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DESIGN OF CONICAL CHANNEL IN JOINING OF AA7075/AZ91 MATERIALS BY MECHANICAL LOCKING METHOD

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Abstract

Original scientific paper

Material types with different chemical and physical properties are joined and employed in industrial applications. The main purpose is to obtain high performance products by combining the superior properties of materials. Many traditional methods such as casting, bonding, rivets and bolts and especially the welding method are used in joining processes. Among the joining methods, mechanical locking method, a novel and ecologically friendly method, stands out as a successful method, particularly when joining dissimilar metal types. Within the scope of this study, the optimization of the channel geometry was performed on the AZ91 mold part among AA7075/AZ91 material pairs joined by using the mechanical locking method. We paid attention that the channel design did not adversely affect the stress values and facilitated the material flow. In the analysis, fixed joint angle and fixed channel depth determined in accordance with the data obtained from the results of the previous studies were used. The analyses were completed by the Static Structural Module of the Workbench 18.2 version of the ANSYS software using the finite element method. The study was carried out on 3D geometric models. As a result, it was determined that the mechanical properties of the samples joined by mechanical locking method significantly changed depending on the channel design. The mechanical properties of the joint improved by approximately 3% with the optimal joint design, while the joint design that will facilitate material flow was achieved.

Keywords: *AA7075, AZ91, finite element method (FEM), mechanical locking method (MLM), mechanical properties.*

MEKANİK KİLİTLEME YÖNTEMİ İLE BİRLEŞTİRİLEN AA7075/AZ91 MALZEMELERİN KONİK KANAL TASARIMI

Özet

Orijinal bilimsel makale

Endüstriyel uygulamalarda, farklı kimyasal ve fiziksel özelliklere sahip malzeme türleri birleştirilerek kullanılmaktadır. Temel amaç malzemelerin üstün özelliklerini bir araya getirerek, yüksek performanslı ürünler elde edilmesidir. Birleştirme işlemlerinde kaynak yöntemi başta olmak üzere döküm, yapıştırma, perçin ve civata ile birleştirme gibi geleneksel birçok metod kullanılmaktadır. Birleştirme yöntemleri arasında yeni ve çevreci bir yöntem olan mekanik kilitleme yöntemi de özellikle farklı metal türlerinin birleştirilmesinde başarılı bir yöntem olarak öne çıkmaktadır. Bu çalışma kapsamında, mekanik kilitleme yöntemi ile birleştirilen AA7075/AZ91 malzeme çiftlerinden kalıp parçası AZ91 üzerindeki, kanal geometrisinin optimizasyonu yapılmıştır. Kanal tasarımının gerilme değerlerini olumsuz etkilemeden, ve malzeme akışını kolaylaşıracak biçimde olmasına dikkat edilmiştir. Analizlerde daha önce yapılan araştırma sonuçlarından elde edilen verilere uygun olarak belirlenen sabit bağlantı açısı, sabit kanal derinliği kullanılmıştır. Analizler sonlu elemanlar yöntemini kullanan ANSYS paket programının Workbench 18.2 sürümü, Static Structural Modülü kullanılarak tamamlanmıştır. Tüm çalışma 3 boyutlu geometrik modeler üzerinden gerçekleştirilmiştir. Sonuçta mekanik kilitleme yöntemi ile birleştirilen numunelerde kanal tasarımına bağlı olarak mekanik özelliklerin önemli oranda değiştiği tespit edilmiştir. Optimum bağlantı tasarımı ile bağlantı mekanik özellikleri yaklaşık %3 oranında artarken, malzeme akışını kolaylaştıracak bağlantı tasarımı elde edilmiştir.

Anahtar Kelimeler: *AA7075, AZ91, sonlu elemanlar yöntemi (FEM), mekanik kilitleme yöntemi (MLM), mekanik özellikler.*

1 Introduction

There are several methods in which dissimilar materials are joined using different methods according to their application areas. They are applied due to the needs associated with the place of use or in order to attain the desired mechanical properties. Among these methods, Mechanical Locking Method (MLM) is an alternative novel and ecologically friendly method for joining material types with different chemical and physical properties. The method allows ferrous materials to be easily joined with nonferrous metals, composite materials, and ceramic

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materials. Also, some problems that occur in traditional joining methods due to thermal cycles may be avoided.

