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Advanced Joinery Method

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Abstract. The incorporation of advanced joining methods and lightweight technologies offers unmatched flexibility to automotive design. It enables the achievement of thin-walled, hollow, and miniaturized components, thereby substantially reducing vehicle weight. The trend of lightweighting not only greatly reduces energy consumption and emissions but clearly boosts dynamic performance and the handling feel, and spurs technological progress in the auto industry. This technological combination, a key direction for future automotive design, is highly significant in promoting the sustainable development of the automobile industry. This paper takes five common connection methods (bolting, riveting, laser welding, ultrasound welding, and snap - fits). It analyzes and compares how these methods perform on the two indicators of connection force and vibration tolerance to find the best way for vehicle lightweight and energy saving.

Keywords: Bolting, Rivet Placement, Laser Welding, Ultrasonic Sealing, Snap-fits

1. Introduction

To confront the energy crisis and cut down exhaust emissions and energy consumption, the automotiveindustry has used different approaches to be more eco - conscious. Because they are light, aluminumand magnesium alloys are being used in a larger number of vehicle components, and composite materialshave had wider application [1]. This has brought about an increase in material diversity and new requestsfor connections, and also higher criteria for connectivity. Therefore, traditional joining methods arehaving more and more difficulties. For instance, conventional arc welding may not be reliable enoughwhen welding different types of metals [2]. For the vehicle to perform dependably, the stability ofconnections is critical, so there is a need to improve current methods or use novel joinery techniques.Studying the shear - tensile strength of the joining structure helps understand how the material respondsto shear or tensile stresses, common in many joining applications. Deciding a joint's overall performanceand reliability, shear - tensile strength is key, especially in lightweight materials where joint failure isfrequent [3]. Studies in this area are centered on giving insights for enhancing load - bearing ability andfinally bettering the capacity to keep joint integrity. Shear stress, a typical stress condition in engineeringstructures, is widely existent in different connection points and load - bearing structures. Knowing thereaction of joint structures under shear stress is of great importance to guarantee the safety and stabilityof structures. Joint structures are usually made of multiple materials joined by means of welding, boltingand others,

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resulting in complex and diverse stress scenarios. To study the shear strength of jointstructures, it's essential to comprehensively consider multiple factors, such as material mechanicalproperties, joint shapes and dimensions, and welding processes. Different materials show differentmechanical properties, including yield strength, tensile strength, and toughness, that directly influencethe shear strength of joint structures [4]. So, a knowledge of material properties is vital for accuratelymeasuring the shear strength of joint structures.

The article additionally looks into the effect of vibrations on connection structures, studying how vibration causes loosening and brings about connection failures because of fatigue. It looks at how to keep the stability and reliability of connections in vibrating environments. Most of the current research is about numerical evaluation simulations, models to predict the behavior of structures under diverse conditions, and experiments to visually study the impact of vibrations on structures. The venture is to optimize the connection process and design, prolong the service - life period, bring down maintenance expenses, and find out the application prospects of different connection approaches.

This article mainly looks into the current research status and improvement techniques of bolting, riveting, snap - fits, laser welding, and ultrasonic welding in terms of strength and vibration resistance. It makes a comparison of the reliability of the five currently used joinery methods via these two aspects.

2. Snap-fits

Snap-fits, also called snap - fit joints or quick - assembly fittings, are a widely used connection methodin component assembly. Its definition can be perceived as a mechanical structure that makes a secureattachment between parts without the use of additional fasteners such as screws or nuts. Primarily relyingon the elastic deformation characteristics of plastic materials, when two plastic components come intocontact with each other through a carefully designed structure and a certain amount of pressure is applied,one of the components (usually the one with a protrusion) undergoes temporary elastic deformation untilit can cross the boundary of the other component (typically the one with a groove or hole).After theboundary is crossed, on account of the plastic's elastic recovery force, the deformed component quicklygets back to its initial form, firmly connecting the two parts. Snap - fits reach this aim by using speciallydesigned geometric patterns. These patterns allow two or more components to interlock or lock togetherunder pressure, making a stable connection. Figure 1 shows a well - known geometric shape model ofthe snap - fits structure.

