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Mechanical Properties and Deformation Behavior of Al/Al-SiC Double-Walled Composite Pipes Under Radial Loading

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Keywords

Double-walled pipe,
SiC,
Extrusion,
Flattening test

Abstract: Composite materials are produced in different material structures depending on their production purposes. This study aimed to produce a circular profile material with partially preserved deformation capability while increasing its strength properties. The composite material was produced with double walls and the outer wall consisted of Al6061 (6061 aluminum alloy) and the inner wall consisted of Al2124-SiC (2124 aluminum alloy-silicon carbide) metal matrix composite. Material variables were the variation of wall thicknesses and SiC reinforcement ratios. The materials were produced in 3 different wall configurations with inner and outer wall thicknesses of 1.5-0.5 mm, 1-1 mm, and 0.5-1.5 mm, respectively. SiC reinforcement ratios were determined as 3, 7, and 11%. The materials were produced by the extrusion method and extrusion variables such as temperature (500 ˚C) and die angle were kept constant. The produced materials were exposed to flattening tests. According to the test results, the flattening resistance of the materials increased with the SiC reinforcement in the inner layer and with the increase in the reinforcement ratio. This increase started to decrease at the 11% reinforcement rate. Likewise, the strength, which increased with the increase in the thickness of the inner wall, decreased as the inner wall reached its highest value. While the Al6061 material, which has a ductile structure, did not show any failure in full flattening, with the increasing inner wall thickness and SiC ratio, failures occurred in double-walled materials both in the lateral regions and at the material-jaw contact points.

Al/Al-SiC Çift Cidarlı Kompozit Boruların Radyal Yüklemeler Altında Mekanik Özellikleri ve Deformasyon Davranışları

Anahtar Kelimeler
Çift katmanlı boru
SiC,
Ekstrüzyon
Yassıltma testi

Öz: Kompozit malzemeler üretim amaçlarına bağlı olarak farklı malzeme yapılarında üretilirler. Bu çalışmada mukavemet özelliklerinin arttırılması ile beraber şekil değiştirme kabiliyeti kısmen korunan bir dairesel profil malzeme üretilmesi amaçlanmıştır. Malzeme çift cidarlı üretilmiş olup dış cidar Al6061, iç cidar ise Al2124-SiC metal matrisli kompozitten oluşmaktadır. Malzeme değişkenleri cidar kalınlıklarının ve SiC takviye oranlarının değişimidir. Malzemeler, iç-dış cidar kalınlıkları sırasıyla 1.5-0.5 mm, 1-1 mm ve 0.5-1.5 mm olacak şekilde 3 farklı kalınlıkta üretilmiştir. SiC takviye oranları % 3, 7 ve 11 olarak belirlenmiştir. Malzemeler ekstrüzyon yöntemi ile üretilmiş olup sıcaklık (500 ˚C) ve kalıp açısı gibi ekstrüzyon oranları sabit tutulmuştur. Üretilen malzemeler radyal yönde yüklemelere maruz bırakılarak yassıltma testlerine tabi tutulmuşlardır. Test sonuçlarına göre iç katmandaki SiC takviyesi ve takviye oranının artması ile malzemelerin akma dirençleri artmıştır. Bu artış % 11 takviye oranında düşmeye başlamıştır. Aynı şekilde iç cidarın kalınlığının artması ile artan mukavemet iç cidarın en yüksek değerine çıkması ile düşüş göstermiştir. Sünek bir yapıya sahip olan Al6061 malzeme tam yassılmada kırılma hasarı göstermezken artan iç cidar kalınlığı ve SiC oranı ile birlikte malzemelerde hem yanal bölgelerde hem de temas noktalarında kırılmalar oluşmuştur.

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1. Introduction

Particle-reinforced metal matrix composites are used in many areas due to their superior properties. The main features of these are high strength, low density, and high wear resistance [1,2,3]. In metal matrix composites, materials such as aluminum, magnesium, and copper are preferred as the metal phase because of their good forming and strength properties, and ceramic particles such as Al2O3, SiC, and B4C are preferred as the reinforcement phase due to their high hardness, low density, and good strength properties [4, 5, 6, 7]. Metal matrix composites are produced in different structures. Radial plain bearings, shafts, sheet, and plate forms can be given as examples [8, 9, 10]. In addition, composite materials are produced in hollow circular or square cross-section profile forms. The studies of Mahmoodi and others on Al-SiC pipe can be given as an example [11]. In this study, the researchers used the friction stir-back extrusion method to produce Al-SiC Composite Tube materials and examined the mechanical properties of the composites they obtained. Profile materials with improved strength values and reduced intensity can be used as chassis material in vehicles such as bicycles and motorcycles where these features are important.