Given that new production processes and the use of advanced design and construction technologies are critical in terms of the environment, quality of life and the development level of countries [1], the need for innovative and eco- friendly methods such as MLM will increase even more. In MLM, the joining process is realized by using the plastic deformation property of one of the joined materials [2]. The mold geometry examined in this study is known to be the most important factor affecting the material flow and distribution of end-product thickness in studies on plastic deformation methods [3]. MLM is similar to friction welding and forging methods based on the plastic deformation method in terms of the forming principle. As in the forging method, plastic deformation processes are carried out using heat and pressure. Direction of metal flow, degree of deformation, friction, and temperature all have a significant impact on the properties of the workpieces throughout the forging process, in order for the metal to deform without breaking or cracking [4]. In MLM, friction, heat and proper material flow are among the main factors in achieving the desired properties in the joint. The most important points of the process are material flow control and mold design [5] as in other plastic deformation methods. Stress concentrations and cracks caused by faulty mold design have a direct impact on the life of the joint and adversely affect the mechanical properties. Therefore, it is required to investigate the zones of stress concentrations at the joint and to determine the proper joint profile with all of the details. Thus, the effect of the profile on the post-production mechanical values may be determined in the joint as a consequence of plastic deformation, and necessary modifications can be made in the design [1]. As a result of these modifications, the joint strength will be increased to the desired values and the industrial application of the method will be ensured. Among the studies on plastic deformation methods, Başdemir et al., examined the effects of plastic deformation on the mechanical and physical properties of materials joined using forging technique together with analysis examples. They found that there were stress concentrations in cross-sectional deformation zones and force requirement increase. Their data were matched with the simulation data [5]. Kodippili et al., in their study on magnesium alloy beam, reported that an appropriate mold design was required to promote metal flow in closed mold forging processes [6]. On the other hand, studies have reported problems such as expensive and complex processes required by the forging method in joining of materials, the significance of surface preparation, determination of thermal cycle values that will not cause structural changes in both metals, and formation of intermetallic compounds [7].

In the analyses made in this study, the mechanical properties of Al and Mg alloy materials were utilized. Al and Mg alloys have excellent formability capabilities as well as high recycling potential, and their mechanical properties vary considerably [8]. The differences in their physical and chemical properties make it difficult to join these materials by traditional methods. The formation of $Al_{12}Mg_{17}$ and Al_3Mg_2 brittle and hard intermetallic phases, particularly in welded joints requiring high temperatures [9,10], results in impaired mechanical properties as a consequence of joining materials. Furthermore, it causes dynamic recrystallization of the material in the seam zone, formation of pores in heat-affected zones, and changes in hardness value [11,12]. This makes the widespread use of these materials in the industry impossible by joining them [13,14]. Mg alloys, the lightest metal, are commonly produced by using the casting method; however, since they have no desired full dense structure and contain segregation, further processes are required for Mg alloys produced by casting method. Additional normalizing, sintering, and pressure are necessary during the production process to improve density. Therefore, it is believed that if MLM, which uses heat and pressure together, is preferred for joining Mg alloys, the requirement for these additional processes would reduce and its industrial utilization would increase. In industrial applications, finite element techniques allowing realistic simulation in a computer environment are used instead of direct production of a selected process in the application region. Cost benefit and an enhanced quality are provided in industrial applications through the studies using finite elements analysis. The ANSYS software is one of the simulation programs that use the finite element method and analyze the problems encountered in the field of engineering. In the literature, it has been stated that the numerical method results to be used in the analyses are compatible with even the most complex experimental results [15]. Hou et al., used experimental and numerical analysis to examine the mechanical properties and residual stresses of AA2024 and AZ31 alloys by using the friction stir welding method. They reported a good correlation between experimental and numerical results [16]. Mercan used the ANSYS program to carry out the stress analysis of the materials joined using the MLM. Consequently, he reported that the maximum stress distribution caused damage in the experimental studies, the cross-section narrowed on the RP (reshaped part) and occurred in areas with sudden cross-sectional changes [17]. Nalawade et al., used FEM-based packaged programs to simulate the thermo-mechanical rolling of steel blooms. They investigated how rolling parameters affected deformation behavior [18].

