Gazi Üniversitesi
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Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

GU J Sci, Part C, 12(1): 282-296 (2024)

Investigation of The Weldability of PLA Plus Sheets with Different Infill Ratios by Friction Stir Welding

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Article Info

Research article
Received: 03/12/2023
Revision: 01/02/2024
Accepted: 20/02/2024

Keywords

Friction Stir Welding
3D Printing
PLA Plus
Infill Ratio
Mechanical Properties
Heat Generation

Makale Bilgisi

Araştırma makalesi
Başvuru: 03/12/2023
Düzeltme: 01/02/2024
Kabul: 20/02/2024

Anahtar Kelimeler

Sürtünme Karıştırma Kaynağı
3B Yazıcı
PLA Plus
Doluluk Oranı
Meknaik Özellikler
Isı Oluşumu

Graphical/Tabular Abstract (Grafik Özet)

In this study, the weldability of PLA Plus sheets with different filling ratios (20, 40, 60, 80 and 100%) prepared by 3D printing at different filling ratios was investigated by friction stir welding. / Bu çalışmada, farklı doluluk oranlarında 3B baskı ile hazırlanan farklı doluluk oranlarında ki (%20, 40, 60, 80 ve 100) PLA Plus plakaların sürtünme karıştırma kaynağı ile kaynaklanabilirliği incelenmiştir.

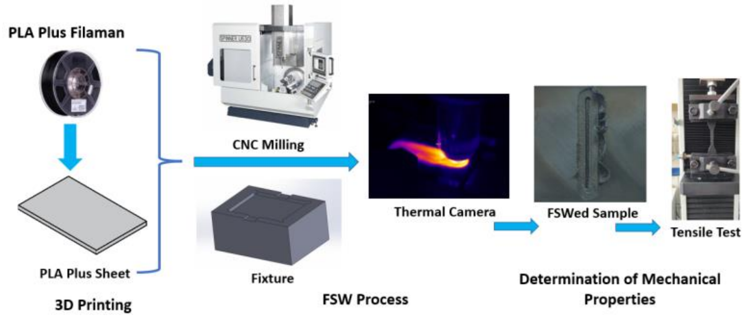

***Figure A**: Flow chart illustrating the welding of specimens from the 3D printing process and determination of weld strength/ **Şekil A:**. 3B baskı sürecinden numunelerin birleştirilmesi ve kaynak mukavemetinin belirlenmesini gösteren akış diyagramı*

Highlights (Önemli noktalar)

- *Friction stir welding of PLA Plus plates with different infill ratios was investigated. / Farklı doluluk oranlarındaki PLA Plus plakaların sürtünme karıştırma kaynağı ile birleştirilebilirliği incelenmiştir.*
- *The mechanical properties and weld strength of the parts changed depending on the infill ratio. / Doluluk oranına bağlı olarak parçaların mekanik özellikleri ve kaynak dayanımları değişmiştir.*
- *While significant welding defects occurred at 20% and 40% infill ratios, FSW was successfully performed at 60% and 80% infill ratios. / %20 ve %40 doluluk oranlarında önemli kaynak kusurları oluşurken 60% ve 80% doluluk oranlarında başarıyla SKK gerçekleştirilmiştir.*

Aim (Amaç): The aim of this study is to investigate the weldability of PLA Plus sheets with different infill ratios printed in 3D printer by friction stir welding. / 3B printerde basılmış farklı doluluk oranlarındaki PLA Plus plakaların sürtünme karıştırma kaynağı ile birleştirilebilirliğinin incelenmesidir.

Originality (Özgünlük):
The weldability of 3D printing of different infill ratios, which are not included in the literature, has been examined and brought to the literature. / Literatürde yer almayan farklı doluluk oranların 3B baskıların kaynaklanabilirliği incelenerek literature kazandırılmıştır.