With the addition of ceramic particles, metal matrix composites exhibit improved strength values up to a certain proportion of particles [12]. Along with increasing strength, ceramic particles, whose structure is quite rigid, also increase the rigidity of the composite material [13]. By producing metal matrix composites in layers, the properties of the material such as rigidity, hardness, and toughness can be balanced or changed at different rates along the material cross-section [14]. There are also studies examining the strength properties and ballistic behavior of metal matrix composites produced in layers [15]. This study focuses on a circular composite material produced layer by layer. In this study, SiC-reinforced Al2124 metal matrix pipe profile material was layered by coating Al6061 on its outer surface. Thus, it was aimed to produce a more ductile composite material compared to the without-layer structure. In the production of double-walled materials, some methods can be used like explosion welding [16], magnetic pulse cladding [17], and extrusion [18]. In this study, mandrel -supported extrusion method was used in the production of composite materials due to the suitability of the shaping properties of the materials. Flattening tests of this material were performed to examine how its stiffness and deformation pattern changed.

2. Material and Method

The outer wall of the double-walled pipes produced within the scope of the study was Al6061, and the inner wall was Al2124-SiC metal matrix composite. Al6061 was preferred as the outer layer because it is a more ductile aluminum alloy (Table 1). Al2124 is an aluminum alloy with high mechanical properties and is suitable for plastic forming (Table 2). For this reason, it was thought that the use of the inner layer would be appropriate. In metal matrix materials, SiC is frequently used with Al alloys as a reinforcement material and gives very good results in terms of strength. Al6061 and Al2124-SiC were combined with three different thickness values. The total wall thickness of the pipes was 2 mm, and these layers were set as 1.5-0.5, 1-1, and 0.5-1.5 mm, respectively (Fig. 3). The SiC reinforcement ratio in the inner layer was determined as 3, 7 and 11% by volume fraction. Al2124 and SiC powders were combined in these ratios and mixed in a three-dimensional ball mixer for 2 hours. SiC ceramic particles with an average particle size of 20 µm and Al2124 powder with an average particle size of 40 µm were used in a single size (Fig. 1). Composite materials were produced by the mandrel-assisted extrusion method (Fig. 2). For this process, extrusion billets were prepared using the powder-in-tube method. For this, firstly, a mandrel was placed inside the Al6061 tubes, and Al2124-SiC powder mixtures were compressed under the press between the mandrel and the Al6061 tube. The prepared billets were sintered at 500 °C for 2 hours and then extruded at the same temperature. The obtained materials and material variables are shown in Table 3.

