A Review of Composite to Metal Joining Using Through-thickness Enhancement (Hybrid Joining)

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ABSTRACT

In the vast majority of cases, the outstanding properties that composite materials offer (high strength, low weight, design flexibility etc.) are only truly realised when combined with other materials such as metals. Traditional joining methods such as adhesive bonding or fastening adopt a 'black metal' approach, where the joint assumes a simple planar configuration which results in a compromise due to the fact that either composite damage has to be tolerated (fastener holes) or the loading capacity is limited by the strength of the matrix resin either at the composite surface or between the first or second plies. Over the past four decades a large number of approaches have been taken to address this limitation, most of them by adopting some type of through-thickness reinforcement/enhancement to enable loads to be spread more evenly into the bulk of the composite, creating a graded hybrid joint.

Based on a full review of known publications (over 550), including patents, that have been published in this area, it is shown that these publications are generated from over 70 distinct groups in over 30 countries dating from the early 1980s. Seven different approaches are identified: 1) the use of through-thickness features to strengthen the interlaminar structure of the composite (z-pins) where in a majority of instances the pins/protrusions are formed/attached to the metal surface; 2) some type of interlaminar structure made from interleaving sheets of metal and composite to produce a more graded joint; 3) interlocking loops; 4) spot joining; 5) interleaving reinforcement; 6) transition fibres and 7) other processes which cannot easily be categorised. Surprisingly, although the published performance characteristics of these hybrid joining technologies are very encouraging, very few of them have found their way to being commercially available with many citing problems including implementation, processing, performance consistency, cost etc. Despite this, there is clearly significant and growing development in this field which appears to have accelerated from the early 2000s.

1.0 INTRODUCTION

It is a well-known fact, that continuous fibre reinforced polymer (FRP) composite systems constitute an extremely versatile group of materials due to their high strength to weight ratio, anisotropic properties and opportunities for design freedom. It is principally the presence and position of the fibres that dictate the strength characteristics of the composite, with the resin present to bind the system together into a solid matrix and transfer loads to the fibres. However, despite such attractive properties, it is rare for a FRP system to be deployed as a single entity and much more common for it to be a component joined to other materials such as metals where other characteristics such as isotropic strength, thermal tolerance, wear resistance etc are required. It is the process of joining FRPs and metals which can prove challenging if a smooth transition of properties is to be achieved. Traditionally, there has been a tendency to treat the composite as a 'black metal' and use conventional joining approaches wherever possible; the most common being mechanical fastening or adhesive bonding. Although these 'traditional' methods are used extensively throughout industry, they suffer from the well-documented drawbacks of either fibre damage and localised areas of high stress (through the need to create holes and carry load through those holes) or by relying on the surface integrity and interlaminar strength of the composite resin, in the case of adhesive bonding. Neither method is perfect; each is often compromised through the requirement of additional/thicker composite material around the fastening regions or larger/more complex bonding geometries to minimise delamination. Each approach adds weight or manufacturing complexity (cost) to the operation and it is often the case that for many structural applications, bonding and fastening are actually combined to ensure maximum integrity. A good example of this would be the aerospace sector, where design guidelines state that the composite/metal joint has to be sufficiently strong to function in the absence of an adhesive even though an all-bonded structure would be inherently stronger, lighter and have greater integrity. This conservative approach is also carried though into military repair strategies for many western nations where the approach to address composite damage to an air platform in theatre would be to bond/bolt a metal patch over the affected zone. Only the Australian Air Force has developed a full structurally bonded patch repair system that is regarded as permanent.

Now that composite and metal assemblies are being used more and more extensively in a wide variety of vehicle platforms, including those in the military, considerable attention has been devoted to developing ways of managing the transition of properties between each material. Metals tend to be isotropic whilst FRPs are highly anisotropic, both at micro and macro levels. Whilst the fibres used often have mechanical properties that exceed those of the metal, the resin matrix is much weaker, is thermally susceptible and often has thermal expansion coefficients an order of magnitude greater. Such differences can lead to abrupt interfacial changes within the joint and high local stresses as a result. Since the advent of FRP materials in the early 1970s, an increasing number of hybrid joining approaches have been developed ranging from the 'black metal' systems through to ever more sophisticated transitional/graded joint systems. Currently, very few of these hybrid systems have achieved universal acceptance either technically or commercially. The main reasons for this relate to potential high cost barriers for implementation of new approaches that are not often compatible with current systems/materials despite the anticipated higher levels of predicted performance over more conventional bonded/fastened structures.

This paper sets out to categorise these approaches and provide the reader with a high level view of the current 'state of the art' detailing the pros and cons associated with those solutions which have been or look likely to be adopted in current and future manufacturing applications.

