip.

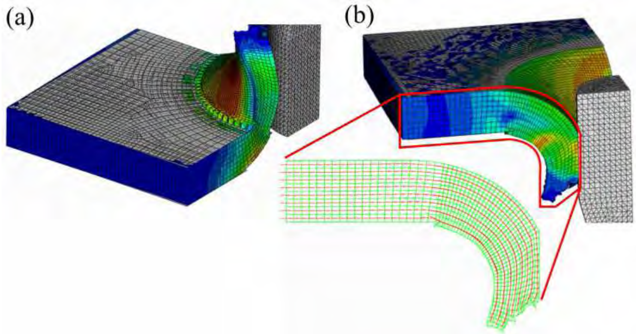


Fig. 6. Deformation of pure matrix indentation: (a) die-sided and (b) pin-sided with material texture in neck area representing probable fiber orientation

Rys. 6. Odkształcenie wcięcia osnowy: (a) od strony formy oraz (b) od strony trzpnia wraz z teksturą materiału w obszarze szyjki reprezentującą prawdopodobne ułożenie włókien

Since the viscous matrix tends more to a fluid behavior, the Combined-Eulerian-Lagrangian (CEL) analysis offers a state-specific method for those inherent large deformation problems. The embedding of Lagrangian elements representing roving on the mesoscale is a new and promising multi-scale approach for the simulation of two-phase and two-state problems (Fig. 7).

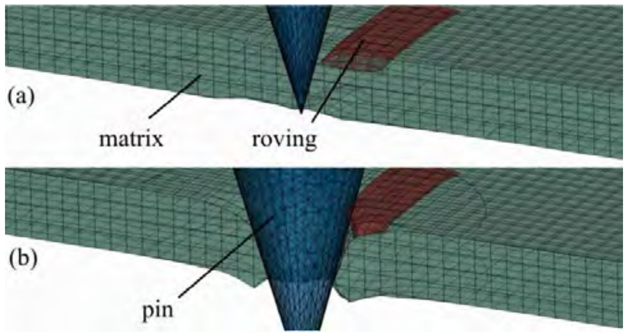


Fig. 7. Deformation of CEL analysis at two different stages: (a) before matrix split and (b) split matrix elements affect roving deformation

Rys. 7. Odkształcenie w analizie CEL na dwóch etapach: (a) przed rozdzieleniem osnowy oraz (b) po rozdzieleniu osnowy mającej wpływ na odkształcenie wzmocnienia

CONCLUSIONS

Textile reinforced thermoplastics in combination with metallic materials are strongly considered nowadays for use in multi-material lightweight constructions. Nevertheless, to fully exploit the specific structural and functional properties of the different materials inside the multi-material assembly, suitable load-introduction systems are required. Therefore, in order to provide element free and form-closed joints, the novel joining method of "thermoclinching" has been developed to join textile reinforced thermoplastic composites and metallic joining partners by means of plastic deformation. To demonstrate the capability of the developed joining technology, un-reinforced as well as reinforced thermoclinching joints were manufactured with varying characteristic joint dimensions. Additional load bearing tests on thermoclinched test specimens showed that the joint load bearing capability is dependent on the main geometrical dimensions in the neck and head area of the joint. Furthermore it was observed that the textile reinforced joints are able to transmit significantly higher loads in comparison to un-reinforced specimens. For comprehension of the fiber orientation during the molding processes and inside the generated joint, the microstructure of the joining zone was analyzed by using computed tomography scans and micrograph analyses. Thereby the intended relocation of the textile reinforced parts into the neck and head area of the joining zone has been demonstrated and thus considerably contributes to the load bearing capability of the joint, as the results of the load bearing tests reveal.

Additionally, the developed numerical simulation concept considers the locally differentiated material structure with an inhomogeneous three-dimensional fiber orientation in the thermoclinching process. The first studies to describe the forming behavior during the thermoclinching process were conducted on slightly anisotropic matrix material and experimentally validated, serving as an efficient basis for the prospective numerical analysis of the thermoclinching process.

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