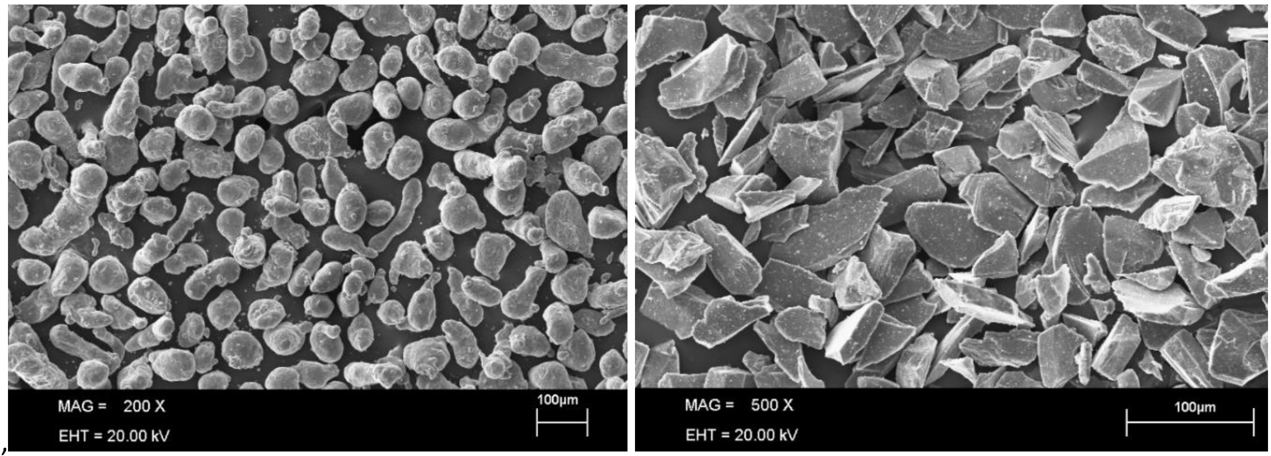


Figure 1. SEM images of a) Al2124 powder, b) SiC particles

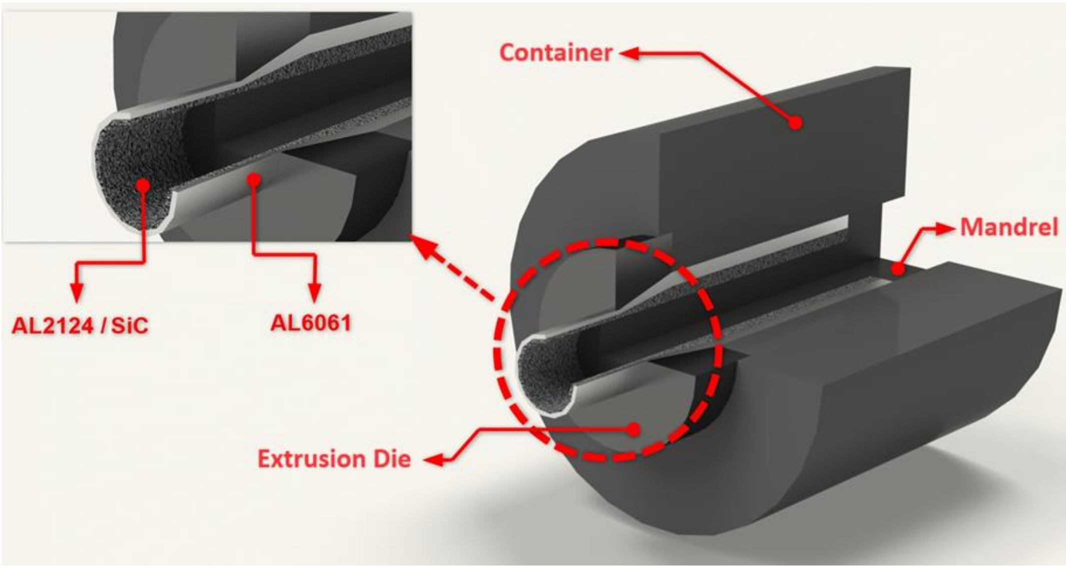


Figure 2. Application principle of mandrel-assisted extrusion method.

Table 1. Chemical content of Al2124 (wt %)

Fe	*Si*	*Cu*	*Cr*	*Mn*	*Mg*	*Zn*	*Al*
0.23	*0.76*	*2.99*	*0.01*	*0.21*	*0.76*	*0.08*	*94.57*

Table 2. Chemical content of Al6061 (wt %)

Al	*Cr*	*Si*	*Cu*	*Mn*	*Mg*	*Zn*	*Ti*	*Fe*
95.8-98.6	*0.04-0.35*	*0.4-0.8*	*0.15-0.4*	*0.15*	*0.8-1.2*	*<0.25*	*< 0.15*	*< 0.7*

Table 3. Produced composite materials and production variables

Composite Codes	*Material of outer wall*	*Outer wall thickness (mm)*	*Material of inner wall*	*Inner wall thickness (mm)*	*SiC ratio in inner wall (%)*
Al6061	*Al6061*	*2*	-	-	-
1_0	*Al6061*	*1,5*	*Al2124*	*0,5*	*0*
1_3	*Al6061*	*1,5*	*Al2124/SiC*	*0,5*	*3*
1_7	*Al6061*	*1,5*	*Al2124/SiC*	*0,5*	*7*
1_11	*Al6061*	*1,5*	*Al2124/SiC*	*0,5*	*11*
2_0	*Al6061*	*1*	*Al2124*	*1*	*0*
2_3	*Al6061*	*1*	*Al2124/SiC*	*1*	*3*
2_7	*Al6061*	*1*	*Al2124/SiC*	*1*	*7*
2_11	*Al6061*	*1*	*Al2124/SiC*	*1*	*11*
3_0	*Al6061*	*0,5*	*Al2124*	*1,5*	*0*
3_3	*Al6061*	*0,5*	*Al2124/SiC*	*1,5*	*3*
3_7	*Al6061*	*0,5*	*Al2124/SiC*	*1,5*	*7*
3_11	*Al6061*	*0,5*	*Al2124/SiC*	*1,5*	*11*