In the present study, an optimal conical channel design was performed in joining dissimilar alloys (AA7075/AZ91) by MLM.

2 Material Method

2.1 Mechanical Locking Method (MLM)

The patent studies (numbered TR201503256B) on the method were completed in 2017, and methodological studies for its use in various industrial sectors have been continuing [2]. In the method, one of the materials to be joined is designed as a mold part (MP) and the other material is designed as a reshaped part (RP). The design of RP varies based on the MP channel space. A conical, T or spherical channel is opened into the MP by using machining or casting methods. As shown in Figure 1, the friction of RP on MP cavity interface, as well as applied additional axial pressure enable the channel section to be shaped. Friction welding machines and milling machines may be used for this purpose. The friction of the pieces generates the heat necessary for RP to take the mold form. Thus, the heat generated by transforming the mechanical energy produced in the system into thermal energy is used. The friction continues until the plastic deformation temperature is obtained. With the impact of additional axial pressure, RP begins to agglomerate. The joining is achieved by allowing the agglomerated material to flow in the mold and take the mold form. The joint forming by the heat generated at the interface and the applied pressure is not a welded joint, but rather a mechanical joint method [19].

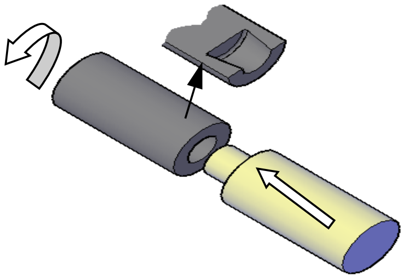


Figure 1. Schematic View of MLM.

The part with low mechanical properties and a low melting temperature is determined as the reshaped part (RP). The other is designed as the mold part (MP). In this study, AA7075 was designed as MP and AZ91 as RP. Figure 2 shows a sectional view of the physical parts of MP and RP in MLM.

The environmentalist aspect of the method includes no waste generation and no need for further process, the accomplishment of joining processes in a very short time, controllable parameters, no need for additional joint and filler metal, as well as its compliance with automation.

2.2 Joining Parameters

MLM parameters are friction time, revolutions per minute, and friction pressure. The channel depth, joint angle, and channel corner radii of the mold part, which have a significant effect on joint quality, must be determined separately for each material type [20]. The physical properties of the channel were optimized in this study in order to increase the mechanical properties of the joint, facilitate material flow, and avoid buckling. Figure 3 shows the model dimensions of the samples to be joined using MLM. Table 1 shows values of the joint profile. the depth of the conical channel and the joint angle were determined based on previous studies. It was found that the joint angle was 10° and the channel depth 13 mm [17].

In the joint, first of all, the end radius values of the channel (r_1) were examined. Then, the compatibility of the corner radius (r_2) values of the channel with the r_1 values was investigated in order to facilitate the material flow. The r_1 values were the region where stress concentrations were the highest, depending on changes in cross-section. Therefore, r_1 values were investigated independently.

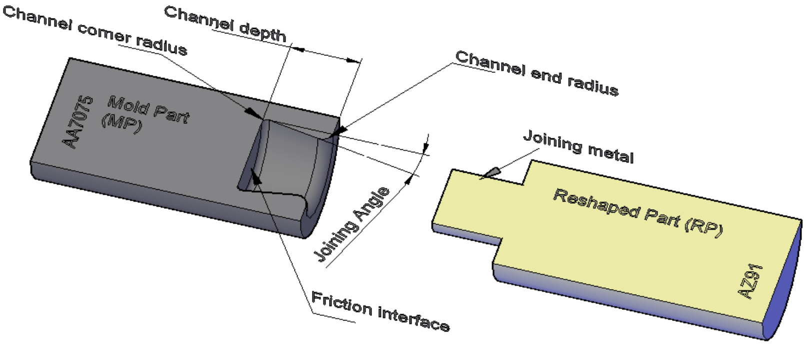


Figure 2. Sectional views of MP and RP.