Results (Bulgular): *The highest weld strengths were 2.14, 9.18, 17.47, 29.4 and 41.12 MPa, respectively. / En yüksek kaynak mukavemeti sırasıyla 2.14, 9.18, 17.47, 29.4 ve 41.12 MPa olarak belirlenmiştir.*

Conclusion (Sonuç): *Significant weld defects occurred at low infill ratios (20% and 40%) due to insufficient material. At 60%, 80% and 100% infill ratios, the welding process was performed successfully. As a result, it can be said that parts can be joined using SKK at infill ratios above 60%. / Düşük doluluk oranlarında (%20 ve %40) malzeme yetersizliğinden dolayı önemli kaynak hataları oluşmuştur. %60, %80 ve %100 doluluk oranlarında kaynak işlemi başarı ile gerçekleştirilmiştir. Sonuç olarak %60 üzeri doluluk oranlarında SKK kullanılarak parçaların birleştirilebileceği görülmüştür.*

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DOI: 10.29109/gujsc.1399512

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Abstract

Although the joining processes of plastics are typically carried out through welding, adhesive bonding, or mechanical fastening elements, the production of complex and large parts often requires welding technology. In this study, the effect of part infill ratio (20%, 40%, 60%, 80%, and 100%) on the welding strength of 3D printed PLA Plus (polylactic acid) parts was evaluated through friction stir welding (FSW). Tensile tests and temperature measurements were carried out to examine the effects of friction stir welding process parameters (feed rate: 50 and 100 mm/min and rotational speed: 1000 and 1500 rpm) on the structure and mechanical properties of friction stir welding. Moreover, visual inspections were performed to detect defects in the weld zone. Compared to the PLA Plus samples given as reference according to the infill ratios, the highest welding strengths were obtained at 80%, 60% and 100% infill ratios (29.4 MPa, 17.47 MPa and 41.12 MPa and 112.38%, 97.48%, 87.04% efficiency, respectively). As a result, it was determined that at low infill ratios (20% and 40%), the weld quality was negatively affected, and a surface tunnel defect occurred in the weld zone. It has been determined that the weld quality in FSW is significantly affected by the temperature occurring during the process. The study has shown that parts printed at different infill ratios, especially on a 3D printer, can be combined with friction stir welding and that the efficiency of the welding process can be increased by optimizing the infill ratios.

Farklı Doluluk Oranlarına Sahip PLA Plus Plakaların Sürtünme Karıştırma Kaynağı İle Kaynaklanabilirliğinin İncelenmesi

Makale Bilgisi

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Öz

Plastiklerin birleştirme işlemleri; genellikle kaynak, yapıştırma veya mekanik bağlama elemanları ile gerçekleştirilmesine rağmen, karmaşık ve büyük parçaların üretimi çoğunlukla kaynak teknolojisi gerektirmektedir. Bu çalışmada; 3B basılmış PLA Plus parçaların sürtünme karıştırma kaynağıyla (SKK) birleştirilmesinde, parça doluluk oranlarının (%20, %40, %60, %80 ve %100) kaynak mukavemetine etkisi değerlendirilmiştir. Sürtünme karıştırma kaynağı işlem parametrelerinin (ilerleme hızı: 50 ve 100 mm/min ve dönme hızı: 1000 ve 1500 rpm), sürtünme karıştırma kaynağının yapısı ve mekanik özellikleri üzerindeki etkilerini incelemek için çekme testleri ve sıcaklık ölçümleri gerçekleştirilmiştir. Ayrıca kaynak bölgesindeki kusurları tespit etmek için görsel incelemeler yapılmıştır. Doluluk oranlarına göre referans olarak verilen PLA Plus numunelerine kıyasla en yüksek kaynak mukavemetleri sırasıyla %80, %60 ve %100 doluluk oranında (sırasıyla 29.4 MPa, 17.47 MPa ve 41.12 MPa ve %112.38, %97.48, %87.04 verimlilik) elde edilmiştir. Sonuç olarak düşük doluluk oranlarında (%20 ve %40) kaynak kalitesinin olumsuz etkilendiği ve kaynak bölgesinde surface tunnel kusurunun oluştuğu belirlenmiştir. SKK'de kaynak kalitesinin işlem sırasında ortaya çıkan sıcaklıktan önemli derecede etkilendiği belirlenmiştir. Yapılan çalışma, özellikle 3B yazıcıda farklı doluluk oranlarında basılan parçaların sürtünme karıştırma kaynağıyla birleştirilebilir olduğunu ve doluluk oranlarının optimizasyonu ile kaynak işleminin verimliliğinin artırılabileceğini göstermektedir.