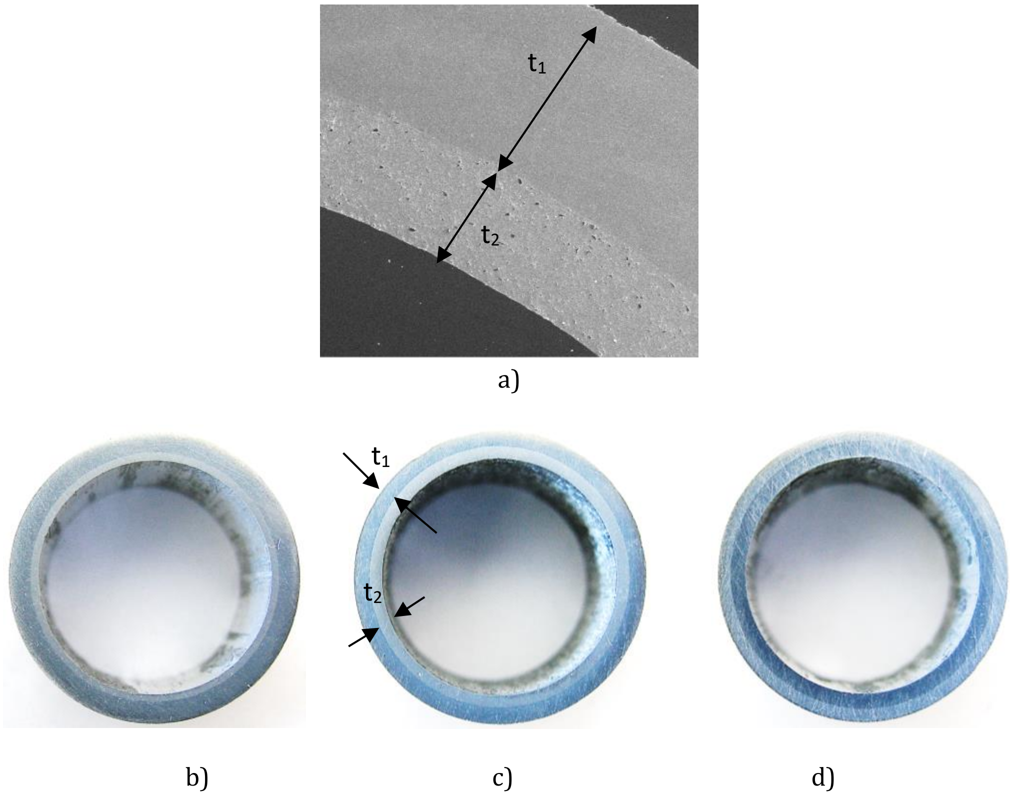


Figure 3. Cross-sectional images of composite pipes with different wall thicknesses, a) SEM image of the wall structure of the material, b) t_1=1.5 mm t_2=0.5 mm, c) t_1=1 mm t_2=1 mm, d) t_1=0.5 mm t_2=1.5 mm

In the flattening test, samples are carried out by applying compression tests on the radial axis of the material in tensile-compression testing devices (Fig. 4). With this test, the strength of the welding areas of welded pipes or the radial deformation ability of the materials can be observed [19, 20]. Therefore, in this study, flattening tests were applied to see the stress and strain properties of composite pipes in the radial direction. Samples were cut from the produced composite materials with 16 mm wide for flattening tests. The flattening tests were carried out according to ISO 8492 standards [21] with the MTS Tensile-Compression test device.

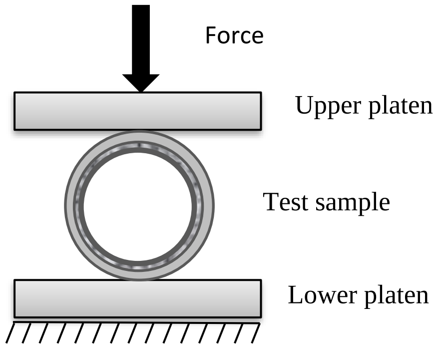
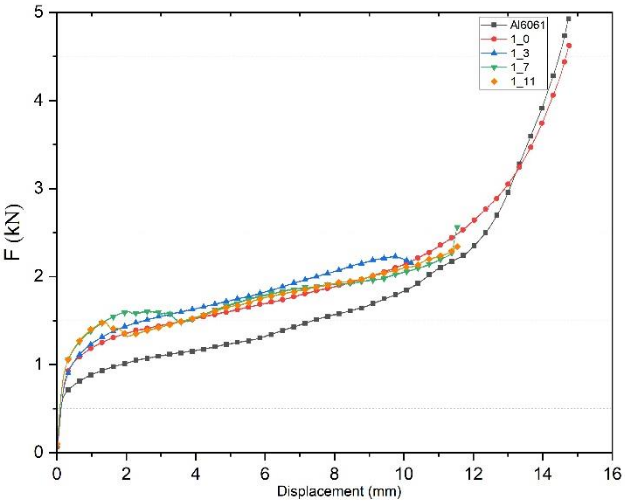


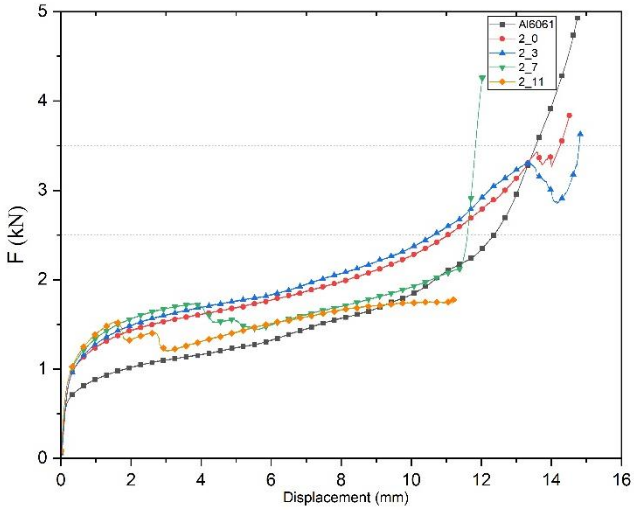
Figure 4. Application principle of the flattening test

