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Comparison of Novel Methods for Mechanical Joining of Metals and Thermoplastic Composites

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ABSTRACT

This paper compares selected novel methods for the mechanical joining of thermoplastic composites and metal sheets, with emphasis on Flow Drill Joining (FDJ), Thermoclinching, Hotclinching, and Insert Clinching. The study focuses on the joining principles, technological characteristics, and the effect of each process on the local structure of the composite, particularly fibre reorientation, fibre damage, and the formation of a mechanical interlock. Based on the reviewed literature, Hotclinching offers a favourable balance between joint strength and production efficiency, while Thermoclinching enables a reliable form-lock at the cost of greater process complexity. Insert Clinching is advantageous because it reduces damage to the composite during the final joining stage, whereas FDJ appears promising due to its element-free principle and minimal disturbance of the fibre architecture. The comparison shows that the selection of a suitable joining method depends mainly on the required load-bearing capacity, process complexity, and the acceptable level of structural modification in the composite.

KEYWORDS: *thermoplastic composites; metal sheets; mechanical joining; flow drill joining; thermoclinching; hotclinching; insert clinching; hybrid joints; fibre reorientation; form-locking joints.*

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I. INTRODUCTION

Thermoplastic composites (TPCs) are among the most promising materials for lightweight hybrid structures because of their high specific strength and stiffness, the possibility of highly integrated part design, efficient large-scale production, and more favourable recycling options than thermoset composites [1,2]. Despite these advantages, the reliable joining of TPCs to metals remains a key technological challenge because the two material systems differ significantly in their mechanical, thermal, and physical properties, which complicates the formation of joints with high load-bearing capacity while minimising damage to the reinforcement and matrix [2,3]. For this reason, advanced mechanical joining methods are being intensively developed for hybrid metal–composite structures. These methods enable the creation of a form-lock, often with access from one side only, and are therefore particularly suitable for automotive and other thin-walled multi-material applications [1,3,4]. A common feature of several modern mechanical joining processes for TPCs and metals is the use of thermally assisted formability in the joint zone, where local changes in fibre orientation, fibre volume fraction, and matrix-rich areas occur and subsequently influence the deformation and strength behaviour of the joint [5,6,7]. One important method is Flow Drill Joining (FDJ). When joining fibre-reinforced plastics to metal sheets, FDJ appears promising because it enables the formation of a mechanically interlocked joint with high practical applicability; studies have also shown that, by appropriately optimising the geometry, material, and surface of the joining element, the process can be carried out without a pre-drilled hole in the composite [4]. For hybrid TPC–metal joints, FDJ is also attractive because it is a thermomechanical process in which the joint zone is formed locally with a high degree of process integration, thereby reducing the need for additional operations compared with conventional screw joints [2,3].

Another important technology is Thermoclinching, i.e. thermally assisted clinching of a thermoplastic composite with metal, which was developed specifically for joining textile-reinforced thermoplastics and metallic components [5,6]. The principle of this process is the local preparation and heating of the joint area in order to increase the deformability of the composite and enable the creation of a mechanical undercut and a form-lock with the metallic partner [6,7]. Compared with conventional clinching, Thermoclinching intentionally induces initial breakage of part of the fibres in the joint area so that they can bend and be reshaped during joint formation [7]. This method is therefore suitable where a pronounced form-lock is required even for stiffer or thicker composite semi-finished products, although the process design must account for the additional step of preparing the joint zone and its effect on the local integrity of the fibres [4,6,7]. Hotclinching is another variant of mechanical joining of TPCs and metals in which the composite is thermally assisted during the process, usually at a temperature below the melting temperature of the matrix in order to maintain sufficient material stability during undercut formation [7,8].

A specific approach is Insert Clinching, in which a metallic insert is first integrated into the thermoplastic composite and only afterwards is the actual clinching between the insert and the metal sheet carried out [2,7,9]. The insert is integrated at a temperature above the melting temperature of the matrix so that the fibres around the insert are predominantly reoriented and adapted to the local geometry instead of being extensively cut or broken [2,9,10]. An important advantage of Insert Clinching is that during the subsequent clinching operation, the deformation is concentrated mainly in the metallic insert and the metallic joining partner, while the TPC itself remains largely unaffected. This makes it possible to use standard clinching tools for metals [7].