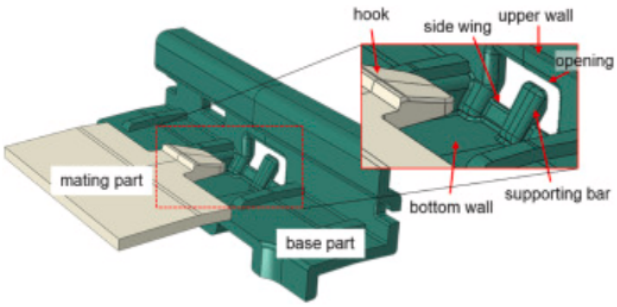

Figure 1. The geometric form of a typical snap - fits model [3]

One of the focuses of snap-fits research is properly and effectively joining two or more addictive manufactured parts. To solve this, a study demonstrates snap-fits are easily assembled, and if

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appropriately designed and disassembled, they offer the possibility to hide the joints and are relatively flexible when it comes to placing them on the joining surface. Figure 2 shows a method of analyzing the force to determine the effective flexural modulus, which is a crucial parameter that describes a material's ability to resist deformation under bending loads on the material, and derive reliable equations to predict the behaviour of cantilever snap-fits. Figure 3 shows another method, which is to reduce the number of connectors by changing the shape of the joints and replacing the traditional connecting parts with snap-fittings [3].

Through analyzing how the dependent variable, maximum retention force, behaves corresponding to the input independent variable, opening force, the study determines the relationship between the force and flexural modulus. Figure 4 gives an idea of the effects of process smoothing and stress cycling on the opening and retention forces.

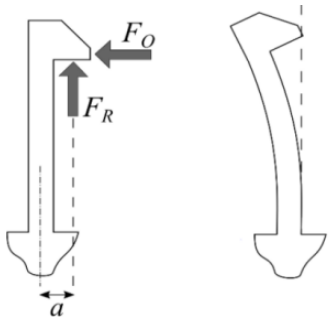

Figure 2. Opening force as well as retention force on a cantilever snap - fit [3]

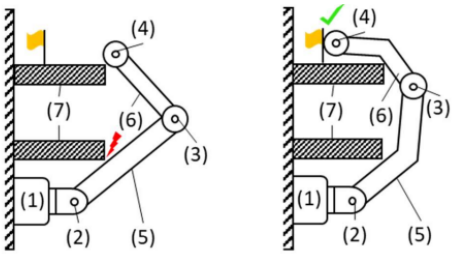

Figure 3. Better connection of the robotic arm [4]

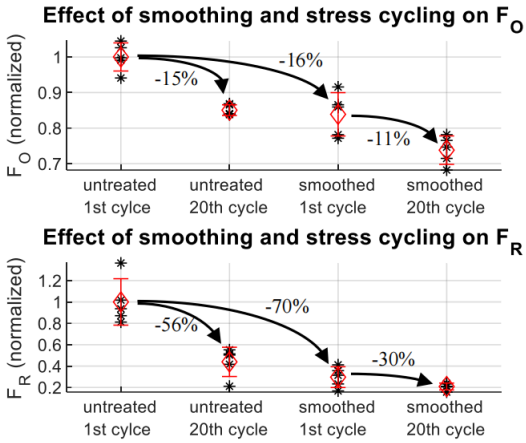

Figure 4. The consequence of process smoothing and stress cycling on opening force and retentionforce [5]

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Rotating machines often deal with torque fluctuations that result in rotor vibrations, premature wear, and noise pollution. However, using centrifugal pendulum vibration absorbers (CPVAs) as passive vibration - reducing devices is confronted with problems due to instabilities that result in localized pendulum motion, which may lower their effectiveness. To cope with this, a solution is to study the local behavior of a CPVA made up of two pendulums rotating around their common center of mass. For this investigation with the confirmed validity of its model, a method is used to set up a dynamical model based on an analytic perturbation approach. This model tries to reveal the distinct traits of the localized response, such as the appearance of quasi - periodic regimes. This contributes to better understanding and potential optimization of CPVAs for vibration reduction in rotating machinery.

Figure 5 demonstrates another method to regulate the vibration amplitude of the Snap structure and control the vibration force by experimentally verifying the adjustable stiffness and frequency response of the isolator by determining the control threshold of pre-deformation based on the payload mass, excitation amplitude and damping coefficient.As depicted in Figure 6, at a fixed payload of 3. When there is a 5 - kg mass, the control displacement threshold of the semicircular ring varies with the excitation acceleration amplitude under different system damping states of affairs [5].