3. Results

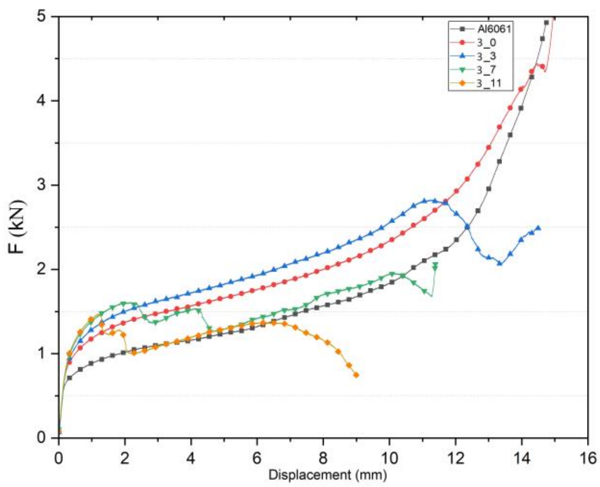
Flattening test curves of composite pipe samples were drawn with force-deformation values. The results were evaluated based on the change of SiC reinforcement ratio at equal wall thickness and the wall thickness changes at constant SiC ratios. In materials with thick outer walls, the resistance to radial forces increased as the materials were double-walled and the SiC reinforcement on the inner wall increased (Fig. 5). This increase was achieved because of Al2124 which has better mechanical properties than Al6061 and thanks to SiC reinforcement. At constant wall thicknesses, the flattening resistance of the materials increased with the increase of SiC reinforcement and reinforcement ratio. This situation was observed at three wall thickness ratios (Fig. 5a-c). However, it was seen from the curves that as the thickness of the inner wall increased, the plastic deformation rates decreased and the number of damage formations increased. Another situation observed in materials reinforced with SiC was the change in the damage pattern. When the curves of the Al6061 and Al6061-Al2124 materials with the thinnest inner wall were examined, it was seen that the materials changed shape completely with plastic deformation without showing any failure damage (Fig 6-a). In Al6061-Al2124 materials, where the inner wall is thick, failure damage occurred on the outer walls towards the end of the tests (Fig. 6-d). Also, failure damage was observed at lower displacements with increasing SiC reinforcement ratio in SiC-reinforced composites. This damage was seen in the upper and lower middle parts of the materials where the outer wall was thickest (Fig. 6-b-c). The reason for this damage is that the materials are exposed to compressive stress on the outside and tensile stress on the inside in these regions (Fig. 7). Also in particle-reinforced composites, the toughness decreases with the reinforcement (Fig. 8). Therefore, the plastic deformation ability decreases under tension loads [22]. In the materials with different wall thicknesses, increasing the SiC reinforcement gave similar results. However, in materials with thicker composite inner walls, the amount of displacement decreased until failure damage (Fig. 5-c) because the rigidity increased with the increase of the composite inner wall.



a)

