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FUNDAMENTALS IN ADHESIVE BONDING DESIGN FOR COMPLEX STRUCTURES AND CONDITIONS

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Abstract

The importance of assembling technologies are rising up in the manufacturing industry. With the development of new materials and their complex structures, new manufacturing and joining technologies are needed. Adhesively bonding techniques are meeting the industrial and technological needs, these techniques are providing an alternative for joining technology and enabling the use of a wider range of materials in product design. And adhesives allow enhanced aesthetics, lighter weight constructions and improved end performance, and also their usefulness build the utilization of multi-material, hybrid structures and for joining of dissimilar materials. Different materials have different physical and mechanical properties. Therefore, processing and joining procedures can also be challenging due to their properties. Adhesive bonding techniques are giving chance to cope with these difficulties. This paper reviews and summarizes state of the art research in adhesive joints for industrial applications in developing the innovative field. This is due to the expanding desires for more capability of strength and light-weight materials.

Keywords: Adhesively bonded joints, Adhesion mechanism and design, Dynamic loading and tests, Environmental effects on adhesives.

KOMPLEKS YAPILAR VE KOŞULLAR İÇİN YAPIŞTIRMA TASARIMININ TEMELLERİ

Özet

İmalat sanayisinde birleştirme teknolojilerinin önemi artarak devam etmektedir. Yeni malzemeler ve kompleks yapıların gelişmesiyle yeni imalat ve birleştirme teknolojilerine ihtiyaç duyulmaktadır. Yapıştırıcılarla birleştirme bu sanayi ve teknolojik ihtiyaçları karşılar, bu yöntemler birleştirme teknolojisine ve ürün tasarımında daha geniş bir yelpazedeki malzemelerin kullanılmasına olanak sağlamak için bir alternatif sunar. Yapıştırıcılar, daha estetik, daha hafif yapılar ve daha iyi performansa olanak tanır, ayrıca bunların kullanışlılığı ve çok malzemeli karma yapılarda kullanıma uygunluğu sebebiyle ile farklı özelliklerdeki malzemelerin birleştirilmesi için elverişlidir. Farklı malzemeler farklı fiziksel ve mekanik özelliklere sahiptir. Farklı özellikleri sebebiyle işleme ve birleştirme süreçlerinde zorluklar olabilir. Yapıştırma teknikleri bu zorluklarla başa çıkma şansı vermektedir. Bu çalışma, daha hafif malzeme ve yüksek mukavemet için artan gereksinimler doğrultusunda; yenilikçi bir alan olarak yapıştırma konusundaki endüstriyel uygulamalar için son araştırma ve gelişmeleri gözden geçirip özetlemektedir.

Anahtar kelimeler: Yapıştırılmış bağlantılar, Yapışma mekanizması ve tasarımı, Dinamik yükler ve testler, Çevresel faktörlerin yapıştırıcılar üzerindeki etkileri.

INTRODUCTION

The development of new materials, fabrication and assembling techniques has become a matter of success for industrial sectors such as automotive aerospace and defense industries, biomedical applications, and microelectronics. Designers and engineers are being challenged continuously to improve designs and manufacturing processes. By empowering the utilization of a more extensive scope of materials in item design adhesives permit upgraded feel, lighter weight developments, and enhanced end execution. The adhesive arrangements permit to make items in innovative, productive and compelling ways. Adhesive bonding is providing to increase the demand for joining similar or dissimilar structural components, lightweight structures, including the different combinations of composite materials and hybrid structures, apart from metallic materials, polymers and ceramics [1].

Adhesion mechanism is a very complex and multi-disciplinary phenomenon which needs knowledge about the polymer and surface chemistry, physics, fracture mechanics, mechanics of materials, rheology and other subjects. There are many debates in the literature about the adhesion mechanism and the diffusion, mechanical, molecular and chemical and thermodynamic effects on it [2-7].

Conventional joining technologies are giving chance to bond the materials, however apart from the adhesive bonding techniques, the base materials are being destroyed. For instance, for mechanical fastening it's needed to drill the materials, for welding applications it's needed to melt a part of materials which can be caused the residual stress, dislocations, and damage to microstructures. And also, welding techniques have limitations for bonding the dissimilar materials. Adhesive bonding is a solution for dissimilar materials joints without destroying the parent materials.