It is probably prudent at this point to clarify the use of the term 'hybrid' within this study. It is not uncommon for the term hybrid joining to be used to describe a situation whereby the two parts to be joined are made from different materials such as metals and composites or where two joining processes are combined to produce a hybrid joint eg bolting/adhesive bonding or spot welding/adhesive bonding. In this paper, hybrid is used in the context of producing a graded or transition joint between metals and FRP materials such that the two materials to be joined differ and the mode by which the joint is achieved may well utilise two distinct joining approaches but it is not a pre-requisite as in the case of graded lamination joints. Not all of the joining technologies reported in this review can truly be called hybrid but the vast majority are and it is the intention of the authors to provide as complete a picture as possible on the strategies that have been considered when looking to join composite materials to metals efficiently.

2.0 COMPOSITE TO METAL JOINTS – A REVIEW

2.1 Review strategy

This review has endeavoured to identify and assess as many key publications as possible that are believed to be relevant to the field of composite to metal joining which are available in the public domain and can be found via the usual searching strategies such as keyword searches in available databases (open and commercial), internet searching, patent search engines etc. The resultant output (over 550 items) consisted primarily of academic papers, posters, project reports, publications and patent filings and spanned the publication period from the early 1980s through to 2016. It is acknowledged that confidentiality issues may have limited the reach of this survey to some extent but solutions that exist outside the framework of this exercise cannot be included. Although the resultant output mainly describes distinct joining approaches, the search also identified some more generic descriptions of fibre/resin interactions and other aspects of FRP use which were deemed of useful background relevance. Due to the space constraints of this paper, only key publications will be described and referenced.

2.2 Publication trends

Analysis of the number of publications each year, shown in Figure 1, reveals that the volume of publications increases at a rapid rate, with significant growth triggered in the early 2000s. This is despite the fact that the first detailed mention of a hybrid joining approach using metal pins joined to a metal surface was discussed in a USSR patent by Gaydachuk and Karpov in 1983[1][2] and even 11 years later the only real alternative, the creation and use of metal features produced by metal scraping, was published in a US patent by MacKelvie[3]. However, it is unlikely that the USSR patent was easily accessible to the engineering community at large; indeed it has still not been possible to track down a full copy of the patent with only references to it being made in a much later publication of 2013[4], and MacKelvie's patent was entitled 'Material Surface Modification' and therefore less obviously associated with a composite/metal joining application. Other key approaches identified are COMELD™ (TWI)[5], where power-beam grown protrusions on the metal surface are integrated into the composite structure; the use of a bolted metal foil/composite laminate (DLR)[6]; HYPER[7]/Hypin[8] using cold metal transfer (CMT) to 'grow' profiled pins on the metal and Teufelberger[9] who have successfully commercialised the integration of CMT-added z-pins into braided/filament wound connections for a variety of hybrid composite applications.