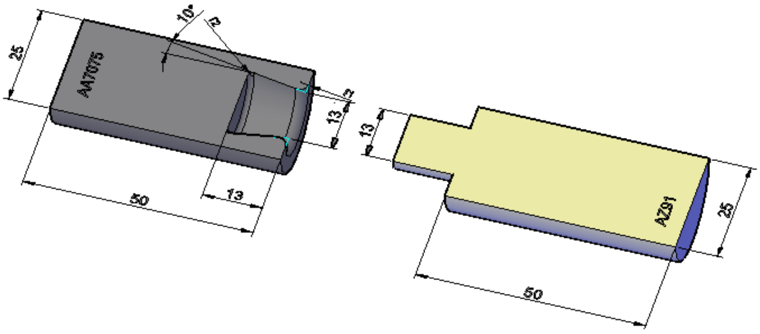


Figure 3. Joint profile values.

Table 1. Joining profile values (mm).

	S1	S2	S3	S4	S5	S6	S7	S8
Joining angle (°)	10							
Channel depth (mm)	13							
Channel end radius (r_1) (mm)	1	2	3	4				
Optimum channel end radius according to analysis results (Opr$_1$)					Opr$_1$			
Channel corner radius (r_2) (mm)					1	2	3	4

2.3 Materials

In the study, the joined material pair was AA7075 aluminum alloy and AZ91 magnesium alloy. Since AA7075 has greater hardness and mechanical properties than AZ91, it was designed as MP; whereas AZ91 was designed as RP. Table 2 shows the mechanical properties of the materials used in the analyses.

Table 2. Mechanical properties of AA7075 and AZ91.

	AA7075	**AZ91**
Intensity (gr/cm^3)	2,81	1,7
Modulus of elasticity (MPa)	71000	45000
Poisson rate	0.33	0.35
0,2% Yield strength (MPa)	503	168
Ultimate tensile strength (MPa)	572	311
Hardness (HV)	175	90

2.4 ANSYS Packaged Program Analysis

The Static Structural Module of the ANSYS package software Workbench 18.2 version was used to do stress analyses. The Von Mises maximum stress values and maximum deformation zones were determined in the stress analyses under static load, and the assessments were completed.

There is no joining at atomic level between the joined material pairs in MLM, as in welding and casting methods. Therefore, the joint type was defined as “No Separation,” and the parts were not separated in the normal direction, but they were allowed to execute a limited sliding motion over each other [17,21]. The contact points of the parts are indicated by the red and blue areas in Figure 4.

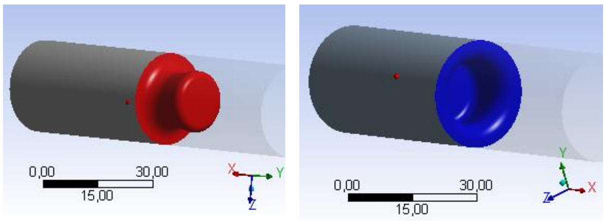


Figure 4. Contact points.

To form a precise mesh structure, the Relevance Center value was set to 100 for the mesh size in all parts. The mesh size was set at 0.75 mm using the Adaptive mesh structure setting. Also, the slow selection was used in mesh transitions to provide a unique mesh distribution. Figure 5 shows the RP mesh structure. Mesh processes were completed using 680838 nodes and 482279 elements in sample no. S1.

The definition of fix support was made by AA7075 for parts in all of the analyses. The analyses were done by using the AZ91 magnesium alloy to exert force in the axial direction (in the direction of the +X axis). The stress-deformation behaviors derived from the uniaxial tensile test were taken into account. The tensile strengths were taken into account while determining the damage load in the analysis, and the damage load was determined in such a way that it would be the maximum tensile stress of the base material AZ91 magnesium alloy and the stress values may be noticed clearly on the color scale. A force of 75000 N was applied, and the stress distributions were determined

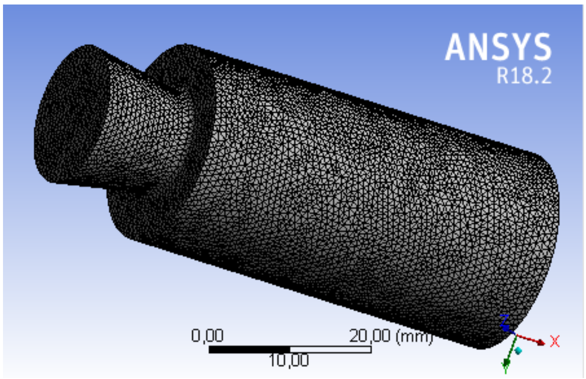


Figure 5. Mesh of RP.