1. INTRODUCTION (GİRİŞ)

Additive manufacturing method is an innovative and high-tech production method that emerged with Industry 4.0. Unlike traditional manufacturing technologies that have been used for many years, this method has gained rapid popularity due to its ability to adjust the infill ratio of the parts, produce complex parts in a same production process, and offer advantages in terms of time and cost. There are various additive manufacturing methods with different working systems in which metal, plastic, ceramic and composite materials are transformed into products. Today, the primary additive

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DOI: 10.29109/gujsc.1399512

manufacturing method for plastic part production is the process of 3D printing. Although there are some legal restrictions on their use, plastic materials have become irreplaceable in most industries due to their lightness and low costs. For this reason, 3D printers using thermoplastic-based consumables are very popular among academic researchers as well as commercial users. However, despite its many advantages, the fact that part dimensions are limited to the printer's table dimensions is a difficult situation for manufacturing in printers. To overcome this deficiency, assembly or joining processes are applied to the produced parts [1]. In particular, the joining of plastic materials manufactured with a 3D printer using the welding method has aroused interest in recent years and therefore the studies on Friction Stir Welding (FSW) have increased [2]. Friction stir welding is a solid-state welding process that has the ability to join similar and dissimilar materials. Studies focusing on friction stir welding are valuable for industrial applications where it is desired to join parts that are not possible to join with other joining methods or are costly. It has been discovered that it is possible to join PMMA (poly methylmethacrylate) parts printed from 3D printed using friction stir welding, and that the welded parts have high welding efficiency [3]. In another study [4], in which the weldability of 3D printed polypropylene/graphene (PP/GNP) nanocomposites was evaluated using FSW, it was proven that high quality strong joints can be made between polymer nanocomposites by determining appropriate FSW parameters. The multi-walled carbon nanotubes has been used to enhance the mechanical properties in the friction stir welding of 3D printed ABS parts [1]. Additionally, it has been reported that the addition of nano powder to the welding process increases the weld strength [5], Forcellese et al. [6] used ABS Plus P430 material and Tiwary et al. [8] conducted various studies examining the effects of friction stir welding parameters on the mechanical performance of welded joints using ABS and PETG plates. Anaç [7] investigated the joinability of PLA Plus/PLA Plus, HDPE/HDPE and PLA Plus/HDPE plates by FSW using two different pin geometries (square and triangle), two different tool feed rates (30 mm/min and 50 mm/min) and two different rotational speed (1000 rpm and 1500 rpm) process parameters. The highest weld strength was obtained at triangle pin geometry, 1000 rpm rotational speed and 50 mm/min traverse speed for joining PLA Plus plates and at square pin geometry, 1500 rpm rotational speed and 50 mm/min traverse speed for joining HDPE plates. In PLA Plus/HDPE sheets, the joining process was performed by offsetting the tool to the HDPE sheet side. Sharma et al. [9] examined the feasibility of combining 3D printed PLA sheets using FSW to increase the use of biodegradable polymers instead of petroleum-based polymers. They examined their effects on welding strength and welding efficiency by using three different rotational speeds (700, 1400 and 2000 rpm), three different feed rates (20, 30 and 40 mm/min) and three different pin geometries (cylindrical, threaded, and conical pins) in the FSW process. They have indicated that the cylindrical pin geometry yields better results in joining, and as the feed rate increases, the welding strength decreases.