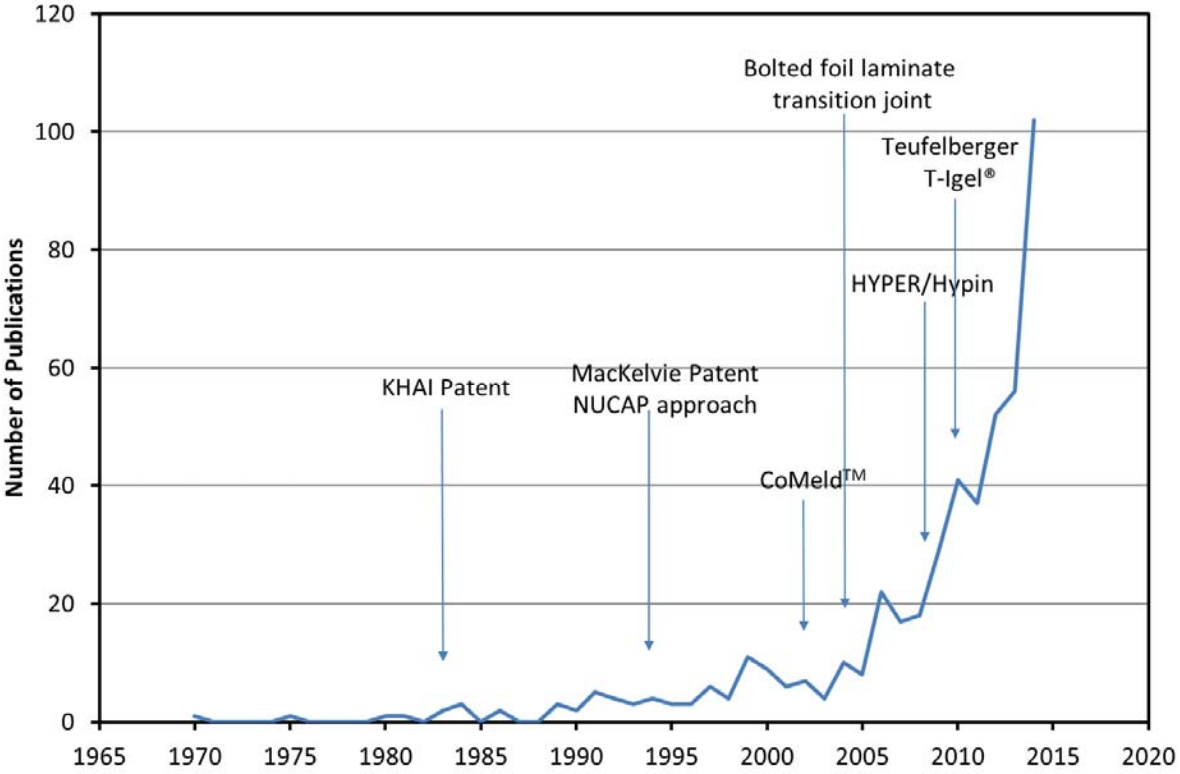

Figure 1 Depiction of number of publication with publication year covering the area of composite/metal joining using transition joints with points at which some key

approaches/innovations have been reported.

Analysis of the publications show that activity has been reported from 30 countries comprising almost 1000 authors from 336 organisations. In most instances, the organisations are research institutes or universities although a smaller number are commercial companies including the aerospace primes, Boeing and Airbus. Figure 2 shows the number and location of such authors and organisations with over 50% of the organisations and 66% of the authors coming from the top three countries of USA, Germany and the UK. It is ironic that Ukraine based KhAI is only a small, albeit active centre within this field despite being the first to propose a practical solution to the hybrid joint at least 10 years before anyone else.

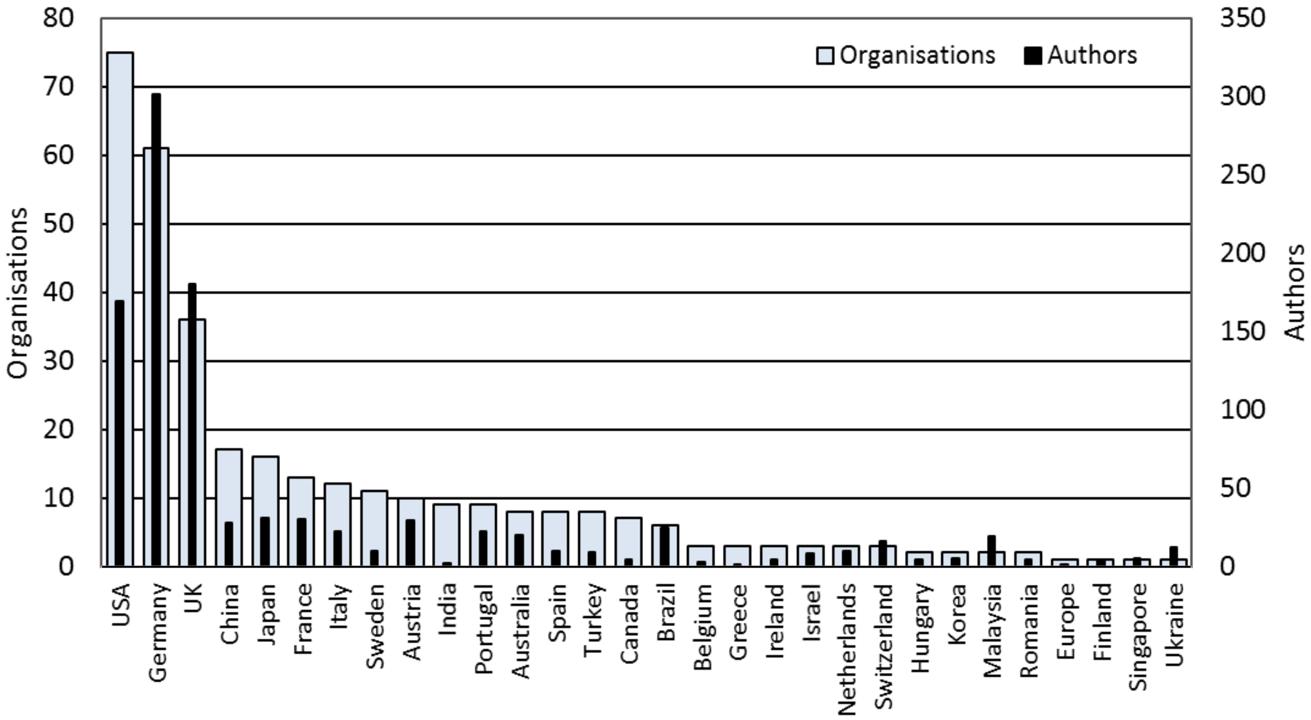

Figure 2 Location and number of organisations and authors active in the area of composite to metal joining