3 Analysis Results

As stated in the literature, the materials in this study were recognized as having non-heat conduction and being rigid in static analysis studies [22], and analysis was done on the assumption that there was no error in the material flow and no residual stress throughout the process. MP depth and angle values were determined based on previous studies [17]. The analyses were done in two phases. First and foremost, it was intended to reduce the stress distribution by creating the channel end radius (r_1) on the MP. Then, based on the results, the optimum r_1 value (Opr_1) was taken as a fixed value and the necessary examinations were completed with the changing corner radius (r_2) values of the channel. While the optimum r_1 value was examined in order to reduce the stress values, the r_2 values were investigated in order to facilitate the material flow. In MLM, the material flow is of special importance in obtaining the RP with the desired properties [20]. Therefore, the r_2 value should be determined at values that will not impair mechanical properties while facilitating material flow.

The maximum stress values came out in the zone where the cross-section was the narrowest on the joint metal in the absence of radius [17]. On the other hand, the maximum stress values appeared at the radius start and end points in the samples with radius. Figure 6 shows the maximum stress zones on sample no. S1. The analysis findings were displayed on RP since it had weaker mechanical properties than the other two materials and was reported to be damaged in the experimental studies [17,19]. It has been reported in the literature that significant stress concentrations and force requirements arise in the sectional deformation zones if the plastic deformation method is used [5].

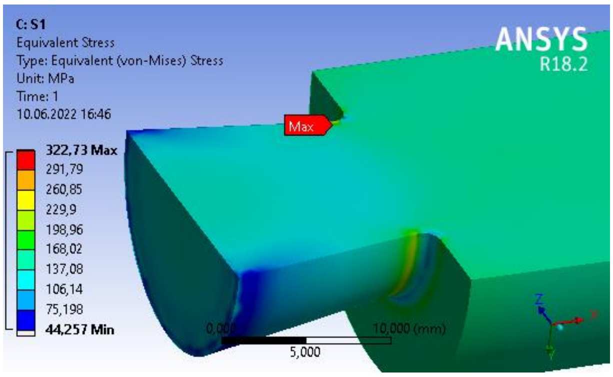


Figure 6. Maximum stress distribution zones.

Figure 7 graphically shows the stress distributions generated with different end radius values of the channel. This graph also shows the stress value (REF) that appeared when there was no radius on the joined samples. The stress distribution according to the determined damage load in the absence of radius was reported to be 321.05 MPa [17].

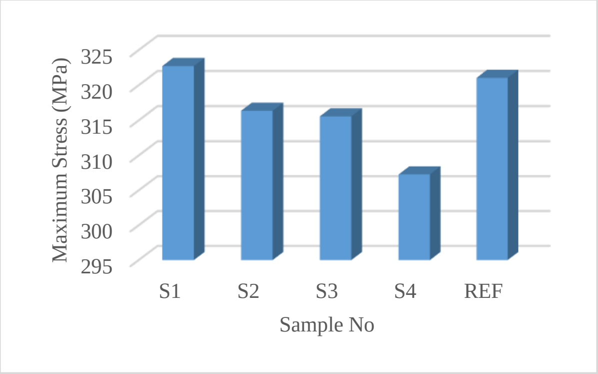


Figure 7. Maximum stress values of S1, S2, S3, S4 and REF.

The maximum stress distribution in the radius samples was determined to be 322.73 MPa in sample no. S1. The given value was very close to the stress value in the non-radius REF sample. This happened due to an increase in stress concentrations at the radius start and end points, as well as the narrow-area (Figure 6). The end radius of the channel reduced stress values in all of the other samples. The lowest stress value was 307.29 MPa in sample no. S4. In the analyses, the increase in the radius values of r_1 increased the cross-section that will bear the stresses and made the stress distribution more regular. Depending on the increased cross-section and proper force flow, the stress values reduced.

