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Review Article

A Review on Welding Techniques of Metallic Foams

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Abstract

Metallic foams are a new type of material class using in the much-diversified area such as automotive, biomedical, and construction etc. Thanks to its porous structure, it stands out with its energy and impact absorption as well as its lightness. Due to the properties, metal foams have the potential for use in many applications. As the number of uses and potential applications increases, it becomes important to develop adequate joining technologies for metallic foams and to select appropriate methods for their widespread industrial use. However, various problems are encountered in welding metallic foams with a foam or a face sheet. The most important feature that causes differences in the welding process and characteristics of these materials is porosity. While the methods such as MIG/TIG could be preferred in the past, the methods such as laser welding have come to the fore with today's needs. The welding of metallic foams is a subject that is still being studied and developed. In this study, studies in the literature are examined to understand the problems encountered in metallic foams during welding and to develop welding techniques. It is aimed to create a wide source for the welding of metallic foams by referring to the methods used and the advantages and disadvantages of the methods with this review. It has been determined that traditional welding methods have started to be replaced by advanced welding methods in the welding of metallic foams.

Keywords: Metal foam, pore, welding techniques, laser welding

Metalik Köpüklerin Kaynak Teknikleri Üzerine Bir İnceleme

Öz

Metalik köpükler otomotiv, biyomedikal, inşaat gibi çok çeşitli alanlarda kullanılan yeni bir malzeme sınıfıdır. Metalik köpükler gözenekli yapısı sayesinde hafifliğinin yanı sıra enerji ve darbe emilimi ile öne çıkmaktadır. Özellikleri nedeniyle birçok uygulamada kullanım potansiyeline sahiptir. Kullanım alanları ve potansiyel uygulama alanları arttıkça metalik köpükler için yeterli birleştirme teknolojilerinin geliştirilmesi ve yaygın endüstriyel kullanımları için de uygun yöntemlerin seçilmesi önem kazanmaktadır. Bununla birlikte, metalik köpüklerin bir köpük veya levha ile kaynaklanmasında çeşitli problemlerle karşılaşılmaktadır. Bu malzemelerin kaynak işleminde ve karakteristiğinde farklılığa neden olan en önemli özellik gözenekliliktir. Geçmişte MIG/TIG gibi yöntemler tercih edilebilirken günümüzdeki ihtiyaçlarla lazer kaynağı gibi yöntemler ön plana çıkmıştır. Metalik köpüklerin kaynağı halen çalışılmakta olan ve geliştirilmesi gereken bir konudur. Bu çalışmada, metalik köpüklerde kaynak sırasında karşılaşılan sorunları anlamak ve kaynak tekniklerini geliştirmek için literatürdeki çalışmalar incelenmiştir. Bu derleme ile kullanılan yöntemler ve yöntemlerin avantaj ve dezavantajlarına değinilerek metalik köpüklerin kaynağı için geniş bir kaynak oluşturulması amaçlanmıştır. Metalik köpüklerin kaynaklanmasında geleneksel kaynak yöntemlerinin yerini ileri kaynak yöntemleri almaya başladığı tespit edilmiştir.

Anahtar Kelimeler: Metalik köpük, gözenek, kaynak teknikleri, lazer kaynağı

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1. Introduction

Metallic foams are defined as metallic solids containing pores (Ishizaki et al., 2013). They can be produced with 20-97% porosity and exhibit characteristic properties depending on the types and amount of the pore. Figure 1 shows the images of metallic foams with different porosities.

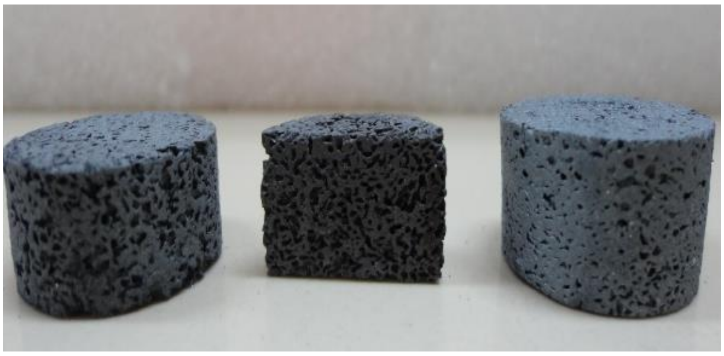

Figure 1. Photograph of the metal foams (Beköz, 2011)