II. Methodology of Research

Characteristics and applicability of selected methods for the mechanical joining of thermoplastic composites and metal sheets

Flow Drill Joining technology

The basic principle of FDJ is that the fibres in the composite are not cut but reoriented around the joint point in accordance with the material flow during joining (Fig. 1). A typical FDJ setup uses a rotating carbide mandrel acting from the metal side, local heating of the TPC, and, on the opposite side, a forming tool that creates the closing head in the final stage. In the schematic process description, the composite is positioned beneath the metal sheet; the TPC in the joint area is first heated locally, then the mandrel penetrates from the metal side, and finally the forming tool shapes the formed metallic bushing into the final joint geometry. From a design perspective, it is important that the tool does not create a thread but primarily forms and flanges a metallic sleeve. Therefore, the mandrel geometry, its conical section, the diameter of the working zone, and the final preforming method are decisive for joint quality. The compatibility between the metal thickness, the TPC thickness, and the amount of metal available to form the bushing and closing head is also a key factor.

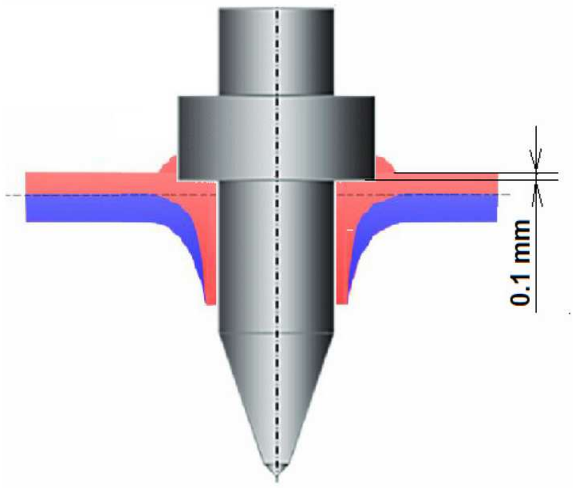

Fig. 1 Flow Drill Joining technology [11]

Thermoclinching technology

Thermoclinching is a thermally assisted clinching process developed specifically for joining textile-reinforced thermoplastics and metallic components. The principle of the process is the local preparation and heating of the joint area in order to increase the deformability of the composite and enable the formation of a mechanical undercut and a form-lock with the metallic partner (Fig. 2). Compared with conventional clinching, Thermoclinching intentionally induces initial breakage of part of the fibres in the joint area so that they can bend and be reshaped during joint formation. In this process, the composite is positioned on the punch or pin side and the metal sheet on the die side. The metallic partner is pre-punched or pre-drilled with a pilot hole. The tool system consists of a tapered pin, a rigid die, and a movable ring anvil. This arrangement is important because the mechanical interlock is not created simply by pressing the layers together, but by controlled deformation of the softened composite through the hole in the metal and its subsequent expansion into the undercut. Before the actual joining step, the composite is locally prepared in the region of the future joint by cutting through the thickness. This step is essential because, in a continuously reinforced thermoplastic composite, it is difficult to force the material through a narrow hole unless the reinforcement is locally released or at least partially separated. Pre-cutting therefore reduces resistance to local deformation and improves process stability. The integration of pre-treatment, heating, and forming was one of the objectives of the later development towards the more robust inline Thermoclinching process.