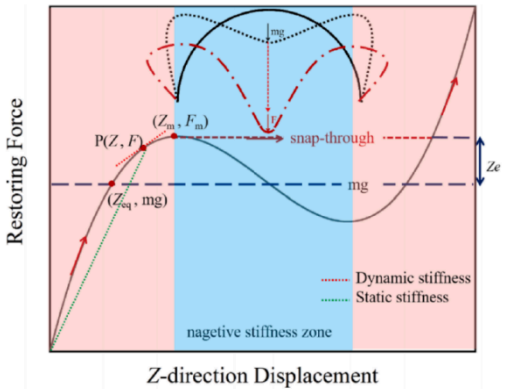

Figure 5. The relation of force to displacement of the semi - circular ring and the snap - throughphenomenon [5]

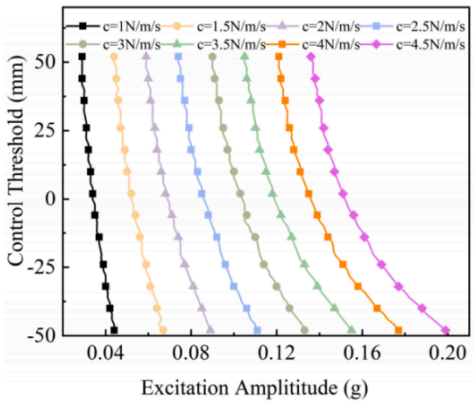

Figure 6. At fixed payload (3.For a 5 - kg mass, under different damping conditions of the system,the control displacement threshold of the semicircular ring changes with the amplitude of theexcitation acceleration [5]

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With the rise in the excitation amplitude, the control threshold of the dependent variable gradually goes down under different damping. Specifically, under varied payload conditions, it shows different trend aspects.

When the level of excitation amplitude increases, the critical displacement point for control shows a large - scale reduction. But as this excitation amplitude gets more intense, the rate at which the control threshold drops slows. In fact, as the damping characteristics of the system strengthen, the speed at which the control threshold's magnitude decreases slows down, showing enhanced adaptability in varying operating circumstances.

The research finds that with vertical compression at its center, the semicircular ring structure initially softens and afterwards shows negative stiffness. One is able to finely tune this stiffness characteristic by modifying the pre - deformed state with a horizontal control displacement. For the case of pretension, the structure shows an extended range of quasi - zero stiffness in the zone of lower restoring forces. In comparison, pre - compression leads to a reverse tendency, giving useful information for the design of snap - fit structures that exploit these features.

3. Bolting

A helical threaded fastener called the bolt is used to join objects with unthreaded holes. For the bolted joint depicted in Figure 7, both layers need holes of appropriate size to accommodate the chosen bolt. A vertical movement of the bolt through the joint site is made. A nut screws onto the other side of the said bolt. During joint setting, preload is used to increase the maximum bearing and shear force capacity. Preload may cause the contact areas of two layers to partially yield, so as to obtain better tightness. A washer may be put in place between the bolt or nut and the member to decrease the likelihood of it coming loose or losing preload. This kind of joint is able to be constructed or taken apart. Making all of them meet standard requirements is easy, so they're widely used in the automotive industry.

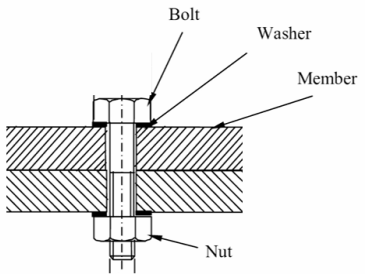

Figure 7. A bolted joint connecting two members [1]

When combining less weight materials, one common problem for the failure of bolted joints is that the joint withstands its yield limit. The maximum force a bolted joint can withstand is influenced by several key factors, including the bolt diameter, the material of the bolts, and the preload applied. These factors work together to determine the overall strength and performance of the joint. Research has been done to investigate the factors that contribute to given materials [2]. We can carry out experiments to find out the best situation if there are new materials that haven't been introduced in any research before. In Figure 7, the experiment tests the process of load-bearing failure process to get the maximum static strength. A non-contact optical device called an extensometer is used to measure the strain and extension of a material under load. Bearing damage was monitored by measuring the creation of transient elastic waves due to rapid energy release from

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localized sources in a material; this process is called acoustic emission testing (AET) [3]. We can analyze the four stages of damage progression shown ---- damage initiation, damage growth, local fracture, and structural fracture.

