CIRP Annals - Manufacturing Technology xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Joining of dissimilar materials

K. Martinsen (3)[a,b,*], S.J. Hu (1)[c], B.E. Carlson[d]

[a] *Sintef Raufoss Manufacturing, Raufoss, Norway*
[b] *Gjøvik University College, Gjøvik, Norway*
[c] *Department of Mechanical Engineering, The University of Michigan, Ann Arbor, MI, USA*
[d] *General Motors R&D, Detroit, MI, USA*

ARTICLE INFO

Keywords:
Joining
Dissimilar materials
Modelling and testing

ABSTRACT

Emerging trends in manufacturing such as light weighting, increased performance and functionality increases the use of multi-material, hybrid structures and thus the need for joining of dissimilar materials. The properties of the different materials are jointly utilised to achieve product performance. The joining processes can, on the other hand be challenging due to the same different properties. This paper reviews and summarizes state of the art research in joining dissimilar materials. Current and emerging joining technologies are reviewed according to the mechanisms of joint formation, i.e.; mechanical, chemical, thermal, or hybrid processes. Methods for process selection are described and future challenges for research on joining dissimilar materials are summarized.

1. Introduction

Among the many manufacturing technologies, joining has been identified as a key enabling technology to innovative and sustainable manufacturing [6]. Due to functional needs and technological limitations, it is usually not possible to manufacture a product without joining of some sort. Products are typically assembled using multiple components [100] and joining processes are essential in manufacturing to provide product function and increase manufacturing process efficiency. Improvements of material properties and traditional processes for monolithic structures as well as extended use of additive manufacturing processes can reduce the need for joining and the number of joints in a product [294]. Nevertheless, the production processes and the required functions of the products make a "joint-free" concept unrealistic in most cases. Moreover, the search for increased product features and performance from hybrid structures with different classes of materials requires the presence of joints. Understanding of joining technologies is therefore a key issue in manufacturing, and there is a continuous development of novel processes as well as improvements of existing processes.

Joining can be complex and spans a wide range of approaches, materials and techniques. Messler [149] defines joining to be: "The process used to bring separate parts of components together to produce a unified whole assembly or structural entity". Campbell [44] considers joining as: "a large number of processes used to assemble individual parts into a larger, more complex component or assembly". In [15,211] two definitions of joining are presented, where the first definition is: "...joining is the act or process of putting or bringing things together to make them continuous or to form a unit". The second definition explained in [15,211] is: "joining is the process of attaching one component or structural element to another to create an assembly".

The Sub-Platform on Joining [6] of the EU Manufuture Technology platform defines joining as: "Creating a bond of some description between materials or components to achieve a specific physical performance". This bond can take many forms, and can be described as being generated by one or a combination of several of the following processes:

Mechanical—a joint formed through a mechanical mechanism,
Chemical—a bond formed through chemical reaction,
Thermal—a bond formed through applying thermal energy.

In this paper we will follow this definition, but add hybrid processes as a 4th class and divide thermal processes into fusion and solid-state processes.

1.1. Joining of dissimilar materials

The drive for more optimal, lightweight and high performance structures, and the trend of integrating an increased number of functions in each part [26] can be met by combining various materials into a multi-material hybrid structure. The different properties of the different materials are jointly utilised to achieve the product performance needed. This trend is reported for several industries such as: Automotive [176], Aeronautics [209,276], Clothing [289], Tooling [186], Implants [217], Power generation [131], and Marine application [22]. The mix of new materials will require a systematic approach to material selection: these materials will interact with each other in new ways, and new

* Corresponding author at: Gjøvik University College, TØL, Teknologivn 22, 2815 Gjøvik, Norway. Tel.: +47 99521849.
E-mail address: kristian.martinsen@hig.no (K. Martinsen).

http://dx.doi.org/10.1016/j.cirp.2015.05.006
0007-8506/© 2015 CIRP.

manufacturing systems might be needed [49]. This requires the ability to simultaneously optimize material choice and geometry. Recent developments include proposals for multi-material design procedures [276], and optimal material selection with respect to light weight and recyclability [209].

A commonly known example is the Boeing 787 Dreamliner which uses composite materials as the primary material in the airframe structure, although also includes 20% aluminium, 15% titanium, 10% steel, and 5% other [279]. In modern car body structures high strength steels can be used in the longitudinal beams for strength, aluminium alloys in bumper beams for lightweight and crashworthiness and composite sheets in panels for lightweight and high stiffness. The EU FP6–project SuperlightCar [223] showed how mass can be reduced by combining aluminium, steel, magnesium and glass fibre reinforced thermoplastics (see Fig. 1).

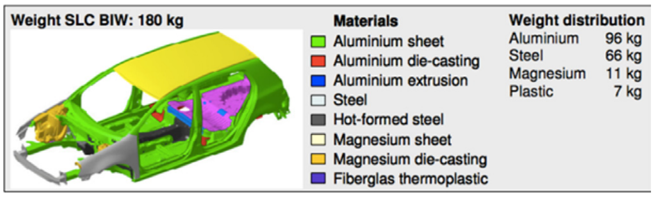

Fig. 1. Material distribution in a superlight car body [30].