In another study, the feasibility of joining 3D printed PLA sheets with FSW was investigated using a conical cylindrical pin. When welding efficiency was examined, it was stated that joining was achieved with 40% welding efficiency at 1400 rpm tool rotational speed and 10 mm/min feed rate [10]. Kumar et al. [11] combined 3D printed Al-reinforced ABS and PA6 thermoplastic composites by friction stir welding. It is stated that the research results will reduce the time loss in joining/filling the cracks of the oil/gas pipeline.

In general, a review of the literature indicates that researchers consider various variables for friction stir welding, including process parameters, types of materials to be welded, tool pin forms, and material production methods (such as plastic injection, additive manufacturing). However, it has been determined that in all these studies, the 3D printed materials used for welding have infill ratio of 100%. No opinions or studies regarding the weldability of parts with different infill ratios were found in the literature. However, it is known that one of the most significant advantages of 3D printers is the ability to produce parts with low infill ratios [12]. Based on this information, in this study, the joining of PLA Plus plates produced at different infill ratios on a 3D printer using the FSW method was investigated. Two different feed rates (50 and 100 mm/min) and two different rotational speeds (1000 and 1500 rpm) were used as FSW process parameters. Thermal images were taken during welding process to examine the effect of part infill ratios (20%, 40%, 60%, 80% and 100%) and process parameters on weld quality. Additionally, visual inspections were made in the weld zone after welding. The data obtained in this study can be used directly in relevant applications in the welding industry.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. Features of Pla Plus Filament (PLA Plus Malzemenin Özellikleri)

Polylactic acid (PLA) is a widely used and preferred material in additive manufacturing due to its ease of production/printing and compatibility with 3D printer technology. For this reason, its derivative PLA Plus filaments were used in the experiments. PLA offers heat resistance up to 140 °C, UV resistance and impact resistance. It has high bio content and thus reduces the carbon footprint. Additionally, it is non-toxic in nature and is a thermoplastic that does not harm human health [13-16]. PLA Plus is a version of standard PLA with enhanced mechanical properties. PLA Plus has a higher level of toughness and higher impact resistance compared to PLA [17]. The properties of the filaments used in the study are given in Table 1.

Table 1. Mechanical/technical properties of filament materials (Filament malzemelerinin teknik/mekanik özellikleri) [18]

Mechanical Properties	PLA Plus
Diameter (mm)	1.75
Brand	eSUN
Color	Black
Tensile Strength (MPa)	63
Elongation at Break (%)	20
Density (g/cm^3)	1.23

2.2. 3D Printing Process of Pla Plus Material (Pla Plus'ın 3B Baskı Süreci)

In the study, an Ender 3 S1 printer was used to print samples of PLA Plus filament in specified dimensions, with printing parameters values of nozzle temperature 210 ºC, table temperature 60 ºC and printing speed 60 mm/sec. To determine the mechanical properties of 3D printed test specimens at different infill ratios (20%, 40%, 60%, 80%, and 100%), tensile test samples (ASTM D638-10) and PLA Plus plates with dimensions of 112x72 mm were printed for friction stir welding. The layer thickness is fixed at 0.1 mm in all samples. The flow process of the printing process is given in Figure 1, the dimensions of the tensile test samples are given in Figure 1 a, and the dimensions of the FSW samples are given in Figure 1 b.
In additive manufacturing method, product quality and mechanical properties are influenced by various process parameters, including material used, nozzle temperature, layer thickness, printing speed, bed temperature, etc. [19, 20]. All samples in the experiments were printed flat in the XYZ axis, while samples with different infill ratios were printed in a grid pattern. For samples with a 100% infill ratio, production was carried out by the extruder following a linear path at angles of 45 and -45 degrees in each layer, respectively. Figure 2 provides images of FSW samples with different infill ratios taken from Ultimaker Cura 5.2.1 software.