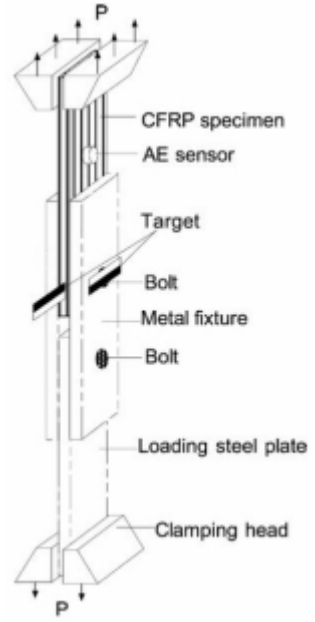

Figure 8. A kind of experimental set to test shear-tensile strength of bolted joints [3]

Through the analysis of the tear point image in different stages, research shown in Figure 8 is done in further study, and some detailed structures and the load-displacement graph are shown in Figure 9. In the situation of two carbon fiber-reinforced plastic laminates based on polymer substrates, the result highlighted the significant impact of laminate lay-up on the joint's load-carrying capability [4]. The influence of microstructural changes and residual stresses during bolting requires more research. The final outcome is proper selection of bolting methods is necessary to maintain joint integrity.

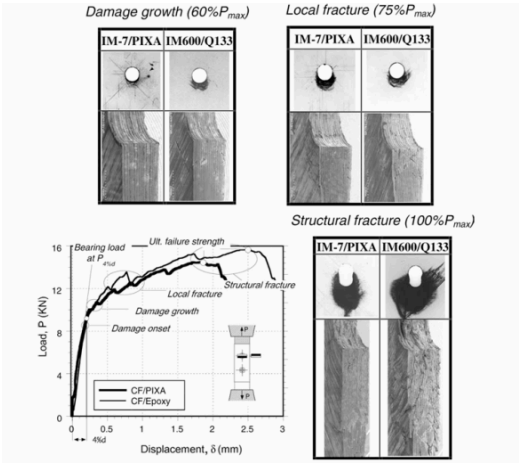

Figure 9. Bearing strength and damage progression result s [4]

Another problem that contributes to the failure of bolted connections is induced by vibration. Research has been done to investigate the effects of vibration when connecting bolts are becoming

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loosened. Finite Element Analysis (FEA) is one of the solutions to simulate the dynamic vibration characteristics of the integral parts connected with bolts in order to identify the impact of loosen bolts in one research [5]. They first create 3D meshed models (figure 10) made up of plenty of triangles and rectangles. Researchers give these basic structures set properties and provide external loads. A system of linear or nonlinear equations generated by the model is solved using computer algorithms.

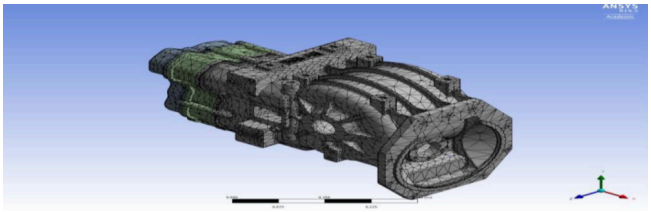

Figure 10. Meshed model of transmission gearbox casing [5]

There are mainly two mechanisms of vibration loosening, vibration conveyor mechanism and inertia torque mechanism [6]. The first one means in a vibration environment, the nut or bolt slides along threads resulting in loosening. The other one occurs in rotating wheels. The fasteners face rotational inertia force, and the force generates inertial torque, making the nut to become loosened. So, proper thread angle, type of nuts, and coefficient of friction are key to preventing vibration from loosening in terms of component selection. The correct method of installation and ensuring the preload are also important factors that prevent the bolted joins from becoming loosening (Figure 11).

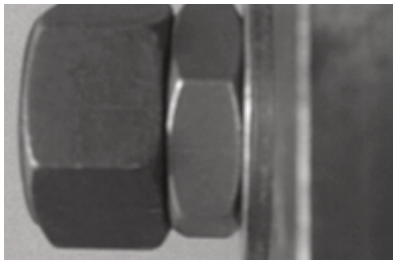

Figure 11. Correct example of installation of lock nut

4. Welding: ultrasonic

Ultrasonic welding is a welding method that utilizes ultrasonic waves to apply high-frequency mechanical vibrations to the surfaces of workpieces [6]. Ultrasonic waves are converted into high-frequency mechanical vibrations via a transducer, which are then applied to the welding location causing frictional heating or viscoelastic heating [7]. After cooling, a weld joint is formed. As shown in Figure 12, there are several different types of ultrasonic welding methods, which can be categorized into spot welding, rotary welding, and continuous welding [7]. Currently, ultrasonic welding, as a green welding technology, has advantages over traditional arc welding in joining dissimilar materials. Therefore, it holds promising application prospects in automotive structural components and connectors for new energy vehicle batteries [8].