Dissimilar materials can be described as: "materials or material combinations that are difficult to join, either because of their individual chemical compositions or because of large differences in physical properties between the two materials being joined" [44].

Hybrid structures can be defined as [12,221]: "A combination of two or more materials in a pre-determined configuration and scale, optimally serving a specific engineering purpose". In this paper we will use the following definition for a hybrid structure: A hybrid structure consisting of two or more components of dissimilar materials joined together to achieve a specific physical performance.

These components of dissimilar materials are to be joined together, and different joining processes have unique strengths and limitations for the joining of dissimilar materials. There are, however, significant challenges when materials of different chemical, mechanical, thermal, or electrical properties are to be joined together. The incompatibility on chemical, thermal and physical levels (thermal expansion, ductility, fatigue/fracture mechanics, elastic modulus etc.) can create problems both for the joining process itself, but also for the structural integrity of the joints during the use phase of the product. Galvanic corrosion, different thermal expansion and other effects of bringing two different materials closely together must be addressed.

To be able to join dissimilar materials, the product design and the joining process design must equalize these challenges. As Messler [149] describes it: "differences must be minimized, inherently through the choice of material or through some other means. This becomes increasingly difficult as the basic nature – atomic level structure, microstructure, and (macrostructure) – of the various materials involved becomes more different."

The field of joining is very large and there are a large number of different joining methods. This paper gives an overview of the state-of-the-art on a selection of processes. Many methods are not mentioned though, and joining of wood, glass and concrete/cement is not covered. The authors have a strong foothold in automotive industry, which to some extent explain the choice of methods described. The joining methods and the knowledge are still applicable for several industry sectors.

2. Review of joining methods for dissimilar materials

In this section, we review the joining process by the mechanisms of joint formation, e.g., mechanical, chemical and thermal processes. Hybrid processes that combine one or two of the above methods are also reviewed.

2.1. Mechanical joining processes

2.1.1. Threaded fasteners

Joining using threaded fasteners or screws has been in practice for a long time. Screws of various forms can be applied in one-sided joining when access from the other side of the components is limited. Bolt and nut combinations are commonly used when access is available from both sides of the components to be joined. Fig. 2 shows some examples of threaded fasteners. When disassembly is required, threaded fasteners are usually the preferred method since unscrewing does not lead to destruction of the components. Screw joints for thin gauge sheet metals do not provide sufficient load bearing length of the screw, so other joining methods or additional elements, such as flow drill screws, collar forming, or spring nuts, are used to increase the load bearing length [71].

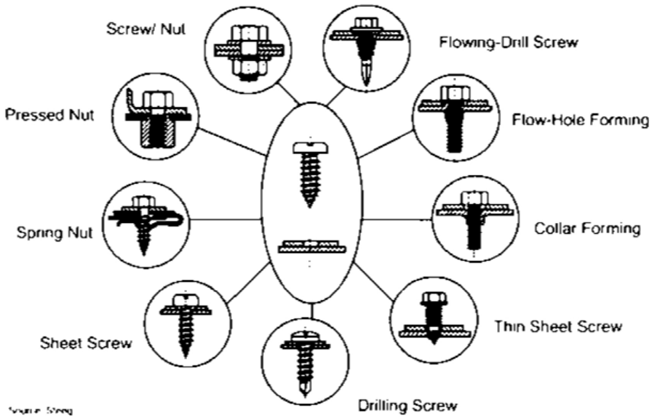

Fig. 2. Example of threaded fasteners [71].

Bolted joints have been in use for more than 500 years [33]. They are simple to use and virtually the only choice for disassembly and reassembly of a product, whether driven by maintenance or remanufacturing. Bolted joints can be designed for tensile or shear loads, or a combination. If the applied force is more or less parallel to the bolt, then the joint is called a tension or tensile joint (see Fig. 3).

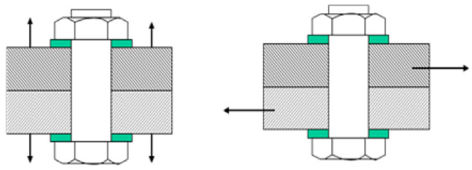

Fig. 3. Bolted joints in tension and shear.

If the applied force is perpendicular to the bolt axis, the joint is a shear joint. For other applications, a joint can be designed to withstand both tensile and shear loads. Bickford [33] provides an excellent overview of joint design, materials consideration, loading and strength analysis.

2.1.2. Flow drill screws

Flow Drill Screws, FDS, fill the void of a single-sided mechanical fastening method for structural automotive joints and at this point is a commercial off the shelf technology capable of both manual and fully automated assembly. The North American automotive industry is now following the trend set by European counterparts who have been using FDS since 1996 [43]. Traditional automotive steel-intensive Body In White (BIW) single-sided joining has been via gas metal arc welding. This fusion method implies however,