In this review paper, it will be discussed the factors affecting the success of the adhesive bonds. Therefore, the effects of surface morphology, joint configuration, adhesive properties, and environmental factors on the joint behavior are described for adhesively bonded dissimilar materials and complex composite structures. In addition, the effect of surface characteristics and roughness on wettability or adhesion, wetting and wetting criteria are summarized, the effect of loading conditions on the mechanical performance of adhesive joints and future challenges for research on joining dissimilar materials are discussed.

1. Influence of adherends of adhesive joints

The joining technologies have been identified as a key technology to innovative and sustainable manufacturing [8]. Today, joining technologies are obligatory for the industry. In addition to existing technologies, there are ongoing researches to the development of novel processes. The joining technologies are also applied for improving the lightweight and high-performance structures for combining various materials into multi-material hybrid structures [9]. The distinctive properties of the different materials are used in the same structure to accomplish the item execution required.

For providing the industrial needs, new and complex materials have been developed, and the new materials will require an efficient way to deal with a material choice: these materials will interact with each other in new ways, and new manufacturing and bonding systems are needed [10]. In this review, it's needed to determine the dissimilar materials and hybrid structures to understand their bonding mechanisms better. Dissimilar materials can be classified as a different type of materials or material combinations. It is difficult to join these type of materials, due to their chemical compositions and differences in physical properties between each parent materials [11].

The segments of dissimilar materials are to be joined with each other, and diverse joining techniques have remarkable qualities and restrictions for the joining of dissimilar materials. However, there are difficulties when materials of various substance, mechanical, thermal, or electrical properties are to be consolidated. The contradiction on substance, thermal and physical properties (thermal extension, ductility, fatigue/fracture mechanics, elastic modulus and so forth) can cause problems both for the joining procedures itself, yet in addition for the structural integrity of the joints amid the utilization period of the product [12]. Therefore, as a solution, adhesive bonding technology is coping with these problems and also bringing extra advantages such as elasticity for impact loads, ease of application and etc.

2. Adhesive Bonding for Dissimilar Materials, Composites and Hybrid Structures

Adhesive bonding methods are widely used in composite and hybrid structures, in addition to other engineering materials. The adhesively bonding processes consist of the following steps [13]: surface preparation: degreasing, grinding etching, and chemical cleaning [14]; applying the adhesives and clamping: adherends are simply fixed and just after applying the adhesive: pressure: joining surfaces must be kept under pressure while curing; curing: the curing can take place at either elevated or room temperatures.

Adhesive bonding has turned out to be an extremely compelling technique for joining dissimilar materials. The composite materials have difficulties for bonding without deformation their complex structures. Adhesive bonding techniques are giving a chance to create complex hybrid composite structures which mostly consist of dissimilar engineering materials.

The primary function of the adhesively bonded joint is the transfer of load by shear [15]. The mechanical strength of the adhesive bonded joint is, in its dominant part, reliant on the adhesive properties (strength and ductility), and joint design (configuration) is also crucial. Adhesive shear stress distribution in an overlap bonded joint, the edges will encounter the stacking peak values, while the central regions will be less influenced [16].

The fundamental advantages of adhesive joining method in contrast with mechanical bonding and welding are [17, 18]: bonding of dissimilar materials, available for hybrid structures, low stress concentration, no distortion, enhancement of fatigue resistance, fixing/sealing, decreasing of weight, smooth and aesthetic finishing, available for assembling the thin and flexible materials, no need for holes or no damages on base materials and good for repairing.

There are some disadvantages of adhesive bonding, such as an inseparable bond, requires the surface preparation in detail, low strength aside from shear loading, trouble in foreseeing bond failure, low-temperature resistance, easily effected from environmental factors, and adhesives may consist of hazardous chemicals [17, 18].