Metallic foams are classified as open-pores, semi-open-pores, or closed-pores according to their pore types (Banhart, 2001). Open pores are in contact with each other and with the environment (Sharma et al., 2020). Porosity is required for a liquid or gaseous environment to pass through the metallic foam in some applications such as heat exchanger, filtration, separation, and catalyst applications (Sharma et al., 2020). Therefore, metallic foams with open pores are preferred for these applications (Banhart, 2001). Closed pores are isolated from each other and from the environment. Metal foams with closed pores exhibit absorption properties and can load-bearing due to the strength provided by the pore walls. For this reason, they are used in areas such as load-bearing components and energy absorbers. Thus, metallic foams are used for many functional and structural purposes in various industries such as automotive, aerospace, biomedical, and construction (Ashby et al., 2000; Smith et al., 2012). Figure 2 shows the SEM images of closed and open pores structure of the metal foams. The semi-open pore is a combination of open and close pore structures. Figure 3 shows the morphology of the pores at high magnification and the image analyzer results on the morphology for metal foam. It is observed that most cells are open and interconnected to each other through the cell wall.

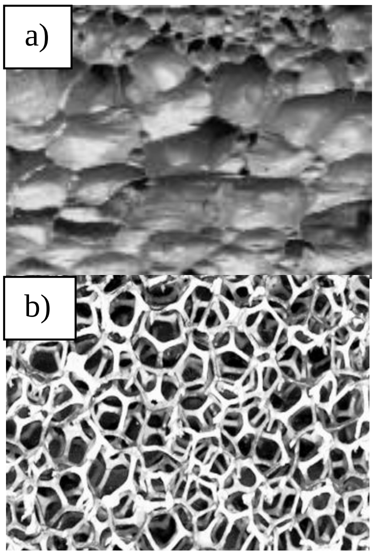

Figure 2. SEM images of closed (a) and open pores (b) structures (Yavuz, 2012)

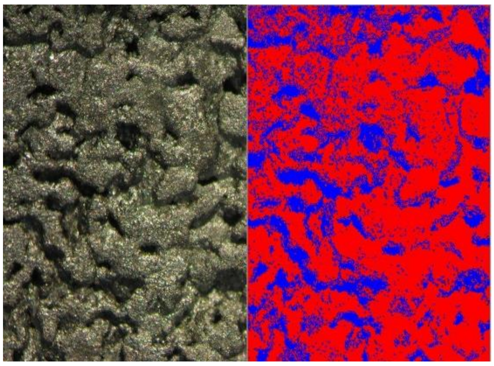

Figure 3. Optical microscope image (left) and illustration of the image analyzer software (right) of metal foam (Beköz, 2011)