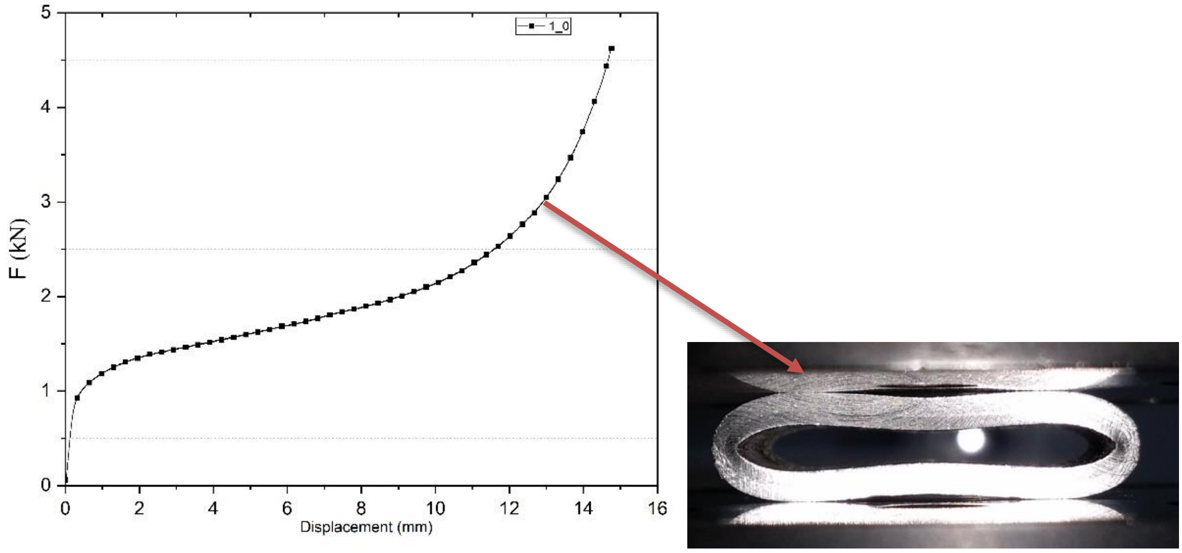


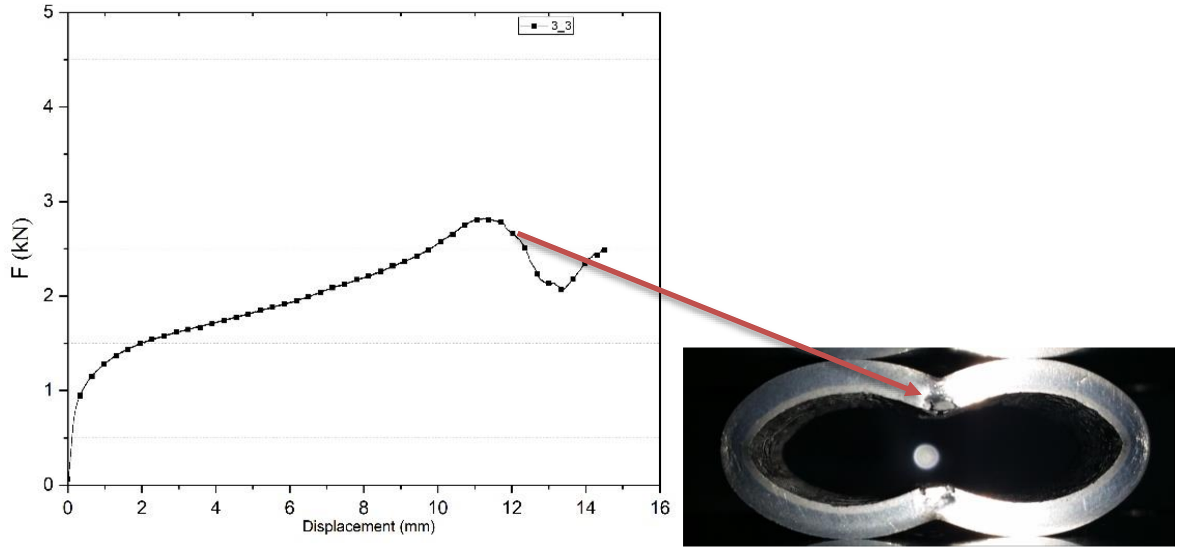
b)

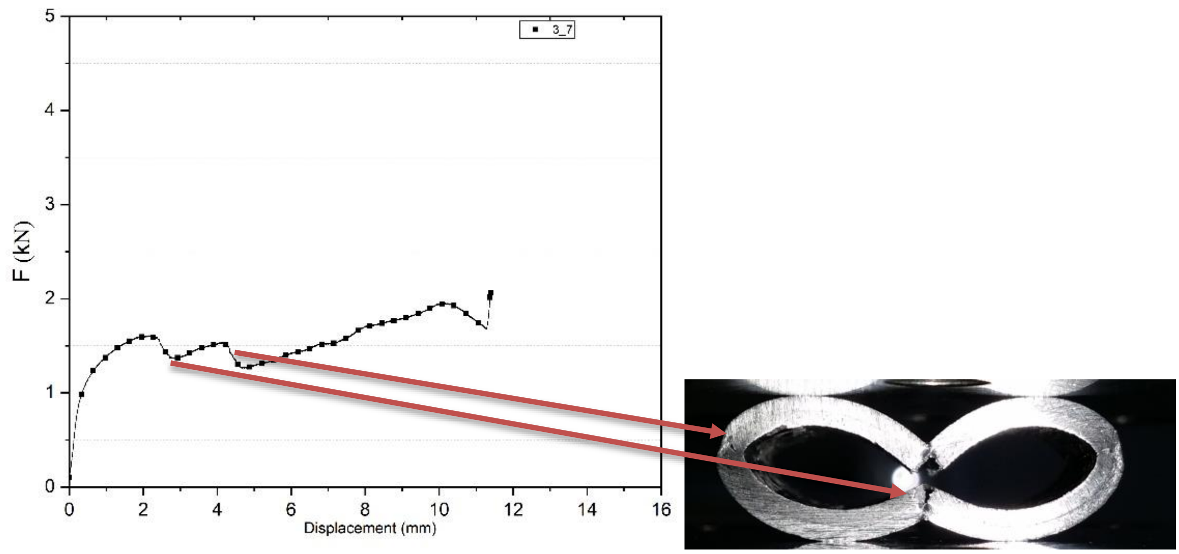


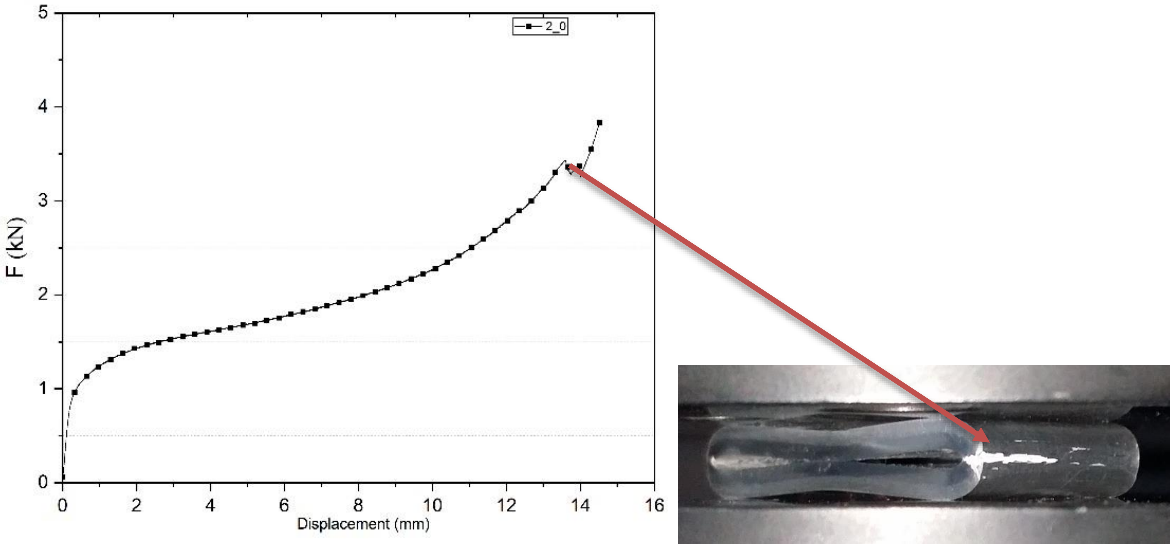
c)