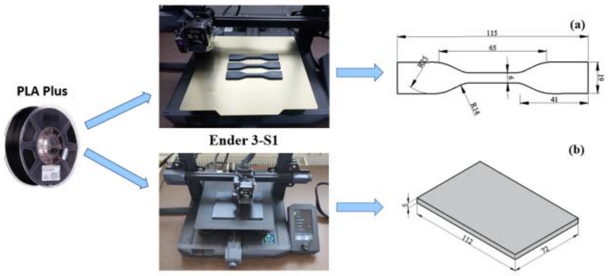


Figure 1. Printing samples from PLA Plus filament (PLA Plus filamentten basılan numuneler)

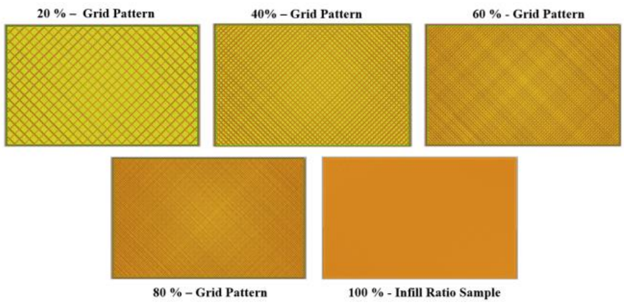


Figure 2. View of FSW sheets at different infill ratios (Farklı doluluk oranlarındaki SKK plakaların görünüşü)

2.3. FSW Process Parameters and Experımental Design (SKK İşlem Parametreleri ve Deneysel Tasarım)

In FSW, weld quality is directly affected by process parameters. Therefore, there are many studies in the literature to determine the effects of process parameters. In some of these studies, tool feed rate, tool shoulder shape [21, 22], tool shoulder surface [23], pin geometry [24-26], tool rotational speed [27-29], tool plunge speed, tool inclination angle [30], tool material and tool design have been studied in detail [31-32]. The reason why weld quality is affected by process parameters is that process parameters play an important role in the amount of heat generated during the FSW process. The material flow and proper mixing of the material in the welding area depends on the amount of heat generated during welding. Insufficient heat can lead to inadequate plasticization of the material, while excessive heat can result in over plasticization and material overflowing out of the welding area.

In the study, tool feed rate and tool rotational speed, which are important parameters affecting the amount of heat generated in the welding area, were used as experimental variables [32, 33]. Process parameters are given in Table 2. FSW process parameters were determined at two different tool rotational speeds (1000 and 1500 rpm), two different feed rates (50 and 100 mm/min) and five different infill ratios (20%, 40%, 60%, 80% and 100%) as 3D printing parameters. Table 3 provides the experiment set designed according to infill ratios and process parameters. For the assessment of weld quality, the tensile strengths of plates printed with a 3D printer (for all infill ratios) were determined and added to Table 3 as reference (Ref) values.

Table 2. FSW process parameter values (SKK işlem parametreleri)

Pin Geometry	Infill Ratio (%)	Feed Rate (mm/min)	Rotational Speed (rpm)
Square	20	50	1000
	40		
	60	100	1500
	80		
	100		

Table 3. Experimental set for PLA Plus plates with different infill ratios (Farklı doluluk oranlarına sahip PLA Plus plakalar için deney seti)