Metal foams are attracted attention, especially in lightweight construction applications as an emerging class of metallic material. Metallic foams provide a combination of important properties with the intersection of the characteristic properties of both metal and foams (Feng et al., 2018). In addition to their lightness, they exhibit absorption (sound, vibration, thermal) and strength (high strength-to-weight ratio) properties (Haferkamp et al., 2004; Hokamoto et al., 2014). Thanks to these features, it is becoming widespread especially in the body in the white part of the automobiles. In 1996, the use of metallic foams in the automotive industry started with the studies conducted by Karmann Car on the use of aluminum foam sandwich (AFS) structures in automotive body parts (Banhart and Seeliger, 2008). In today, metallic foams are used in some parts of important automotive brands such as BMW, Audi, and Ferrari, but they face some problems during the commercialization phase (Garcia-Moreno, 2016; Changdar and Chakraborty, 2021). One of the most important problems of metallic foams not being widely used is welding (Shirzadi et al., 2004; Smith et al., 2012). As a result of the increase in application areas, the need for efficiently welding of metallic foam to a foam or a bulk material has arisen (Murakami et al., 2007). Welding is one of the common industrially preferred easy and inexpensive joining techniques, thus offering more applicable and cost-effective solutions for joining metallic foams. However, it is hard to weld the metal foam parts due to their porous structures. Therefore, the researches about this issue are very limited. Today, since a clear success cannot be achieved in one technique, there is a need to combine metallic foams produced with different techniques. In addition, in most of the production techniques in the production of porous parts, the size of the produced part is limited, so the shape of the part to be made is also a limiting factor in terms of welding (Ashby et al., 2000). In addition, impurities trapped in the pores of the metallic foam can impair the weldability of the part. Porosity is the most important factor in welding metallic foams. Because it is susceptible to cracking in the heat-affected zone (HAZ) during welding. It may produce low ductility near the joints, especially where porosity is limited as the inter-particle bonding zone (Selcuk et al., 2013). The foam structure tends to collapse with rising temperature, so the welding process should be done without any collapse of the foam structure (Changdar and Chakraborty, 2021). The welding of metal foam, in general, is quite complex and involves many factors to be considered. Among these, maintaining the integrity and structure of the porous structure is the main challenge. As a result, in order to obtain good weldability in metallic foams; it is necessary to understand the influence of porosity, chemical composition, contamination level of the weld metal on the weld properties (cracking, ductility, residual stresses, distortion, and toughness) (Bucher and Yao, 2018). However; studies on the welding of metallic foams are not enough in the literature. The studies that have been carried out are generally tested for the suitability of a method. In this review, it was aimed to create an efficient source for welding of metallic foams by comparing the methods in the light of the studies in the literature.

2. Welding Techniques

MIG/TIG Welding

Metal Inert Gas (MIG)/Tungsten Inert Gas (TIG) welding methods are a gas shielded arc welding technique. In these techniques, welding is performed by creating an arc between the electrode and the workpiece. The electrode, arc and welding zone are protected by an inert shielding gas (Ar, He) from the adverse effects of the environment (Vural, 2014). In the MIG welding process, a metal electrode is melted and dripped onto the joint, then materials welded by solidification of the droplets (Shih et al., 2011). The short-circuiting or dip metal transfer variants of MIG welding are appropriate to use as they provide low energy input requirements that reduce the HAZ and minimize distortion (Selcuk et al. 2013).

In the TIG welding process, non-melting tungsten is used as the electrode. Again, the welding zone is protected by an inert gas (Yao et al., 2019). These techniques are often preferred in industrial applications due to their easy applicability and low cost (Seeliger, 2002). However, in TIG welding of some foam metals, the filler metal is used to prevent shrinkage and condensation due to melting in the weld area (Changdar and Chakraborty, 2021). These techniques are not suitable for highly porous metallic foams, but suitable for welding AFS part to AFS part or AFS part to aluminum dense sheet (Shirzadi et al., 2004; Seeliger, 2002;

Busic et al., 2016). Due to the high hardness and low thermal conductivity properties of AFS parts, the thermal degradation is low (Banhart et al., 2002). The successful use of AFS parts by welding with each other is found in the literature. TIG welding process is more controllable so it can produce desired results in most cases (Selcuk et al. 2013). The schematic representation of TIG welding is given in Figure 4.

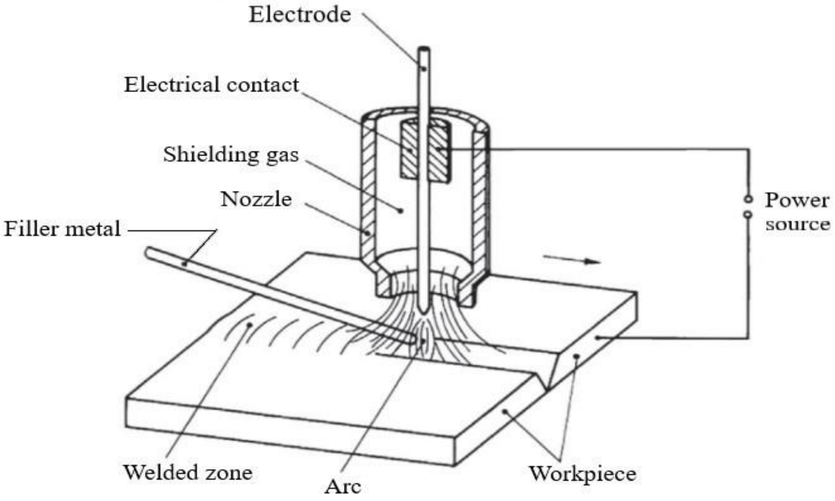

Figure 4. TIG welding process (Vural, 2014)