2.3 A joining hierarchy

2.3.1 Overview

It is evident that there is a distinctive hierarchy of approaches for joining FRPs to metals based upon seven distinct strategies:

1. Metal protrusions – metallic z-pins normally attached to the metal surface
2. Interlamination – creation of a graded joint through the mixing of metal and prepreg layers
3. Interleaving reinforcement – not strictly joining, using metal laminates to create a functional interlayer
4. Interlocking loops – wrapping/winding fibres around and through metal loops

5. Spot joining – adaption of conventional single point attachment for composites
6. Transition fibres – integration of metal fibres into the prepreg
7. Others – a range of diverse alternatives.

Figure 3 summarises these approaches and their sub-sets where it can be seen that there are a significant number of 'others' which are difficult to categorise. In the following sections, each strategy and its variants will be described.

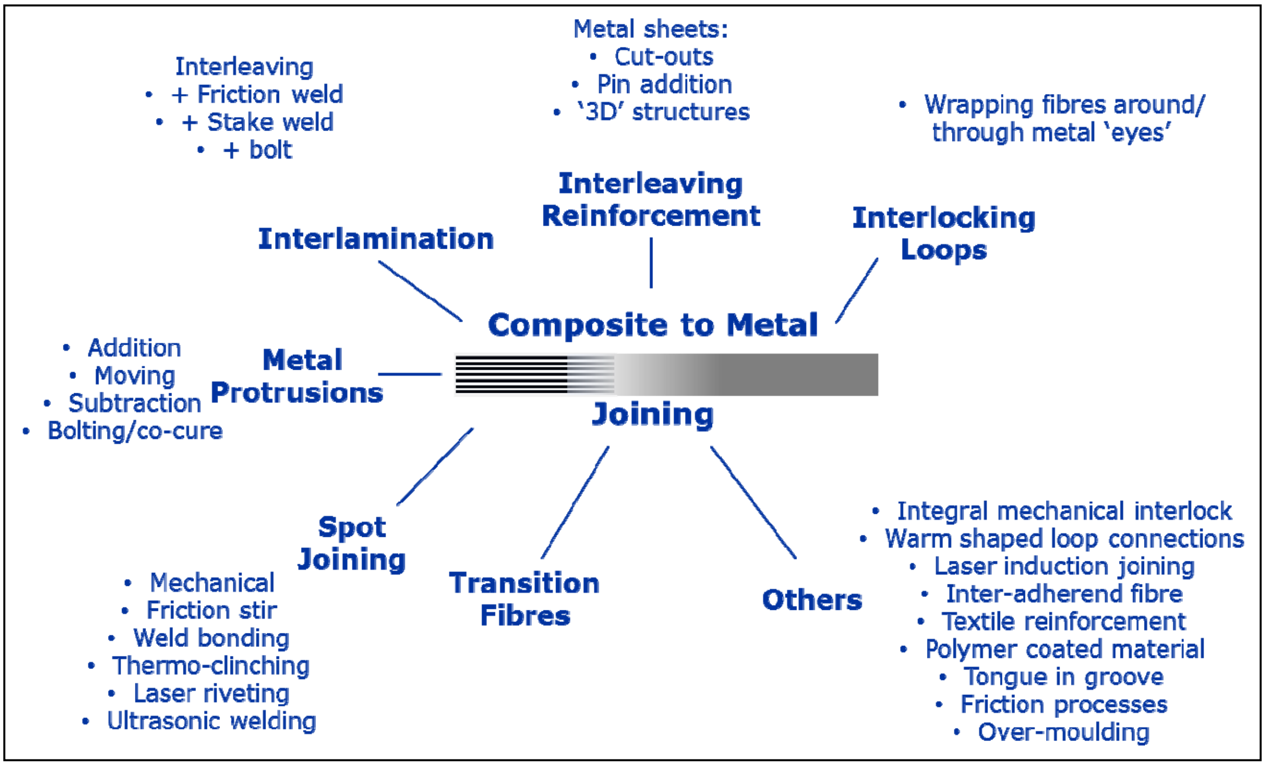

Figure 3 A summary of the main approaches used for joining composites to metals

2.3.2 Z-pins

Probably the most widely reported and investigated joining technology for hybrid transition joints between composites and metals is that associated with the addition of protrusions of some type to the metal surface within the joining region. The primary idea being that the protrusions will position themselves through the composite material to a certain depth, thereby creating a mechanical reinforcement in the z-direction and enabling load to be transmitted through the volume of the composite rather than just through surface attachment. In essence, this system combines bonding (either via the resin or an adhesive) with mechanical attachment but without the need to create fibre damaging holes.