Thermoclinching consists of several stages. After the parts are positioned in the tool, the composite in the joint zone is locally heated above the melting temperature of the matrix in order to significantly increase its formability. Process descriptions in the literature also mention infrared heating above 200 °C. The purpose of this heating is not merely to soften the polymer, but to enable movement and reorientation of the fibres in the thermoplastic matrix during the subsequent motion of the tapered pin. The tools are heated simultaneously so that the composite does not cool too quickly during forming and retains its ability to deform. From the perspective of TPC behaviour, this stage is critical. At temperatures above the matrix melting temperature, matrix flow can occur and the fibres can reorient much more freely than at lower temperatures. This is one of the main reasons why such processes can reduce the risk of cracking and fracture in the joint zone. At the same time, thermally assisted forming does not preserve an unchanged composite; on the contrary, the joint region develops a new local architecture that must be considered when assessing load-bearing capacity. In the second stage, after the required temperature has been reached, the tapered pin moves axially downwards towards the metal sheet. During this motion, it penetrates the softened composite and extrudes the material towards the pilot hole in the sheet. The literature describes this step as a reorientation of the fibres both through the thickness and in the plane of the laminate. Because the pin has a tapered shape, it causes not only local compression but also lateral deformation, so that the fibre bundles around the joint are not only bent but also spread and rearranged. In the third stage, once a sufficient volume of composite has been forced through the hole in the sheet, the material is compressed by the ring anvil and the rigid die, thereby forming the final undercut and the shaped closing head of the joint. This geometry ensures that, after cooling, the composite cannot simply be pulled back through the hole in the metal sheet. The mechanical interlock is therefore created not by a thread, rivet, or friction alone, but by geometric interlocking of the formed composite behind the metal sheet. According to one detailed process description, the formation of the joint itself takes less than 1 s, although the subsequent consolidation and cooling require a longer time.

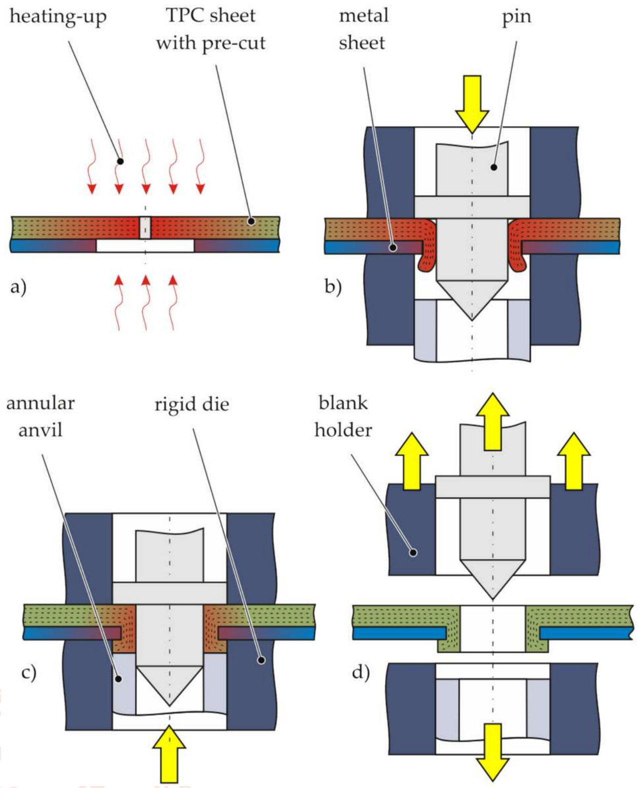

Fig. 2 Schematic illustration of the Thermoclinching process based on [12]: (a) positioning of the pre-cut joining partners and heating of the joint zone, (b) permeation of the fibre-reinforced structure with the tapered pin, (c) formation of the undercut, (d) release of the finished joint.