A spin-off company of Karmann's metal foam applications built a new lift arm on a truck by MIG welding (Banhart, 2005; Banhart and Seeliger, 2007). As part of a French / German research project, AFS parts were tested for aerospace cone section applications, were successfully welded by TIG welding (Schwingel et al., 2007; Banhart and Seeliger, 2007). In another study, Shih et al. (2011), used principal component analysis (PCA) with Taguchi methods combined with the micro-hardness and bending strength for weldment quality characteristics optimization of welded aluminum foam sheets by MIG welding. The experimental setup of the welding process performed in the study is given in Figure 5. Tests were carried out over eight control factors as filler material (Type No: 4047 and 5356), current (80 A, 90 A and 100 A), welding speed (80 mm/min, 90 mm/min, and 100 mm/min), gas flow rate (10 L/min, 13 L/min, and 16 L/min), workpiece gap (1 mm, 1.7 mm, and 2.4 mm), arcing angle (40°, 45,° and 50°), groove angle (0°, 10°, and 20°), electrode extension length (15 mm, 17 mm, and 19 mm). As a result of the optimization, 100A MIG current, 80 mm/min welding speed, 13 L/min gas flow rate, 1.7 mm gap, 50° arcing angle, 20° groove angle and 15 mm electrode extension length values were found to be optimum values with the 5356-filler material. It was observed that the bending strength S/N ratio increased by 4.3260 dB and the hardness ratio increased by 1.4995 dB in the welded parts with optimum parameters. This confirms that with optimization, weld quality can be improved and MIG welding can be used for aluminum foam panels.

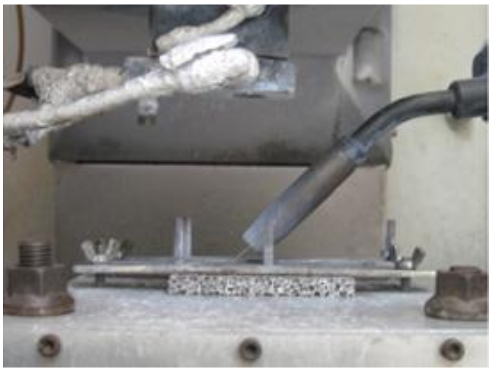

Figure 5. MIG welding process (Shih et al., 2011)

Diffusion welding

Diffusion welding is a solid-state welding technique. The parts are welded using heat and pressure for sufficient time to form diffusion and joint. The parts to be welded are placed in contact under inert gas or in a liquid. The schematic representation of the diffusion welding of metal foams is shown in Figure 6. Preferably, welding is carried out without filler material, by applying heat and pressure. Welding is formed by the diffusion of atoms at contact surfaces over time (Vural, 2014). In diffusion welding, reaction products such as oxides formed can reduce the bond strength. At the same time, high bond strength can be achieved by adding suitable elements that will activate diffusion, such as Cu, in iron-based metallic foams (Selcuk et al., 2013).

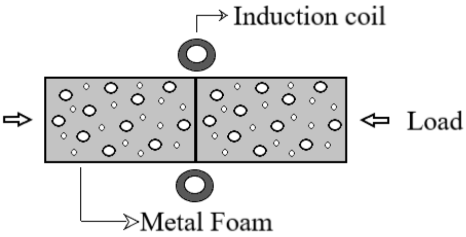

Figure 6. Diffusion welding process of metal foams (Kitazono et al., 2002)

Kitazono et al., (2002) investigated the weldability of superplastic 5083 Al-Mg alloy sheet with aluminum foam sandwich (trade name: ALPORAS) by diffusion welding in their study. The sheet was placed between the two foams and the welding process was performed by locally heating with an induction coil. ALPORAS foam and 5083 sheet were placed, the experimental atmosphere was carried out at 773° and 823° K. After raising the experimental temperature, constant stress of 0.2 MPa was applied to the foam uniaxially for 30 minutes. In the examinations made after the experimental procedure, it was observed that there was Mg diffusion from the 5083 sheet to the ALPORAS foam. Compared to adhesive bonding, it was stated that the mechanical strength is better in diffusion bonded parts at higher temperatures.