A key differentiating factor with this approach relates to how the pins/protrusions are created within the structure. In principle, this can be achieved in four ways:

- Addition – whereby the pins are added to the metal surface using such means as direct welding, embedding into holes or 'grown' using additive manufacturing

- Subtraction – removal of substrate material using mechanical methods or power beams to create the desired structures out of the bulk

- Movement – either manipulation of the surface mechanically or by power beams to move material and form new structures or create new fully formed metal components with integral surface features through moulding/casting processes

- Bolting/co-curing –a variant on conventional fastening but where the fixing is carried out prior to composite cure.

As mentioned earlier, the first, by published date, publications were submitted in the Ukraine when it was part of the Soviet Union. The authors, Gaydachuk and Karpov describe in two USSR patents[1][2], methods by which metal pins would be attached to a metal substrate by a variety of means via either addition (pressing into holes or welding) or subtraction by milling the metal surface to produce appropriate features. Diagrams showing the subsequent incorporation of the modified metal surface are very similar to what has subsequently been reported by numerous other groups. However, the fact that the patent was filed behind the 'iron curtain' and only described by Karpov et al in a much more recent (2013) KhAI report [4] makes it difficult to classify this approach as the first due to its hidden nature. In fact it would take nine more years (1994) for a similar approach to be reported in the open literature via a patent application [3]. In this case, the metal surface was modified through machining (scraping) the surface to create controlled burrs or hook-like features which could be pushed into a flexible material such as a fibre mesh. A key difference from the KhAI approach was that no metal was added or removed from the surface, rather it was moved and formed in place. This approach was further developed and utilised by a Canadian company (NUCAP) to create the NUCAP Retention System (NRS®) for retaining brake and clutch pads with nothing other than the fibre binding resin and the mechanical lock of the formed features. This product range can therefore be described as the first commercial application of the modified z-pin metal surface and is still in use today. A similar approach for joining carbon fibre composites to metals was recently (2014) reported by Droder et al in Europe [10].

It wasn't until 2004 when Dance and Kellar filed a patent [5] describing COMELD™, where metal surface z-pins could be used to create a hybrid joint, was published in the open literature. The patent primarily described the method for the production of the pins/protrusions rather than the joint, which was described in the patent as an application of the technology. The innovative step was the use of power beams (electron beam or high power laser) to move the metal around the surface of the work-piece and build up a range of structures and geometries, some of which could act as z-pins. A considerable amount of work was then carried out to evaluate the performance of COMELD™ joints, which offered the potential of higher strength and greater damage tolerance. However, a number of challenges were encountered which restricted the development of the technology; the key ones being associated with difficulties of getting effective integration between the treated surface (and features) and the composite due to the need to accommodate the volume required by the protrusions. This resulted in poor consolidation of the composite at the base of the protrusions, resin rich areas and the formation of voids due to insufficient free resin being available. Additionally, the complete freedom afforded by the beam technology to create almost any shape, pattern, profile, density of protrusion made it very difficult to conduct a sufficiently thorough empirical study which would enable the development of suitable design rules.

Since then, a number of other groups have reported work carried out on similar z-pin reinforced joints and configurations. The primary differences being in the way in which the pins are created and attached to the metal surface. In 2008, details were published, initially via a patent application by Meyer et al (EADS)[7], describing the HYPER (Hybrid Penetrative Reinforcement) approach where titanium pins were created using additive manufacturing methods. Unfortunately, the terminology gets rather confusing as EADS also coined the term *Hypin* to describe the same technology[8]. Use of the HYPER joint is the second commercial application of such hybrid joints, this time using it as a means to attach a carbon fibre shell to the top of a bicycle seat[11]. As an alternative to welding, additive manufacturing or embedding pins in place, the Froneus Cold Metal Transfer (CMT) process has been developed to create surface mounted z-pins for hybrid joint applications[12]. In contrast to other additive processes, CMT utilises a combination of fusing one end of a wire to the metal surface and through control of the heating process is able to sever the wire at a pre-determined position either leaving a sharp tapered spike or a round ball-like feature on the end of the pin. The process enables considerable flexibility in terms of position and design of each pin.