Hotclinching technology

Hotclinching is designed as a single-stage, heat-assisted clinching process without auxiliary elements and without a pilot hole (Fig. 3). It is based on conventional clinching but uses a modified tool consisting of a standard punch, a retainer, and a split die composed of a tempered solid sleeve and a spring-loaded anvil. Heat is supplied by heating inserts in the die. The process sequence is as follows. The layers to be joined are placed between the tools so that the TPC is on the die side. The composite is heated by contact to approximately 180 °C, i.e. to a temperature close to the Vicat softening temperature but below the melting temperature of the matrix. This point is essential: the objective is not to melt the TPC but to increase its formability while maintaining sufficient stability in the lower region of the joint. After heating, the retainer is activated, followed by the punch, which begins to deform the composite through the thickness. Joint formation proceeds through three mechanical stages: offsetting, upsetting, and flow pressing. During the first stage, the spring-loaded anvil generates counterpressure, which stabilises the neck region of the upper layer. During the subsequent punch stroke, the lower thickness of the TPC decreases and the material begins to flow radially, creating an undercut. The form-lock is therefore not created by forcing material through a hole, as in Thermoclinching, but by gradual local displacement of the material and flow pressing into the die cavity. The material phenomena in Hotclinching differ from those in Thermoclinching precisely because processing takes place below the melting temperature. A review study of TPC forming phenomena states that, in Hotclinching, classic matrix percolation flow is not observed as in processes above the melting temperature; instead, squeeze flow, transverse compaction, bending, torsion, and displacement of fibre bundles are dominant, without typical deconsolidation. CT analyses of hotclinched joints show that the fibres reorient through the thickness in the heated zone and bend in the direction of punch movement in the neck region. At the same time, significant fibre breakage occurs around the undercut and in the anvil groove because the local tensile stress exceeds the strength of the reinforcement. In other words, in Hotclinching, fibre breakage is not introduced by pre-treatment, as in Thermoclinching, but occurs during the deformation itself.

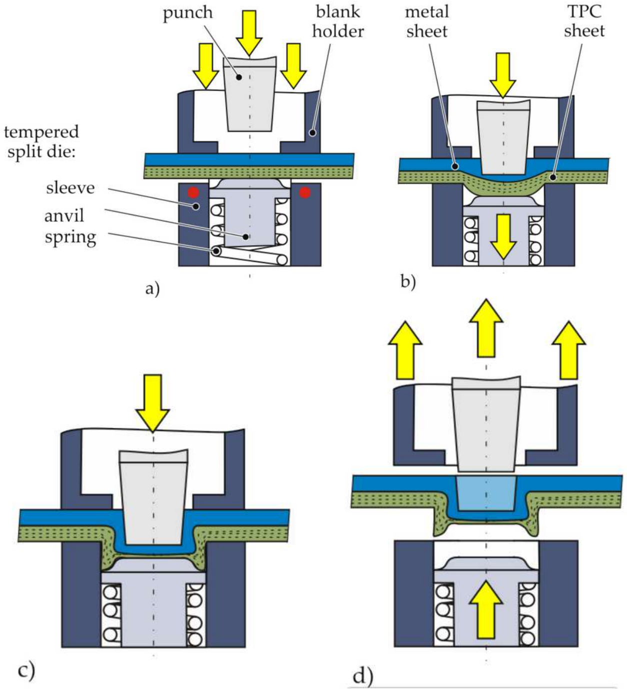

Fig. 3 Schematic illustration of the Hotclinching process: (a) positioning, heating, and fixation, (b) offsetting, (c) upsetting and flow pressing, (d) release of the finished joint. [12]

Insert Clinching technology

Insert Clinching is a two-stage method that separates composite forming from the actual clinching operation. In the first stage, a metallic insert (clinch insert) is integrated into the composite during production of the TPC part. Only in the second stage is this insert joined to the metal sheet by a standard clinching process using conventional tools (Fig. 4). Insert integration takes place at a temperature above the melting temperature of the matrix. The TPC is first heated and transferred to an open compression mould, after which a tapered mandrel is advanced once the mould is closed. Rather than drilling or cutting a hole in the conventional sense, the mandrel displaces the fibres and molten matrix laterally and forms the hole according to the moulding-hole principle. The insert is guided precisely so that it remains flush with the composite surface [3,4]. The mandrel is then replaced by a ring-shaped counterpunch, which recompresses the displaced material and presses it into the undercut of the insert. As a result, the undercut is filled by both fibres and matrix. After cooling, the part is removed from the mould with the integrated insert. During this stage, there is a significant local change in fibre orientation and fibre distribution; however, according to microstructural analyses, no fibre breakage was detected. This is followed by the second stage, namely the actual clinching of the insert with the metallic partner. In this stage, the TPC is practically not deformed; only the metallic insert and the metal sheet are formed. Standard clinching characteristics such as neck thickness, bottom thickness, and undercut can therefore be used to evaluate the joint. Another practical advantage is that the TPC can be positioned either on the punch side or on the die side, which increases the application flexibility of the process [3]. From a mechanistic point of view, Insert Clinching is therefore the least damaging to the composite during the final joining operation, because the most demanding deformation of the TPC is shifted to the preceding insert-integration stage. Comparative studies explicitly state that, whereas Thermoclinching intentionally induces initial fibre breakage and Hotclinching causes fibre breakage during deformation, Insert Clinching is characterised primarily by fibre reorientation during insert integration [7,12].