Ultrasonic welding

In the ultrasonic welding method, a combination of normal and vibratory forces is created by using moderate pressure between the two parts to be welded and oscillating motion at ultrasonic frequencies in the direction parallel to the contact surfaces. Thus, shear stresses occur, which remove surface films and ensure atomic bonding of surfaces, and welding takes place. It is seen as a suitable method for welding metallic foams and metal sheets with its relatively low welding temperature, time, and energy input. Ultrasonic metal welding systems can be varied as spot, seam, and torsion (Born et al., 2003; Born et al., 2006; Vural, 2014; Feng et al, 2018). The components of all ultrasonic welding systems are given in Figure 7.

Born et al., (2003) investigated the weldability of aluminum foams and sheets as well as the weldability of ferrous alloys to examine the applicability of the method to other foams in their study on ultrasonic torsion welding. In the study, various welds were made using AFS (Shell: 1 mm AlMn1- Core: AlSi7), foams (AlMgSi0.5, AlSi7, 316L, and GJS400) and sheets (AlMg3, Al99, AlZnMgCu0.5, DC01, and X5CrNi1810). No melting occurred in the welding of the structures containing both aluminum and iron when the welding temperature reached a maximum of 350 °C. Welding time is less than two minutes. Sheet and foam structures were successfully welded by ultrasonic torsion welding.

Later, Born et al., (2006) made a study on ultrasonic welding systems. Welding performance was investigated for AFS (Surface sheets: 1mm AlMn Core: AlSi7) and 0.5 mm thick AlMg3 alloy sheet. Welded joints were tested with monotonic shear and tension and under cyclic shear. As a result of the study, welding was made successfully in each system and optimum values were specified for each system. It has been stated that ultrasonic welding can be used for welding metallic foams in various fields such as automotive manufacturing, engineering, and construction industry, electrical or mechanical fasteners, and concluding that it involves dispersion of oxide layers, intermetallic reactions, and mechanical interlocking.

Feng et al., (2018) studied the welding of 1A99 aluminum sheet with open-pore copper foam by ultrasonic spot welding. Foam (0.2 mm thickness) and sheet (0.3 mm thickness) were tested at 10, 30, 50, and 70 J of welding energy for optimization. The experimental setup used in the welding process is given in Figure 8. Copper foam and aluminum sheet were successfully welded preventing large collapses with the USW technique. It has been stated that for welding energies higher than 30 J, the effective joint density is better, and the joint tensile strength is reduced.

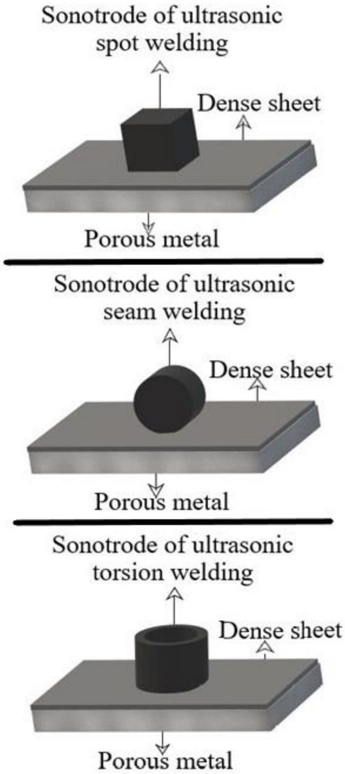

Figure 7. Ultrasonic welding systems (Born et al., 2006)