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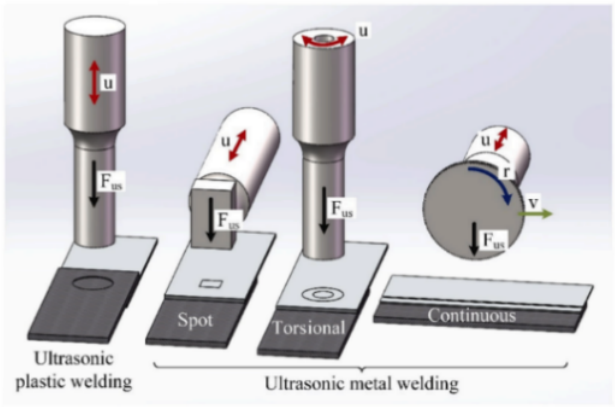

Figure 12. Spot welding together with rotary and continuous welding [8]

To find the reliability of ultrasonic welding, researchers did experiments on its strength. They adjusted parameters such as ultrasonic frequency, welding time, and applied pressure in order to find the combination that yielded the highest strength indicators. For example, in the experiment conducted by Xin Li et al. A Telsonic M4000 ultrasonic welding machine having a maximum power of 5000 W was employed for welding. The welding was done under conditions where the clamping force was 2 kN and the vibration frequency was 20 kHz.

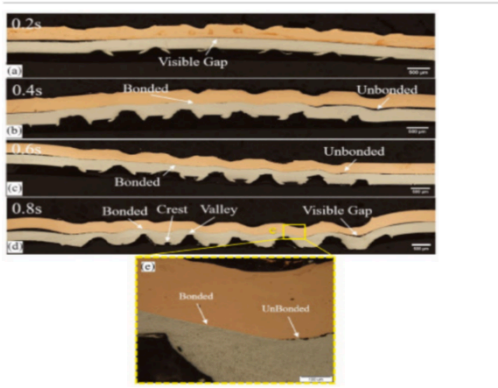

Figure 13. OM image of the cross - section of Al–Cu joint welds when the welding pressure isconstantly 4. With 5 bar and 90% amplitude, welding time is (a) 0. 2 s, (b) 0.4 s, (c) 0.6 s and also (d)0. 8 s, (e) shows a magnified view of the region that is boxed in (d) [9]

Components were put through welding for different time - lengths from 0. 2 and 1.After a 2 - second period, tensile tests were carried out to measure their strength [4]. Besides, researchers measured the Vickers hardness of the samples and examined cross - sections to better figure out their strength and the patterns of strength variation. The Vickers hardness test involves using a diamond indenter in the shape of a square-based pyramid, which is pressed into the surface of the material being tested at a specific load, held for a period, then unloaded, followed by measuring the length of the diagonals of the indentation.Before stretching the samples, they were cut and polished to expose the weld's cross - section. Then, electron microscopes were used to observe their structure and measure Vickers hardness. Some researchers also made use of X - ray analysis to discover the chemical composition of the joint [8]. Figure 13 shows the microstructure of the ultrasonic weld joint between copper and aluminum that has been sliced and ground.

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It was found in the study that as the welding time got longer, the number of bonding points increased, encouraging metallurgical reactions at the interface and leading to stronger joints [7]. Figure 13 shows the interfacial microstructures of ultrasonic welds between aluminum and copper at different welding times—0. 2, 0.4, 0.6, and 0.8 seconds—are depicted.It is found that when the welding time is 0. At 2 seconds, a continuous non - bonded region line comes into view. At 0.At the 4 - second point, the bonded area spreads, and it's 0. With 8 seconds of welding, a bond has largely developed on the surface, yielding a larger welded area where the non - bonded area is almost invisible. This situation shows favorable metallurgical reactions at the weld seam. However, a very long welding time can make the brittle intermetallic compound (IMC) layers grow thicker, increasing the risk of fatigue crack initiation at the seam edges [8]. These compound layers come into being because of reactions between dissimilar welding materials. As presented in Figure 14, the image of the IMC layer at the interface of copper - aluminum ultrasonic welds shows that when the welding duration is extremely short. After a 2 - second period, a very thin and continuous IMC layer forms at the weld interface. As welding time and temperature go up, the thickness of the IMC layer also goes up, to 2. 2 μm in a 1 - long welding time. 2 seconds.In consequence, the strength first goes up and then comes down as the welding time increases, as shown by the strength test results in Figure 15. When the welding went on for 1 second, under a pressure of 1. With 97 kN and an amplitude of 54 μm, the lap shear strength of the aluminum/steel joint got to a maximum of 62. The shear strength was 7 MPa [10], after which it showed a decline in 1 second.