The use of CMT has resulted in probably the most significant commercial success for z-pinned hybrid joints where the joint concept termed IGEL[13] is used on coaxial parts to enable the fibres to be filament-wound or braided around the pins to create a high performance structural hybrid joint. The process is called T-Igel® and is delivered by Teufelberger[9]. Other groups (Graham[14] and Joesbury[15]) have reported work utilising CMT on a range of joints including double lap systems using glass and carbon composites. The effects of joint geometry and pin position are explored.

Other approaches for creating and attaching z-pins include:

- Insertion of the pins through the uncured composite lay-up, followed by placing the lay-up into a double lap shear joint (composite as the male component) and then using compression to bring the pin ends in contact with the two metal sides, the pins are welded resistively in place before the whole assembly is cured (Childress[16])

- Creating the pins using laser surface modification and then integrating the processed metal surface into the body of a thermoplastic composite though pressure and friction-generated heat caused by the Friction Press Joining process where a friction stir welding tool with no pin is applied over the metal while in contact with the composite (Fuchs[17])

- Creation of shaped metal bodies, produced by injection moulding of a resin supported 'brown state' system and then sintering to burn off resin and leave only metal with formed protrusions (Ferri[18])

- Bolting/co-curing where bolts are used as z-pins by virtue of co curing the bolts in place prior to fastening (Matsuzaki[19]).

It is important to emphasise that a considerable body of valuable work has built up based upon the findings of these and other groups on the creation and performance of z-pin reinforced hybrid joints but reporting the detailed findings is well beyond the scope of this paper. However, some key facts do emerge which are now summarised.

Joint performance potential:

- The joints produced can tolerate significant loading and high levels of energy absorption before failure, in many instances considerably greater than a traditional bonded or bolted joint. In particular, the through-volume reinforcement effect enables such joints to be damage tolerant and not fail catastrophically which is a significant consideration within theatre, especially for land and sea platforms.

- The potential to produce fastener-free and therefore lighter/stronger joints

- The potential to create a truly graded joint with minimal transition stress and superior fatigue properties.

Manufacturing challenges:

- The effective integration of the pins within the composite material can be challenging due to the resistance of high fibre content composite materials to the mechanical insertion process, which in effect requires displacement of fibres around each pin. The resultant structure can contain resin rich regions, voids, poor seating/consolidation of the base composite on the metal surface and fibre misalignment.

- Using the matrix resin as the key bonding agent when co-curing the metal and composite together can result in lower bond strengths when compared to secondary curing using an adhesive.

- The quality of the pin attachment to the metal surface can be variable leaving the pins in the joint potentially susceptible to fatigue failures.

- There is a lack of design knowledge in terms of pin density, position, profile, height etc

2.3.3 Interlamination

In contrast to the use of z-pins, an alternative approach is to create a transition joint, which focusses on creating a graded structure where interleaving sheets or foils of metal and composite are used to taper from one material into the other. This method seeks to reduce/eliminate any abrupt transition zones and maximise the total surface area for bonding but spreading it through the bulk of the composite. Whilst the concept is relatively easy to envisage, the primary challenge to success is how to integrate the laminate of pure metal foils, at the metal end of the joint, into a solid metal structure. Additionally, the preparation of such interlaminates can be quite time consuming.

Probably the earliest reported interlamination work is by Kolesnikov in 2004[6] where a range of lamination configurations were assessed for joining carbon FRP to titanium. To secure the laminations, bolts were used to clamp down the structure and so it is not surprising that failure was observed around the bolt holes. Subsequent work by others in the field focussed upon co-curing the laminates to form a bonded structure with efforts made to strengthen then joint between the laminated all-metal end and the bulk metal. In one instance this was achieved through the use of laser stake welding (Woizeschke[20]) and in another, friction stir welding was used to fuse the metal laminates together (Lewis [21]). In both instances the fusing of the metallic laminates achieved limited success in that thermal damage of the neighbouring composite resin could be avoided but it was not possible to completely fuse the metal/metal laminate regions throughout the transition area resulting in some delamination occurring in these areas during testing.

2.3.4 Interleaving reinforcement

Similar to interlamination the interleaving reinforcement concept is based around the incorporation of modified metal foils or layers, which have design elements similar to that seen for the z-pin hybrid joint. Although in this instance, the pins are used to internally reinforce the composite or to act as a bonding interlayer between two sheets of composite in a lap joint configuration. Examples of this approach include the use of the CMT process to produce metallic inserts with pins mounted on both sides of the sheet (Ucsnik[22]) or the cutting and push forming of metal features out of the sheet as in GRIP Metal™[23] or Arrow-Pin[24].