Figure 5. Force-displacement curves obtained from flattening tests, a) with different SiC ratios at 1.5-0.5 mm wall thicknesses, b) with different SiC ratios at 1-1 mm wall thicknesses, c) with different SiC ratios at 0.5-1.5 mm wall thicknesses


1_0
F (kN)
Displacement (mm)
a)


3_3
F (kN)
Displacement (mm)
b)


3_7
F (kN)
Displacement (mm)
c)



d)

Figure 6. Different failure damage images of composite pipes under flattening tests, a) Al6061-Al2124-(1.5-0.5 mm), b) Al6061-Al2124/SiC (3%)-(0.5-1.5 mm), c) Al6061-Al2124/SiC (7%)-(0.5-1.5 mm), Al6061-Al2124-(1-1 mm)

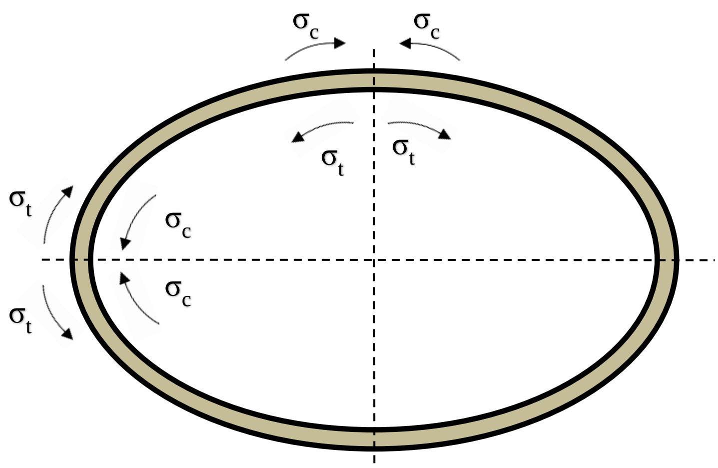


Figure 7. Stress zones and types that occur during the flattening test in pipes (σ_c=compression stress, σ_t=tensile stress) [23]

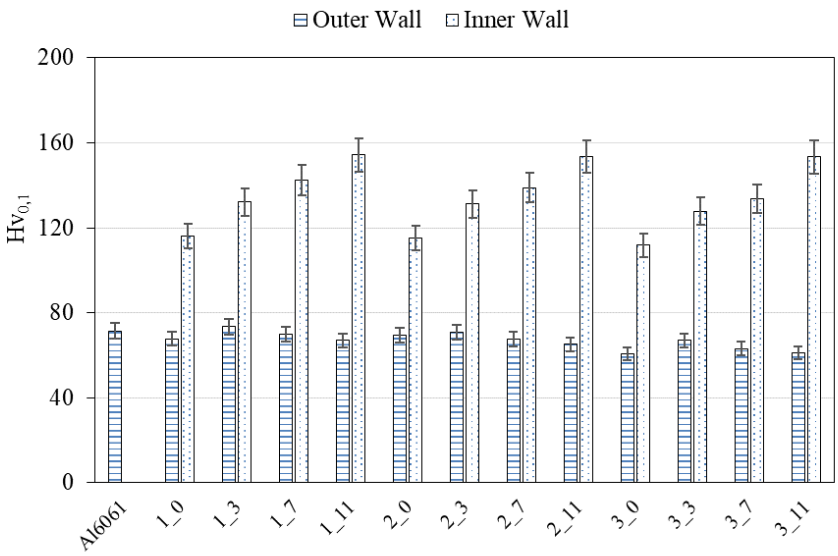


Figure 8. Hardness values of inner and outer walls of composite materials

Different mechanical behaviors were observed as the wall thickness varied while keeping the material content constant. In Al6061-Al2124 materials, flattening resistance increased with the increase in the thickness of the inner wall. While no failure damage was observed in the material with the thinnest inner wall, failures were observed on the outer walls of materials with medium and thick inner walls at the end of the flattening test. In materials containing SiC reinforcement, the flattening resistance, which increased when passing from the thin inner wall to the middle inner wall, decreased again at the thickest inner wall. It was observed that as the thickness of the inner wall increased in three different SiC reinforcement ratios, plastic deformation rates decreased, and the frequency of single or multiple damages increased. When looking at the damage types, damages were seen in the middle regions of materials that had SiC reinforcement as 3%. In the thin inner-walled materials containing 7% and 11% SiC, damage was seen only in the middle regions. In other wall thicknesses, damage was seen in both the middle and lateral regions. Also, when the SiC ratio increased in materials, the force and displacement values of damage decreased. This also indicates that the material loses its deformation ability, that is, its toughness, with the increase in SiC ratio [24, 25].