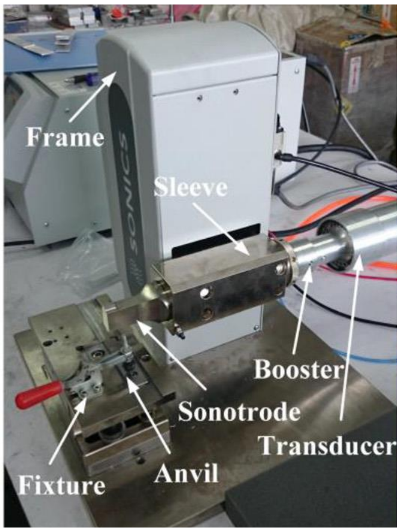

Figure 8. Ultrasonic spot welding system (Feng et al., 2018)

Friction stir welding

Friction stir welding (FSW) is a solid state welding technique. The parts are welded by pressing a rotating mandrel-like tool between the welding line of the two workpieces to be welded and applying butt joint welding along the line (Sulaiman and Emamian, 2014). Due to its advantages such as providing high quality and low energy consumption, it has recently attracted attention in the welding of metallic foams and the production of foam panels (Peng et al., 2019). FSW is considered as suitable for welding aluminum foam panels because it is a solid-state welding method with low heat input. FSW promotes pore closure, which can result in a non-porous weld interface. It is suitable for welding these parts due to its microstructural refinement for aluminum foams. In addition, the application of FSW on aluminum foam parts is beneficial in breaking an oxide layer that may form on the particles through shear deformation within the bond area. Thus, it allows to obtain better bond strength. Besides all these, In FSW, changes in microstructure occur as a result of reorientation and deformation of sintered metallic particles. This creates a potential weak zone in the joint, reducing the fatigue performance of the welded metallic foam (Selcuk et al., 2013).

Busic et al. (2016), investigated the weldability of aluminum foam sheets with AlSi1MgMn T4 cover and AlMg3Si6 core by friction stir welding. In the study, the effect of the parameters in the method on the weld joint was examined. As a result of the experimental investigations, it was stated that the applied pressure for the welding process may be lower than the compressive strength value of the foam in the core. It is stated that with a suitable design and setting of welding parameters, friction stir welding can be used to weld aluminum sandwich panels together. Su et al. (2021), welded aluminum foam precursors using friction stir welding, then foamed the precursor by applying heat treatment and examined the metallurgical structure. In the study, $AlCu_4Si_6Mg_4$ metallic powder was used as raw material and TiH_2 was used as the space holder in the core part, and aluminum foam panel precursor was produced by using 3003 alloy in the outer part. Then, the precursors were welded at a plunge depth of 0.1 mm, an inclination angle of 3°, at a welding speed of 100 mm/min, and a rotation speed of 1200 rpm. Finally, the precursors were foamed at 540 ˚C–610 ˚C for 15-20 min. As a result of the study, FSW was successfully applied. In the tests that were performed, no flaw caused by welding was observed. The schematic diagram of the study is given in Figure 9.

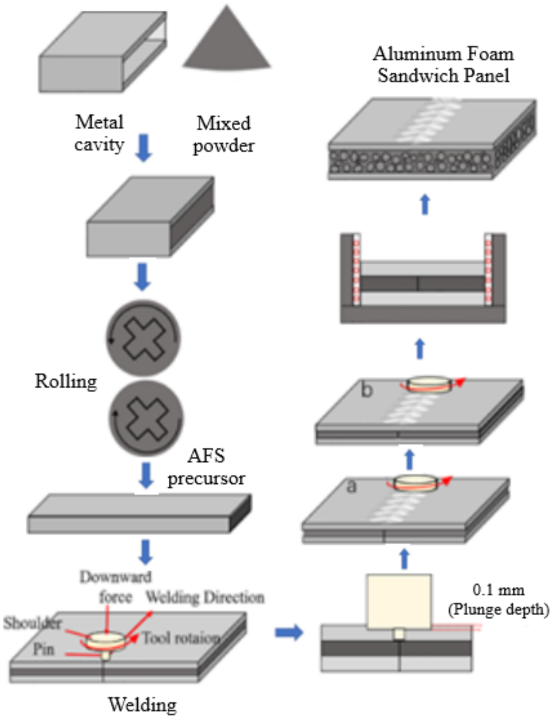

Figure 9. Friction Stir Welding Process of AFS precursor (Su et al., 2021)