2.3.5 Interlocking loops

The use of interlocking loops is a highly specialised approach to hybrid joining where a small number of groups have focussed on the development of transition structures. Fibres are threaded through embedded metal loops in the metal reminiscent of the eyes of needles or the fibres are directly embedded within the metal component, which in turn are then integrated in to a polymer composite structure. The rationale for such an approach is either to maximise strength through the avoidance of breaking fibres[25] or to create an electrically isolated transition between a carbon fibre composite and aluminium by using glass fibres embedded within the aluminium[26].

2.3.6 Spot joining

The field of spot or point joining of composites without recourse to pre-drilled holes is a rapidly growing area driven primarily by the automotive sector that prioritises volume production needs over ultimate performance, in contrast to the aerospace sector, which is driven primarily by high performance zero-defect processing. In view of this significantly different attitude, there have been a large number developments within this area, wherever possible using conventional metal joining processes which have been modified to accommodate the very different characteristics of FRP materials. It should be mentioned that these processes often only work for thermoplastic composites, where localised heating can be used to melt the resin and induce some level of adhesive interaction.

Many of these processes are not strictly hybrid joining in that although the materials to be joined differ, ie composite and metal, there is often only one joining effect ie mechanical interlock. In view of this, only a high level description will be given for each process type.

- Mechanical spot joining is probably the simplest type of point joining that can be applied to a composite to metal joint and essentially comprises a fastener or rivet being forced through the composite and then into the metal, relying upon the rate of insertion to minimise the damage to the surrounding composite. Examples include Rivtac® and Rivkle® (Bollhoff), Spin Blind Riveting (SBR), Self Piercing Riveting (SPR)[27] and thermo-mechanical flow drill joining[28].

- Friction stir spot joining uses frictional heating and applied pressure ofrom a tool or an insert to penetrate through the composite and form a joint. Many variants have been studied, the main ones being:

    - Friction Element Welding (FricRiv)[29]

    - Friction Spot Joining (FSpJ)[30]

    - Refill Friction Stir Spot Welding – RFSSW[31]

    - Dissimilar friction stir welding[32]

    - Friction Stir Scribe (FSS)[33]

- Weld bonding is a variant on the spot welding process, one of the primary joining processes within the auto sector, however for this to be implemented effectively; a hole is required to be made through the composite so that a metal/metal joint can be produced where the composite is sandwiched between two metal sheets. It is common for adhesive to also be incorporated within the joint to produce a stiff lightweight structure[34].

- Thermoclinching is a new process that requires at least one of the components to be a thermoplastic system. The idea is that a metal component with pre-formed holes is placed over the thermoplastic component and a heated tool is applied through the hole to melt the underlying thermoplastic matrix. Once molten the tool is pulled upward, drawing with it some of the thermoplastic material which then fills and overflows the hole whilst cooling. What is left is a solid button of thermoplastic through the hole mechanically locking the structure in place[35].

- Laser Riveting is a very recent development and shows that process conditions can be identified which allow laser beam welding of Ti-6Al-4V and carbon fibre composites using Ti-6Al-4V pins with significant heat effect of the composite structure[36].

- Ultrasonic Welding has been demonstrated between aluminium plates over thermoplastic carbon composite material where sufficient heat was generated by the process to successfully melt the underlying composite matrix and create a bond[37].

It is probably true to say that in the majority of the spot joining processes described, at least some damage is inflicted upon the composite. However, the built in redundancy that has been factored into the materials and the final structures has been shown to be more than adequate for the design requirements even with some damage present. Clearly this approach will only work in some industrial sectors and not in others.

2.3.7 Transition fibres

In a similar manner to interlocking loops, some research has been carried out to investigate the effects of combining and mixing different fibre types within a transition region to modify and smooth the mechanical properties of the composite. Examples include the development of a new hybrid composite material consisting of a mixture of carbon and stainless steel fibres to merge electrical and load bearing functions[38] and carbon fibre reinforced aluminium wires where much higher strength systems can be achieved[39].

2.3.7 Others

The review also identified a wide range of other joining technologies that could be loosely described as hybrid systems but which could not be easily categorised. Examples of some these are now provided:

- Integral mechanical interlock – utilises the concept of interlocking between appropriately shaped elastically deformable surface features. Designs exist that consist essentially of a close-packed orderly 2-D array of posts with free ends that have been thermally (or otherwise) plastically shaped to create a bulbous feature. When pressed face to face, two such arrays interlock when the small-scale ball ended posts interlock. A commercial example of this technology is Dual Lock™ from 3M.

- Warm shaped loop connections – primarily developed for thermoplastic FRP systems whereby an additional flap on the component can be warmed up to moulding temperature, formed around a load introduction element (eg metal bush) and welded afterwards to the main body of the component[40].

- Laser/induction joining – an automated process involving the combination of laser surface texturing of the metallic component followed by induction joining of the treated component to a thermoplastic composite material resulting in a hybrid joint structure. The process is being developed through the EU funded project FlexHyJoin[41].