This indicates that the ultrasonic welding interface can bring about good metallurgical reactions, reaching sufficient bonding strength and an adequate weld area in relatively short times. This makes sure of the reliability and operability of ultrasonic welding.

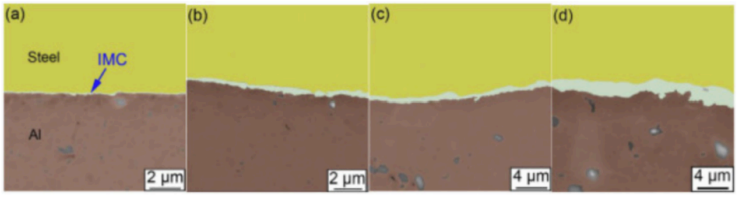

Figure 14. Cross - sectional SEM micrographs of Al/steel joints that were welded with differentultrasonic welding periods: (a) 0. 2 s, (b) 0.4 s, (c) 0.8 s, and also there is (d) 1. 2 s [11]

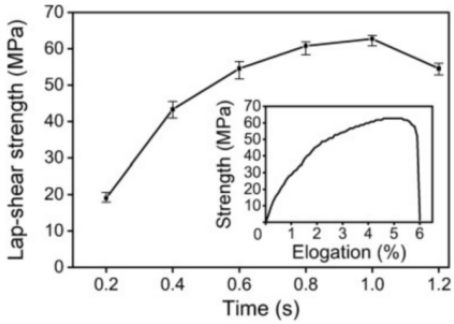

Figure 15. The association between joint strength, different lengths of welding time, and elongation [12]

In structural applications of automotive weld joints, vibration is unavoidable. Repeated loading can cause cracks to develop little by little, leading to failure at loads below the material's strength, a situation called fatigue failure. As shown in Figure 16, there is a micrograph of the damage in a

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welded joint as a result of fatigue. In view of the durability and safety of vehicles, the fatigue resistance and vibration tolerance of weld joints are of great importance. Even though research in this field is scarce, considerable progress has been made. Researchers have carried out fatigue tests on welds of different kinds of materials, including aluminum - to - steel welds [6] and the welding of lightweight magnesium alloys [2]. Once ultrasonic welding was done, they applied sinusoidal loads having different peak values at 50 Hz and a stress ratio of 0. 2 given to the welded sections for testing. Following the ASTM E466 standard, the loads were applied via a fully computerized Instron 8801 servo hydraulic test system [6], so the results obtained are highly comparable. Specifically, some researchers employed life prediction models to predict the fatigue life and contrasted the predicted results with experimental findings [2].

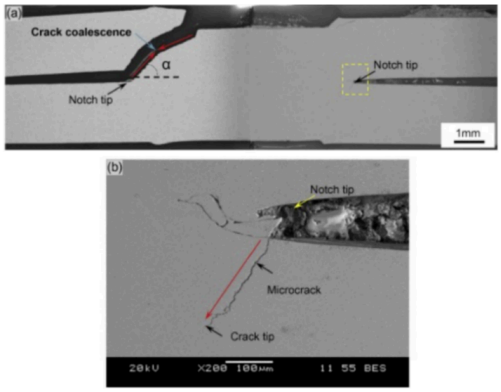

Figure 16. A micrograph of the fatigue - caused damage in a welded joint [6]

The experimental results imply that there are mainly two kinds of fatigue failure: the interfacial failure kind and the Transverse Through Thickness (TTT) failure kind [7]. The interfacial failure mode comes about as a result of poor bonding at the interface, causing a failure at the joint. In contrast, the TTT mode features the growth of cracks that propagate from one surface across the whole thickness to the opposite surface, resulting in failure. As presented in Figure 17, panels (a), (b), and (c) show the interfacial failure mode, indicating the weaker joint has broken apart. Panels (d) and (e) show the TTT failure mode, with a crack that traverses the entire component rather than being only in the joint area. These various failure modes are associated with the peak load (Pmax), and P means the maximum load [6]. Usually, higher values of P are more likely to result in interfacial failure with shorter lifespans. In comparison, lower P values are related to TTT failure, which tends to have longer lifetimes. However, some joints exhibit a reverse trend, such as the Al-to-ASTM A36 steel fatigue samples under high Pmax loads exhibiting TTT failure and at lower Pmax loads transitioning to a mixed TTT and interfacial failure mode, which contributes to their longer lifetime under lower loads.Figure 18 shows that this alteration of failure mode is observable. Figure 19 shows the lifetime plots of a number of joint materials, indicating that the longest lifetime can be accomplished with a Pmax of 0. 5 kN, getting near to 10^7 cycles. The experiments on joint lifetime make it evident that ultrasonic welding assures a level of fatigue and vibration resistance, which makes the joint stable and reliable.