Laser welding

It is the type of welding in which the energy source required for welding is provided by laser. Different types of lasers can be used for laser welding such as Nd:YAG, CO_2, diode etc. (Vural, 2014). The laser welding has a high energy density (~10^{11} W/m^2) considerably higher than conventional welding techniques such as TIG (~10^8 W/m^2) and also relatively higher than high energy density welding techniques such as plasma welding (~10^{10} W/m^2) and electron beam welding (~10^{13} W/m^2). In this way, the welding process also takes place quickly, so that a noticeable decrease in the deformation energy and as a result, the undesired deformations after welding are minimized (Vural, 2014; Metschkow, 2006). The most important reason why it is suitable for welding metal foams is that it provides locally limited energy input, so it is less in the heat-affected zone (Haferkamp et al., 2006). Thanks to its easy adjustment, energy density suitable for the sheet and foam part can be used for welding foam panels. Besides, since it is a highly automated process, it provides advantages in terms of precision and control. By increasing the depth of molten metal in the laser applied area, it prevents the formation of bubbles in the weld area, thus providing better welding strength (Changdar and Chakraborty, 2021). The schematic representation of the laser welding is shown in Figure 10.

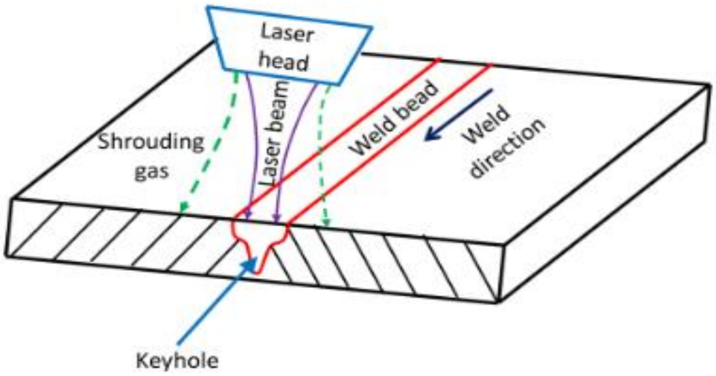

Figure 10. Laser welding process of metallic foams (Changdar and Chakraborty, 2021)

Murakami et al. (2003), used laser welding to examine the welding behavior of the lotus type porous copper foam in different pore growth directions in their first study. Welds were made at different welding speeds, perpendicular and parallel to the pore directions using Nd:YAG type laser. As a result of the study, authors stated that a smooth surface, low porosity, and full penetrated weld seam with lower laser beam power in welds performed perpendicular to the pore direction is obtained. A successful weld seam was not obtained in any of the conditions performed in the parallel direction.

Later, Murakami et al. (2006), investigated the effects of the pore growth direction of the lotus type porous magnesium foam on the weld zone profile and the mechanical properties of the joints with both experimental and numerical simulations. As a result of the study, it was determined that the melt anisotropy occurs in both perpendicular and parallel states, and the weld seam is more porous in the parallel state. The data obtained as a result of the 3D finite element analysis are compatible with the experimental results. This indicates that the melting property is related to the thermal conductivity difference caused by the pore anisotropy.

Longerich et al. (2007), aimed to find the appropriate welding method by welding the metallic foam to a composite structure by capacitor discharge and laser method to be used in a cooling system in their study. Iron and nickel-based metallic foams were more difficult to weld by capacitor discharge welding which is a resistance welding method. Failures occurred in the foams due to the need to apply high electrode force. Laser welding has been successfully implemented in metal foams. The authors stated that as a result of the experiments for the development of the mechano-technological properties of iron-nickel-based metallic foam in laser welding, its density should be higher than 2.5 g/cm^3 and its thickness should be at least 10 mm for welding.