3. Effect of surface preparation on adhesive joints

The roughness of surfaces is critical points in the adhesive bond joints [19]. Surface treatments are applied to accomplish the most maximum mechanical quality. Bond quality and strength can be essentially improved by surface treatment processes. The development of appropriate surface properties is giving chance for surface preparation process specifically on impacts the durability of the adhesive bond [20]. The explored elements influencing the durability of these joints utilizing the clean surface approach. The most widely recognized misguided judgment in surface readiness is that the main necessity for a decent bond is a clean surface. A clean surface is a vital condition for attachment but it is not an adequate condition for bond strength. Most adhesives can meet this requirement, because of the material bonds between the surface atoms and mixtures containing the adhesive (mainly covalent, but some ionic and static bonds may be present) are arranged. [21]. These links are the heap exchange component between the adherends. Most adhesive bond failures can be seen because of surface preparation, with the absence of surface quality planning, which is the most critical insufficiency [20].

The essential point of the surface treatment is to increase the surface energy of base materials. Surface treatments decrease wetting (contact) angle, increment surface tension, and accordingly increment bond strength and quality [22]. An assortment of surface treatments has been utilized with different degrees of achievement to increase surface energy, increment surface roughness, change surface chemistry, and along these lines increment bond quality and strength of adhesive joints: chemical cleaning and etching, sandblasting of grinding, stress release treatment, plasma treatment and laser treatment.

Surfaces are likewise essential to the studies on microstructures, friction and wear, the joining of all materials, the catalysis of chemical reactions, oxidation and corrosion, the mechanical behavior of thin bodies and electronic devices, and a wide assortment of other wonders. The surfaces phases dependably contrast in conduct from the interior phases, due to the quick auxiliary changes which must happen at near phase boundaries [1]. Therefore, surface molecules are unbalanced if compared to the bulk molecules. The unbalanced molecules lead to the excess energy which is called 'surface free energy'. While employing the adhesive bonding process, it's needed to get benefit from the surface free energy mechanism, which is characterized as vitally important to shape a unit zone of new surface or to move an atom from the mass to the surface.

4. Effect of joint configuration on adhesive joints

Joints have difficulties in the design of structures, especially in composite and hybrid structures, since they involve in discontinuities in the geometry of the material structure or potentially material properties, and high local stress concentrations.

In addition to surface preparation, the joint configuration is related to product design. A wide variety of joint types are discussed by designers [23]. In common, joint configurations have been classified in the literature as single-lap joints, double-lap joints, scarf joints, and stepped-lap joints (Fig. 1). There are also many other configuration types mentioned in the literature, such as strap joints, butt joints, butt strap joints, corner joints, stepped-scarf joints, T-shaped joints, L-shaped joints, double-doubler joints, tubular lap joints, and etc. Researchers described a well-ordered system for adhesive joints (single, double, and step lap joints, and scarf joints) to use in hot/wet situations under static and cyclic loads [24].

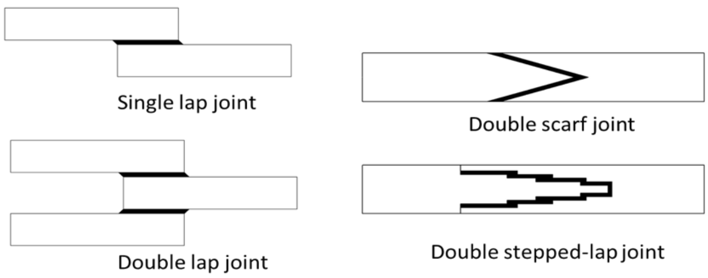

Fig. 1. Adhesively bonded joints configurations

The durability and strength of adhesively bonded joints depend on the stress distribution in the joint, which is related to joint configuration and geometry, the mechanical properties of adhesive and adherend, and also the type of loads. The geometry of adherend, adhesive and spews are seen in Fig. 2 [25–29].

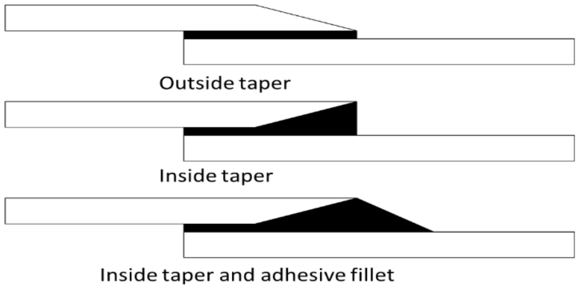

Fig. 2. Adherend shaping, adhesive geometry and spew geometry

The single-lap joint is the most widely recognized joint, but stress distribution is concentrated at the end of the overlap. Therefore, researchers have been studying on the single-lap joints which include a different shape of adherend geometry, adhesive filling (or recessing) and spew geometry. Removing portions of the adhesive (recessing) from the edge of overlap can contribute its aesthetic and weight reduction. The previous studies are showing that spew shape and size are affecting the stress concentration and fatigue failure [29–33]. Especially the peak stress is based on the size and shape of the spew. And smoother transition of spew in a joint can cause to decrease the stress concentration remarkably [30].