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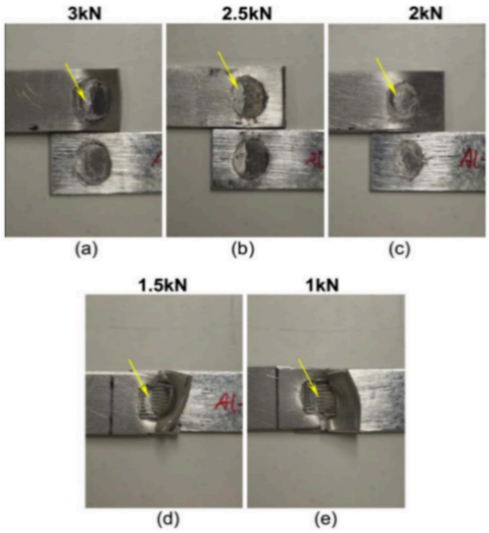

Figure 17. Typical fatigue failure locations (indicated by yellow arrows) at different Pmax values ofdissimilar USWed Al 6061-to-galvanized HSLA steel joints at the 1500 J energy input: 3 kN (interfacialfailure mode) (a), 2.5 kN (interfacial failure mode) in situation (b), 2 kN (interfacial failure mode) insituation (c), 1. 5 kN (TTT which stands for transverse through - thickness crack growth) (d), 1 kN (TTT)(e) [6]

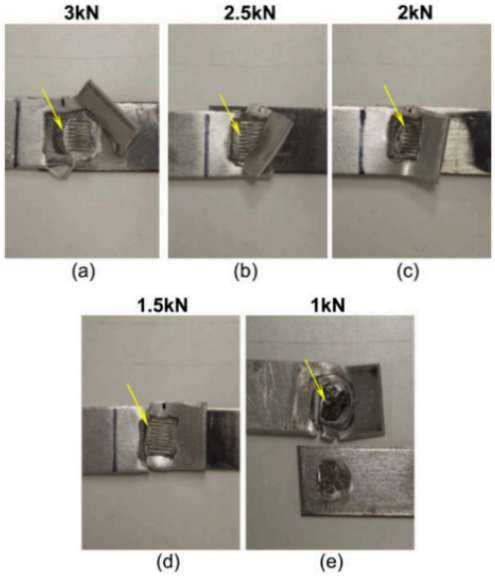

Figure 18. Typical fatigue failure locations (indicated by yellow arrows) at different Pmax valuesof dissimilar USWed Al 6061-to-ASTM A36 steel joints at the 1250 J energy input: 3 kN (transversethrough-thickness crack growth mode (TTT) (a), 2.5 kN (TTT) in situation (b), 2 kN (TTT) insituation (c), 1. 5 kN (TTT) (d), 1 kN as shown in [6]

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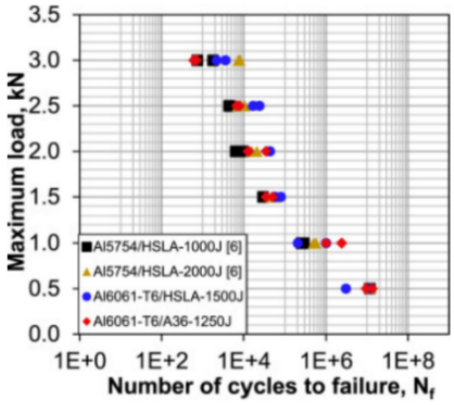

Figure 19. The greatest cyclic stress of tensile shear vs. the number of reversals to failure (2Nf) inthe double-log scale for USWed Al 6061-T6-to-galvanized HSLA at 1500 J energy input (a) and Al6061-T6-to-ASTM A36 steel at 1250 J energy input (b) [6]

5. Riveting

Widely in use, riveting is an important connection way. To connect two or more work - pieces, people make use of rivets. An axial force is applied to upset the shank in a hole, form a head, and join the parts. To lessen the total weight of motor vehicles and further increase energy efficiency, a feasible method is to use composite materials and light alloys on a large scale to take the place of steel. While using adhesives is a workable process, rivet fastening is often needed in many situations to enhance connection reliability.