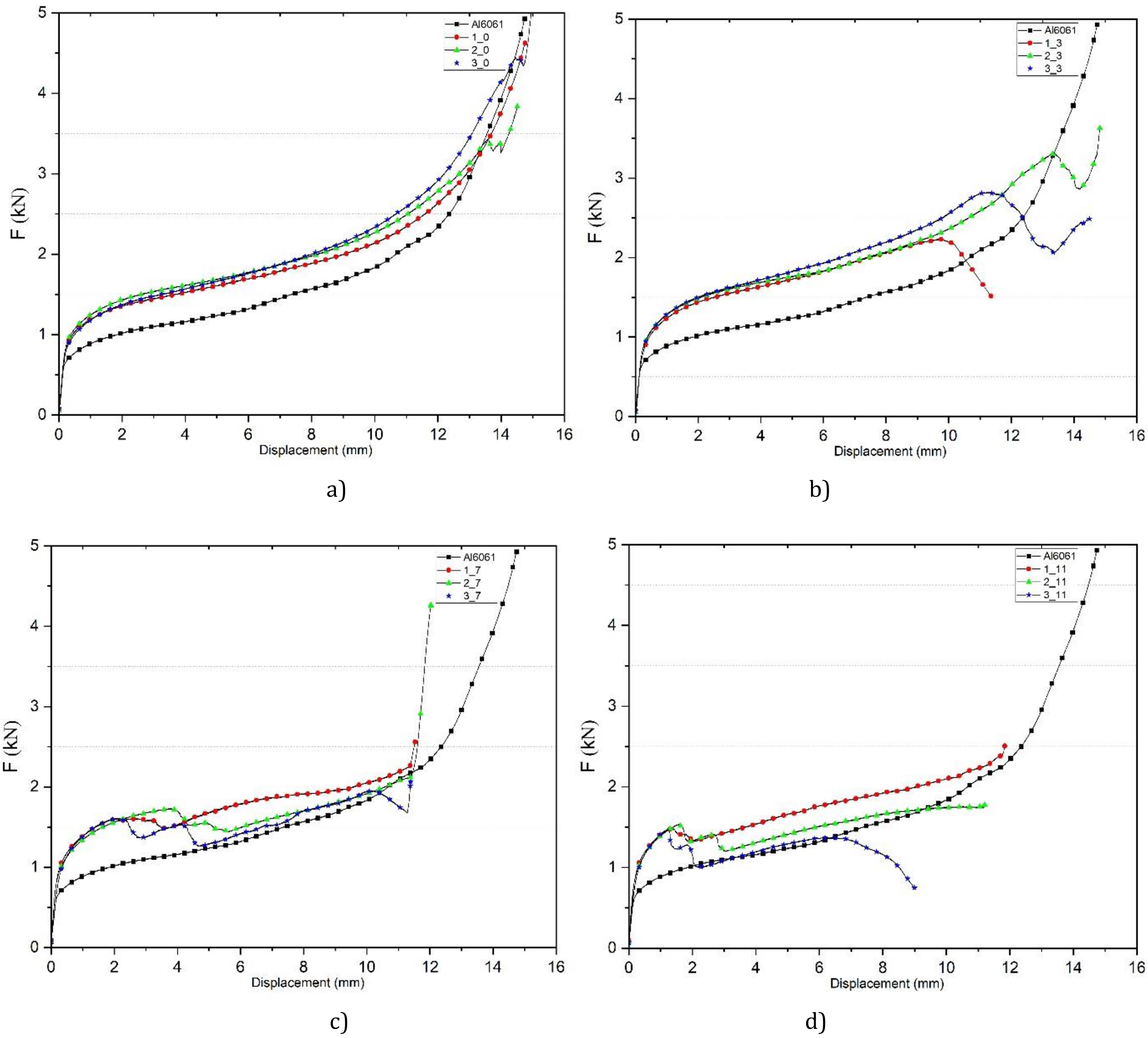


Figure 9. Force-displacement curves obtained from flattening tests, a) Al6061-Al2124 pipes with different wall thicknesses, b) Different wall thicknesses with 3% SiC ratio, c) Different wall thicknesses with 7% SiC ratio, d) Different wall thicknesses with 11% SiC ratio

4. Discussion and Conclusion

This study focused on producing double-walled composite pipes. Their mechanical properties were examined with flattening tests under radial forces. The inner and outer wall thicknesses of the materials and the SiC reinforcement ratio in the inner wall were production variables. Wall thicknesses were adjusted at three different rates as 1.5-0.5, 1-1, and 0.5-1.5 mm. SiC reinforcement was applied as 3, 7, and 11%. Composite pipes were produced by the mandrel-assisted extrusion method. When Al6061 material was double-walled with Al2124 in the inner wall, the flattening resistance increased. In addition, the flattening resistance increased with SiC reinforcement and the increase of the reinforcement ratio. With the increase in flattening resistance, failure damages were observed in all Al6061-Al2124 and Al6061-Al2124/SiC materials, where the inner wall was the thickest. The displacement and force values that caused failure damage decreased with increasing of inner wall thickness and reinforcement ratio of SiC. Failure damages occurred firstly at the upper and lower parts of the materials. These damages were encountered in both the middle and lateral regions of the materials where the inner wall was thicker and the SiC reinforcement ratio was 7% and 11%.

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