Haferkamp et al. (2003), investigated the weldability of closed-pored AlMgSi1, AlSi7, and AlSi12 aluminum foams produced by powder metallurgy principle, and sandwich materials (core: AlSi7 cover: AlMn1). Porous aluminum structures were butt welded with both CO_2 (6 kW) and Nd:YAG (4 kW) lasers. Different types of filler materials were also tested in the study. As a result of the examinations, it has been stated that the application of pore-forming fillers is more advantageous, the welding of the porous parts and bulk parts is more stable, but the penetration depth is less.

In the study of Reisgen et al. (2010), examinations were made on laser welding by following two different bonding strategies with CO_2 laser to open-porous nickel-based metallic foams produced by slip reaction foam sintering. As a result of the study, it was stated that the foam density should be at least 2.6 $g.cm^{-3}$ and the thickness should be at least 10 mm for homogeneous permeability to ensure a successful welding of a usable foam in the cooling system.

Nowacki and Moraniec (2015), investigated TIG and laser welding of AlSi foams and AlSi–SiC composite foams in their study. In the study, the materials were examined by TIG welding, laser welding without filler and laser welding using filler. It has been stated that the results of the study, parts can be welded with all 3 welding processes, but the TIG welding method should be chosen as the last choice. The authors stated that the desired quality could not be achieved in the welds produced without the use of filler. Efficient results have been obtained in laser welding performed using filler.

Młynarczyk and Depczyński (2014), studied the laser welding of iron foam with 57% porosity and superalloy Hynes H230® sheet. Laser welding was carried out using Nd:YAG type laser. The laser welding system used in the study is given in Figure 11. Foam and sheet successfully welded. It has been determined that there is no significant diffusion of alloying elements that will affect the quality of the welded joint and the final product.

Figure 11. Laser welding system (Młynarczyk and Depczyński, 2014)

Burzer et al. (1998) investigated the production of sandwich structures by laser welding using foam, dense metal and filler metal made of various aluminum alloys. All samples were welded using Nd:YAG-Laser with a maximum power of 2 kW. It was stated that laser welding is suitable for the production of aluminum sandwich structures.

3. Conclusion

The developments and future trends presented in metallic foams illustrate the wide range of research directions for further development. Although metallic foams have unique properties, they still have not reached the expected potential in terms of usage areas today. One of the reasons for this is the inadequacy of joining techniques. The joining of metallic foam has been associated with challenges related to inherent characteristics, such as porosity, contamination, and inclusions, at levels that tend to influence the properties of a welded joint. There are limitations in welding of metallic foams due to the ability of the HAZ region to withstand stress. For these reasons, low heat input techniques are recommended for welding porous metals to reduce the stresses generated in the HAZ region and minimize the risk of shear adjacent to the weld, provided they are compatible with the composition of the metallic foam.

In this review, studies on welded joints of metallic foams in the literature were examined. The main features that should be considered for the method to be selected in welding metallic foams can be listed as follows: the chosen method should provide low energy input, no damage should occur to the foam during welding, and the area in the heat effect zone should be under control. Although traditional welding methods (TIG, MIG etc.) were considered suitable for the welding of metallic foams in previous years, it has been stated that laser welding is more suitable in recent studies and many studies have focused on this method. However, studies have an appreciable success in ultrasonic welding.

By paying attention to the important points, the use of appropriate parameters and designs, the welding problem of metallic foams can be eliminated. Also, FSW and laser welding can be advantageous as they tend to close the pores in the weld area.

In terms of welding, porosity is the most important point. Consideration should be given to the effect of pore morphology on the porous weld piece to minimize the detrimental effects of porosity in the weld and improve weldability. Pore morphology (shape, size, specific surface area) have important effects on welding characteristics such as thermal conductivity, thermal expansion, and hardenability. The developments and future trends also presented in the text show the following in foam metal welding: In order to choose the most suitable joining method, attention should be paid to the geometry, density and porosity of the weld part. Each technique has advantages and disadvantages in terms of joint configuration and features that can be obtained. Also, cost is a factor to consider.

Ethics in Publishing

There are no ethical issues regarding the publication of this study.

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