Figure 8 shows the stress distributions on the sectioned sample no. S4. It was observed that the stress concentration increased at the radius start and end points, but the stress was regularly distributed over the entire section. The mechanical properties of the joined materials could be improved with the proper designs to be used in the MLM. This is confirmed by the fact that the stress value in sample no. S4 was 4% lower than the non-radius sample. The r_1 value (4mm) of sample no. S4 was used as a constant value in the samples S5, S6, S7, and S8.

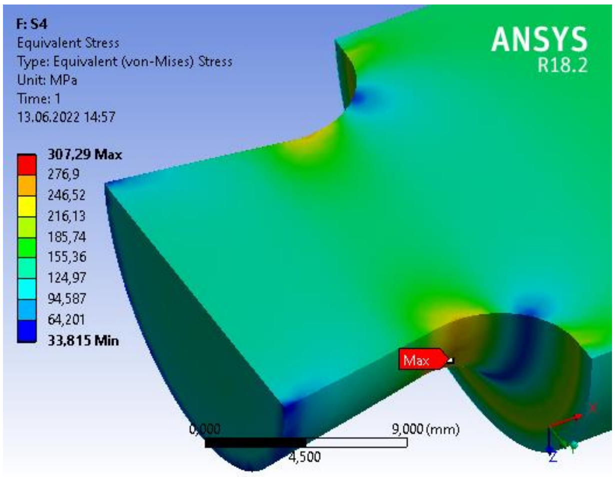


Figure 8. Stress values of S4.

The r_1 value in samples S5, S6, S7, and S8 was determined to be 4 mm based on the results of the analysis. Figure 9 graphically shows the stress values of these samples with the channel corner radius (r_2). The stress values for sample no. S4 with the optimum r_1 value and the model from which REF was taken were displayed together. The primary goal in the analysis of these samples is to determine the optimum design that will facilitate the material flow without impairing the mechanical properties in the joining process. Because it is well-known that during the plastic deformation process of RP, the flow becomes difficult due to the rapid cooling and solidification of the flowing material [20]. The presence of radii in the channel instead of sharp corners will facilitate the flow of the material solidified by rapidly cooling as it passes away from the friction interface.

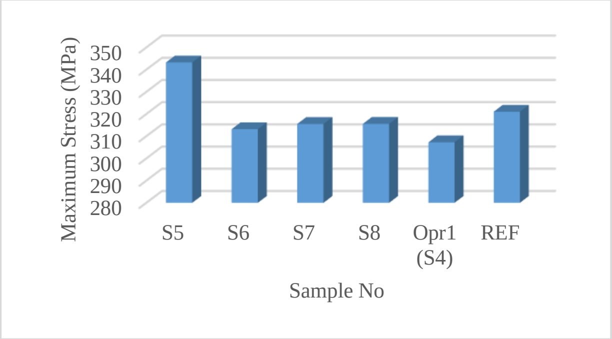


Figure 9. Maximum stress values of S5, S6, S7, S8, Opr_1 and REF.