- Inter-adherend fibre – Matsuzaki et al[42] demonstrated the potential for a fibre bundle to be ‘stitched’ in place through a FRP/Aluminium joint to act as an inter-adherend (IA) fibre. The IA fibre is threaded through the metal via two holes and co-cured directly into holes made in the composite material. The presence of the IA fibre was shown to act as a z-pin system and successfully arrested crack growth through the joint during tensile testing.

- Polymer coated material (PCM) – this technique is only really applicable to thermoplastic composites and requires that a compatible polymer to the thermoplastic resin can be deposited in advance on a metal surface to form an intimately bound coating. An example of such a system is the bonding of aluminium to a carbon fibre/PEEK composite[43]. This has been achieved through the use of specialist solvents to dissolve PEI and coat the metal. Joining was then achieved through the application of sufficient heat (induction, hot plate, resistive implant welding) within the joint to melt the polymer surfaces and cause a weld to be effected. A very similar approach was also reported by a company who used a reformulated powder coating system that was compatible with polypropylene (PP) to create structural bonds between aluminium and a glass/PP composite through a co-forming process[44].

- Tongue and groove – with the advent of cheaper and faster precision cutting offered by water-jet technology, the prospect of using some of the oldest methods to join natural composites ie wood can be explored. The simplest of these is to utilise the tongue in groove joint whereby what is essentially a butt joint can be created between the metal and the composite using the full thickness of the composite and all of the fibres having the potential to transmit load through the adhesive into the metal. The significantly increased surface area combined with the large area/volume that the joint occupies has shown impressive results; in some cases parent material failure is seen before the adhesive joint fails[45].

- Friction processes – a number of process variants use the frictional heat generated by a friction stir welding (FSW) tool to cause a joint to be formed between the metal and underlying thermoplastic composite material. This has variously been called Friction Press Joining and Friction Lap Welding[46],[47]

- Overmoulding – utilising the ability to melt and mould a thermoplastic composite system over a metal insert with possible formed features for further mechanical interlocking it is possible to show another way to create hybrid joints[48].

3.0 CONCLUSIONS

There would appear to be no shortage of ideas to address the challenge of joining composites to metals, although very few appear to have successfully made the transition from an academic concept into a mature joining technology used extensively in many applications and industries. The apparent benefits of improved performance, tailored design, reduction in mass etc would appear to be largely challenged by manufacturing issues including resistance to (potentially disruptive) new processes, extra complexity (cost), uncertain quality control, possible increased production time and potential increased cost (at least initially). Certainly, where metal protrusions are used, significant difficulties are encountered using conventional composite materials because there is insufficient space for a high density of protrusions to penetrate, potentially resulting in resin-rich regions, voids and poor compaction. The opportunity for new composite materials to be developed by suppliers has not yet been exploited due to the simple fact that the quantities required at present are negligible and therefore not financially viable. In addition, the quality and performance of the protrusions can also be variable depending upon how they are produced and the manner by which they are attached to the underlying metal substrate. To date, fewer than five commercially used examples of this technology can be found, despite the growing rapidly field of composite to metal joining. In other areas, such as spot-joining, uptake is much more marked, especially for the automotive sector but in many ways this is to be expected as the processes are less disruptive and tend to treat the composite as ‘black metal’, relying upon built in redundancy within the chosen composite materials to tolerate the local damage.

At present, there is a tendency to be conservative and rely upon bonding and bolting either individually or in combination. Despite this apparent inertia, the sheer volume of ideas, research and publications that are being produced means that commercial volume uptake will happen but from which area and when, is difficult to predict. Recent unpublished work carried out by the authors assessing the protrusion approach showed that the parameters influencing the final performance of the joint; position, density, geometry, height(s) and material structure, all have a critical part to play. Until sufficient work is carried out to understand the relationships between these parameters, to enable design rules to be developed and the joints to be accurately modelled, it is unlikely to be adopted for anything other than specialist applications. However, early data [21] suggests that there is the potential to control the final joint properties depending upon the application eg high strength and stiffness or more damage tolerant and flexible.

Composite materials have an increasing role to play in all areas of military and civilian technology but regardless the application, it is not possible to realise their full potential until suitable joining approaches are developed and matured sufficiently to offer cost effective high levels of consistent performance. Development of such solutions will require more focussed research and development to bring about success. There will also be the need to develop suitable methods of standardisation and qualification to ensure consistent joint performance (especially for primary structures) and it is likely that the internal complexity of many of these joints may require further development of modelling and NDT capability. Until that time, end users will have to rely upon the more traditional ways of bolting and bonding.

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