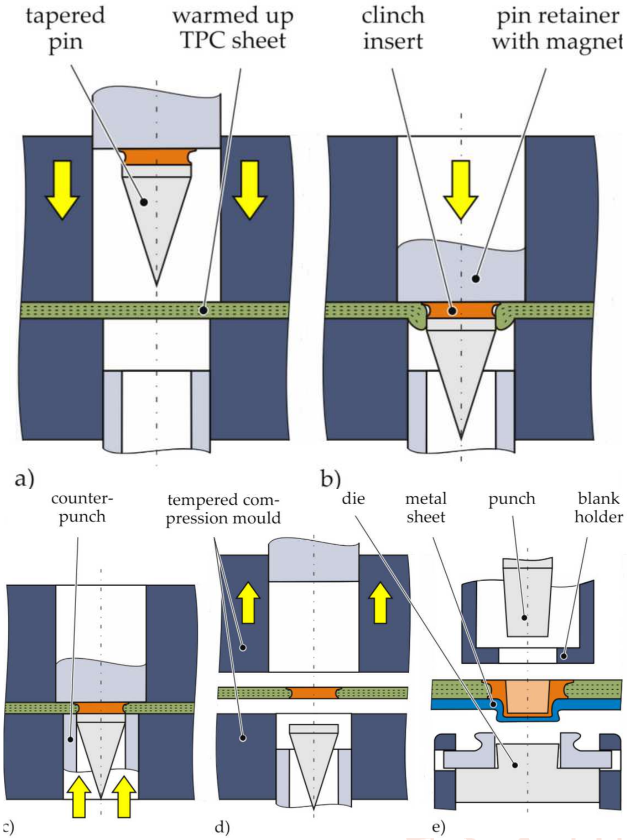

Fig. 4 Schematic illustration of the Insert Clinching process: (a) compression mould closing, (b) movement of the pin tool, (c) recompression of the displaced material by the counterpunch, (d) demoulding, and (e) subsequent standard clinching process with a rigid or opening die. [12]

Results and Discussion

Research indicates that, in the mechanical joining of thermoplastic composites and metals, the influence of the joining technology on the local structure of the composite—particularly fibre orientation and the formation of the mechanical interlock—is a key factor governing joint behaviour.

Among the clinching-based methods compared, Hotclinching offers a favourable balance between joint strength and production efficiency while achieving a high shear load-bearing capacity. Although Thermoclinching provides a reliable form-lock, the process is more complex because it requires local pre-treatment, heating, and subsequent consolidation. Insert Clinching is a two-stage process and is sensitive to insert orientation; however, it is less damaging to the composite because the primary deformation occurs during insert integration.

FDJ is a promising approach because it enables the formation of a joint with relatively low disturbance of the fibre architecture while offering a short production cycle and one-sided accessibility. Overall, FDJ appears to be the most favourable option in terms of material compatibility and minimal disturbance of the composite structure, whereas Hotclinching seems to provide the best compromise between joint strength and production efficiency.

Conclusion

This paper compared selected mechanical joining methods for metal sheets and thermoplastic composites, focusing on FDJ, Thermoclinching, Hotclinching, and Insert Clinching. The comparison showed that joint performance depends mainly on the balance between load-bearing capacity, process complexity, and the extent of local structural changes in the composite. Hotclinching appears to offer the most favourable compromise between strength and production efficiency, while FDJ is promising because of its element-free principle and relatively low disturbance of the fibre architecture. Thermoclinching provides a reliable form-lock but requires more demanding process preparation, whereas Insert Clinching is advantageous because it minimises composite deformation during the final joining stage.

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