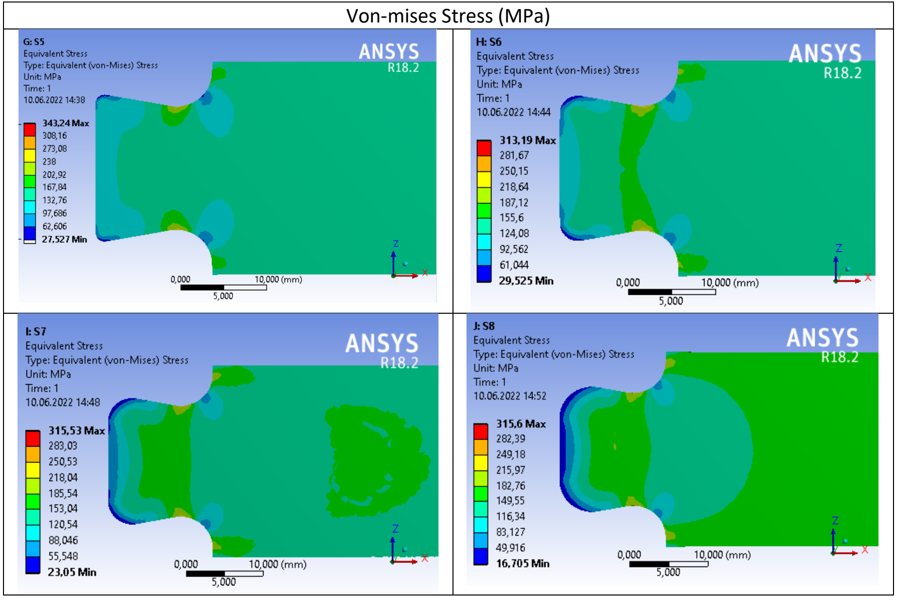
Except for sample no S5, the stress value of the other samples was lower than that of the non-radius sample (REF). It was determined that radius values less than 2 mm affected the stress distribution negatively due to stress concentrations that occurred at the radius start and end points, and it would be more appropriate to have no radius.

The stress values in all samples were higher than sample No. Opr_1. While sample no. S5 had the highest stress value (343.24 MPa), sample no. S6 had the lowest stress value of 313.19 MPa. This is thought to be associated with the small radius value in sample no. S5, as well as the insufficient force flow and stress concentration in sample no. S1. The r_2 values, on the other hand, reduced the material cross-section. Decreased cross-section caused a slight increase in stress values. Nonetheless, the r_2 value of 2 mm (sample no. S6) was appropriate for facilitating material flow, producing a joint metal with no porosity, and avoiding buckling as the stress values were very close in samples S6, S7 and S8. However, as a result of the metallurgical analyses of the experimental studies, increasing the radius value based on the quantity of porosity generated should be assessed.

Table 3 shows the stress distributions of samples S5, S6, S7, and S8 on sectioned samples. It is noticed that the stress distribution decreased in the flange region at the friction interface and became more regular with increased radius values. It was thought that this would allow the flanges, which have been formed with increased radius values, to flow faster.

The overall deformation values in all samples were very close to each other in the examinations. Figure 10 shows the deformation values on sample no. S8.

Table 3. Stress distributions of S5, S6, S7, and S8.



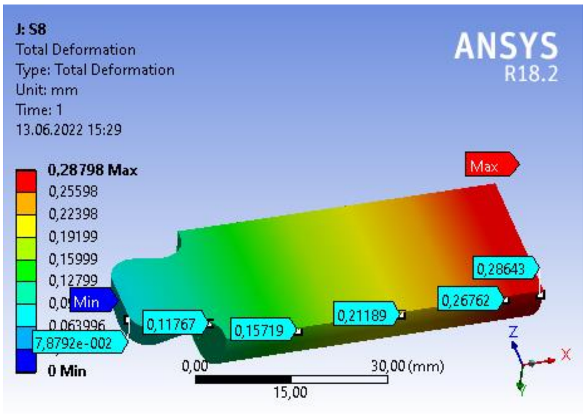


Figure 10. Deformation values of S8.

4 Conclusions

In this study, the material pairs AA7075 Aluminum alloy and AZ91 Magnesium alloy were joined utilizing the MLM. It was tried to determine the optimum channel design using different channel geometries. The examinations yielded the following conclusions.

- Mechanical properties lowered by 3% in MLM depending on the joint design, and a joint design that facilitates material flow was obtained.
- It was determined that the appropriate channel end radius decreased the stress values in all the samples.
- The highest stress value was obtained as 343.24 MPa in sample S5. The main reason for high stress is that radius values are not compatible with each other.
- The lowest Von-Mises stress value among the samples with channel end radius (r_1) was 307.29 MPa in sample no. S4. This value was 4% lower than the reference model without radius.
- The lowest Von-Mises stress value among the samples with channel end radius (r_2) was 313.19 MPa in sample no. S6. The corner radius values of the channel slightly increased the stress values; however, the raised stress values were at an acceptable level since they facilitated flange formation.

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Declaration

Ethics committee approval is not required.

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