Nowadays, there are some researches about the adhesive bonding of dissimilar materials to create uniform stress distribution by using more than one adhesives [34–38]. The model of mixed adhesive bonding is seen in the Fig. 3.

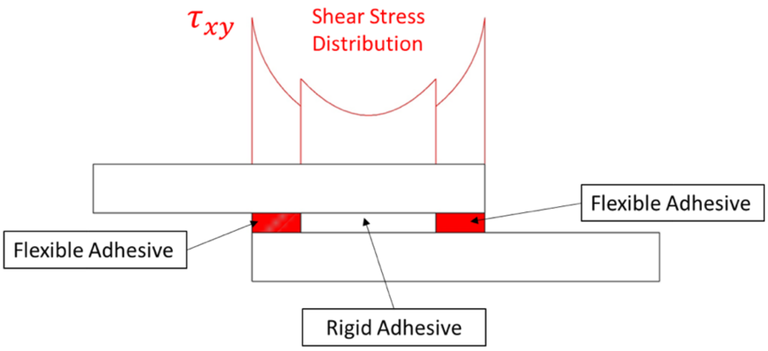

Figure 3. Mixed-adhesive bonded joint

Dissimilar material bonding by adhesives can have difficulties due to the diversity of thermal coefficient expansion of each material. In dual adhesive application can improve the joint strength and stress distribution (reducing of the stress concentration) [37, 38, 29].

5. Effect of environmental conditions on mechanical performance of adhesive joints

Adhesively bonded joints can be affected by environmental conditions and can be significantly impaired, especially when exposed to harsh environments. The environmental factors can affect the properties and the mechanical performance of the adhesively bonded joint [40]. These factors must be taken into account as a critical factor and the adhesive system must be designed regarding the service conditions for long term durability.

The essential environmental factors are determined as temperature (high and low) and humidity. The exposures can be for long or short term and can cause irreversible chemical and physical deformation on adhesives.

As the temperature increases, and when humidity absorbed, the bond strength decreases, and the polymeric material can lead to a wide range of effects. Both of the conditions can cause reversible and irreversible plasticization, swelling and degradation. At low temperatures, the strength of bonding can be measured higher. However, depending on the glass transitions, reduction of polymer properties and reversible dehydration will be seen, and these deformations will cause to decrease the mechanical, chemical and physical performance of the joint. At high temperatures, the adhesive properties are permanently deteriorated.

The humidity decreases the physical and chemical properties of the adhesives and also the interface between the adhesive and the adherends. It's known that humidity range is affecting the level of plasticization, strength loss, and increased ductility of adhesives. For understanding the effect of environmental factors, it's needed to be analyzed the bonding and failure behavior of different materials under the different environmental conditions. The constitutive and fracture tests on adhesives show that the adhesion strength and stiffness associated with the increase in ductility generally decreases as the humidity content increases [41].

Several studies have been carried out on the effects of various environments on some adhesive properties, but it is still necessary to analyze the performance of specific adhesive and adherend combinations, fatigue, and fracture studies of the adhesive systems. For example, the impact of environmental factors on multi-material structures, including sandwich and hybrid composites, can have a particular interest and components with different reactions to the same environmental conditions.

6. Effect of loading conditions on the mechanical performance of adhesive joints

Since most of the structural adhesives are polymer based, their mechanical performance is affected by the loading rate due to their viscoelastic properties [42,43]. Thus, the loading rate conditions over the adhesive joint must be taken into consideration in the joint design process. In the literature, many researchers studied the influence of the loading rate on the performance of the adhesive joint.