When exposed to vibrations for a long time, the rivet joints may develop fatigue and weaken gradually. This happens because of repeated stress cycles which cause micro - cracks to form and propagate, ultimately degrading the joint's structural integrity. Vibrations may cause rivets to loosen, especially when the joint isn't installed correctly or materials change in size due to temperature variations or other causes. Loose rivets can harm the tightness and strength of the connection, which might lead to failure under load.

Shot peening's effect on SPR joint performance assessment was carried out by subjecting AA5052 aluminum alloy (AA5052 - H32) sheets to the shot peening process. As a consequence, the two AA5052 sheets, one shot - peened and the other not, were put into the SPR process to compare the effect of shot peening on the static and fatigue properties of commercial SPR rivets [1].

The results showed that there was a substantial improvement in the fatigue limit and general durability of the SPR joints made with the shot peening method.

Applying a shot - peening process before SPR effectively produced compressive residual stresses in the surface layers of AA5052 aluminum alloy sheets, which reduced the effects of cyclic vibrations that would have started and propagated micro - cracks. The idea presented in past studies could be valid when it comes to stating that shot peening improves the material's fatigue - resistance by altering the surface microstructure and redirecting stress to the surface [2].

In particular, the study of static and fatigue features showed that the shot - peened SPR joints had a better joint inter - relation and were less prone to slackening, whether in thermal cycling or under variable loading. This improvement is mainly because of the strengthened interfacial bond strength and the reduced stress concentrations caused by peening.

To end with, when combined with the SPR process, it provides a practical and useful answer to the problem of fatigue - induced degradation in rivet joints. The findings highlight the significance

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of pre - treatment strategies for optimizing the performance of joints susceptible to high - cycle fatigue and aid in developing more reliable and durable structures.

After a long time of being exposed to vibrations, fatigue can cause damage in rivet joints. This damage weakens the joints and will eventually make them break down. This takes place because repeated stress cycles cause the formation and propagation of micro - cracks, making the joint fail. The effect of vibration on the joints might result from rivets that were not well - installed at first and/or because their dimensions are changing due to temperature changes or something else. Loosening rivets leads to losses in tension and strength of the connection, and could also cause failure under load.

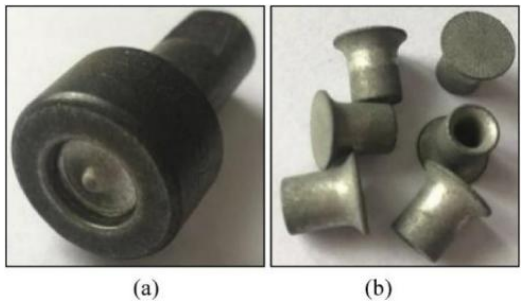

Figure 20. Boss - concave die and semi - tubular rivets as per [1]

The results showed a significant improvement in the fatigue limit and the overall durability of the self-piercing rivet (SPR) joints through the treatment of the shot peening method.

6. Conclusion

In this study, we explored five advanced joining techniques, namely bolted joints, riveted joints, laser welding, ultrasonic welding, and snap-fit connections. We assessed their strength in the joints and their resistance to vibration. These methods are particularly necessary in the automotive industry, where the rigorous struggle to reduce the weight and gain energy robustness is always on the march. The integration of these advanced joining techniques with lightweight materials has reinvented the automotive landscape, allowing the manufacturing of slimmer and more energy-efficient vehicles.

Each of the joining techniques in this paper has its benefits and challenges to be faced. Bolted joints, although a fairly old method, are still the best choice when one needs a reliable and versatile connection, especially if the components are lightweight and the materials chosen are pre-loaded and used with the utmost care.

It has been demonstrated through research that proper preload and material selection have a major impact on the strength and vibration resistance efficiency of the joint. Nevertheless, The potential challenges posed by yield limit exceedance and vibration-induced loosening need our attention.

For one thing, riveting becomes the most used type of the technique which excels at the process of the joining of unlike materials and the achieved structural integration. Using a combination of peening and self-piercing riveting increases the fatigue strength and, hence, the durability of the components, which, in effect, prolongs the lifetime of the parts.

Laser welding and ultrasonic welding are the first of the things that we are going to deal with here. Through the highly developed language of the laser light that is very fast as well, it is mainly used for the critical joining of parts of the car body. The ultrasonic welding method that employs

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high-frequency mechanical vibrations represents an eco-friendly technique alternative to traditional arc welding, especially in the joining of dissimilar materials. Furthermore, the ultrasonic frequency and welding time are important parameters and their fine-tuning is crucial to achieve the maximum joint strength and reliability.

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