According to the studies, the strain dependency causes an increase in the strength of the joint under impact loading [44]. And the plastic deformation of adherends is the major contributor to the total energy absorption of the adhesive joints. The failure strength of the adhesive is not affected by the loading rate; however they are affected by the strength of adhered material [45] At different extension rates and temperatures, the failure load increases with increasing extension rate. The adhesive demonstrates a higher rate dependency at high temperature [46]. The shear strength of the adhesive increases with increasing loading rate [47].

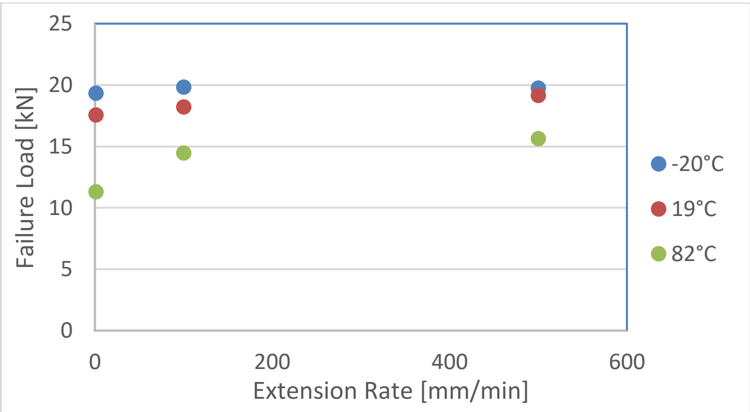

Figure 4. Summary of tests at different extension rate and temperature [46]

In recent studies, it was pointed out that the adhesive joint design under impact loading must be based on data obtained by impact tests, not quasi-static tests [48, 49]. Therefore, new techniques have being developed to measure dynamic and impact loads [50]. The impact resistance of adhesive bonds are studied in previous studies using shock waves, and the results showed that the shock wave reaches the interface between the adherend and the adhesive, and splits into two transmitted and reflected waves, and the adhesive absorbs shock through the plastic deformation in the adhesive [51]. When analyzing the bending mode behavior and energy absorption ability of adhesively bonden joints, it will be seen that some part of the external load (shock wave) pressure will be absorbed by the adhesive [52]. The energy absorption by the adhesive, decreases dramatically with increasing strain rate, and the yield strength of the adhesive increases significantly while the failure strain decreases with increasing strain rate [49].

The studies summarized above show that the mechanical performance of the adhesive joint varies based on the loading rate. Therefore, the design of the adhesive joint must be carried out considering the loading rate condition on the adhesive joint. It is also noted that any adhesive joint design that may be undergone impact loading must be designed based on the data obtained by dynamic tests.

CONCLUSIONS

The development of new materials, fabrication and assembling techniques has become a matter of success for the manufacturing industry. For providing the industrial needs, new and complex materials have been developed, and the new materials will require new manufacturing and bonding technologies [10]. Adhesive bonding technology is providing for joining similar or dissimilar structural components for improving the lightweight and high-performance structures for combining various materials into multi-material structures [1,9,17,18].

The roughness of surfaces is critical points in adhesive bond joints [19]. Surface treatments are applied to accomplish the most maximum bond quality and strength.

The joint configurations are also essential for adhesive bonds, which have been classified in the literature as single-lap joints, double-lap joints, scarf joints, and stepped-lap joints to use in hot/wet situations under static and cyclic loads [24].

Adhesively bonded joints can be affected by environmental conditions, which can affect the properties and the mechanical performance of the adhesively bonded joint [40]. Increasing the temperature and absorbing the humidity, the bond strength decreases. Both conditions can cause reversible and irreversible plasticization, swelling and degradation. At low temperatures, depending on the glass transitions, reduction of polymer properties and reversible dehydration are seen. There are several studies on the effects of various environments on some adhesive properties, but it is still necessary to analyze the performance of specific adhesive and adherend combinations, fatigue, and fracture studies of the adhesive systems.

Because most of the adhesives are polymer based, their mechanical performance are affected by the loading rate due to their viscoelastic properties [42,43]. The strain dependency causes to increase in the strength of the joint under impact loading [44]. The shear strength of the adhesive increases with increasing loading rate [47]. The primary function of the adhesively bonded joint is the transfer of load by shear [15]. Some part of the dynamic impact load pressure is absorbed by the adhesive [52]. The energy absorption decreases dramatically with increasing strain rate and the yield strength.

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