	Layer Thickness (mm)	Pin Geometry	Infill Ratio	Feed Rate (mm/min)	Rotational Speed (rpm)	Ultimate Tensile Stress (UTS) (MPa)	Efficiency (%)
Reference	**0.1**	**-**	**20**	**-**	**-**	**15.45±1.42**	
1	0.1	Square	20	50	1000	1.58±0.35	10.23
2	0.1	Square	20	50	1500	1.95±0.42	12.62
3	0.1	Square	20	100	1000	1.76±0.13	11.39
4	0.1	Square	20	100	1500	2.14±0.21	13.85
Reference	**0.1**	**-**	**40**	**-**	**-**	**17.68±1.63**	
5	0.1	Square	40	50	1000	4.49±1.31	25.39
6	0.1	Square	40	50	1500	9.18±0.91	51.92
7	0.1	Square	40	100	1000	2.66±0.93	15.04
8	0.1	Square	40	100	1500	2.71±0.69	15.32
Reference	**0.1**	**-**	**60**	**-**	**-**	**17.92±0.96**	
9	0.1	Square	60	50	1000	3.91±0.76	21.82
10	0.1	Square	60	50	1500	3.88±0.98	21.65
11	0.1	Square	60	100	1000	5.18±0.66	28.9
12	0.1	Square	60	100	1500	17.47±0.49	97.48
Reference	**0.1**	**-**	**80**	**-**	**-**	**26.16±0.85**	
13	0.1	Square	80	50	1000	4.88±0.63	18.65
14	0.1	Square	80	50	1500	4.29±0.81	16.39
15	0.1	Square	80	100	1000	29.4±2.21	112.38
16	0.1	Square	80	100	1500	21.86±0.19	83.56
Reference	**0.1**	**-**	**100**	**-**	**-**	**47.24±1.36**	
17	0.1	Square	100	50	1000	25.88±0.27	54.78
18	0.1	Square	100	50	1500	31.32±1.76	66.3
19	0.1	Square	100	100	1000	38.39±6.34	81.27
20	0.1	Square	100	100	1500	41.12±7.7	87.04

Figure 3 shows the technical drawing of the fixed process parameters and pin geometry used in the FSW process. Tool shoulder penetration depth was determined as 1 mm, pin height as 3.5 mm, pin penetration depth as 4.5 mm, and tool shoulder diameter as 20 mm. Since the thickness of PLA Plus plates was 5 mm, the gap between the pin and the plate was 0.5 mm. Since there was no pin contact in the area colored red in Figure 3, the heat generated during the FSW process resulted in the joint.

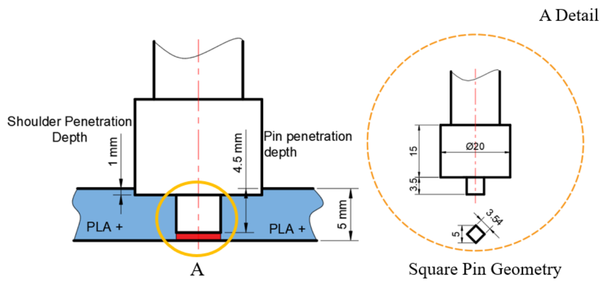


Figure 3. View of process parameters and pin geometry in FSW (SKK işlem parametreleri ve pin geometrisi)

2.4. Characteristics of FSW Equipments and Test Materials (SKK Ekipmanlarının ve Test Malzemelerinin Özellikleri)

There are two important equipment in the application of the FSW process. The first of these is a conventional or CNC milling machine for joining PLA Plus plates printed on a 3D printer. In this study, Spinner U630 CNC (22 kW, 12000 rpm, y-axis 530 mm, z-axis 465 mm and table size 650 mm) milling machine was used for the FSW process and SolidCam commercial software was used to extract G-codes. Figure 4 shows the FSW process and the image of the measurement made with a thermal camera during the process, the sample view after the welding and an example sample during the last tensile test. The second important equipment in the FSW process is the fixture. During the FSW process, movement of parts or separation of parts from each other negatively affects the welding. Therefore, special molds are designed and produced to fix PLA Plus plates.

Figure 5 shows the welding direction according to the CNC machine, the input and exit hole locations of the pin, and the areas where hardness measurement was made. The plunge into the entry and exit points was made from the top of the part at a speed of 10 mm/min, and the tool was kept at the entry point for 10 seconds to generate the necessary heat in the weld. Three repeated tensile tests were performed to determine the weld strength, and five repeated measurements were made from the weld zone, the heat affected zone and the main material to determine the hardness change. For tensile tests, a WDW-5 model universal tensile testing device with a capacity of 5 kN was used. Tensile tests were performed at room temperature at a tensile speed of 2 mm/min. To better evaluate the quality of the weld, temperature measurements were made during FSW using the Fluke Ti32 thermal camera.

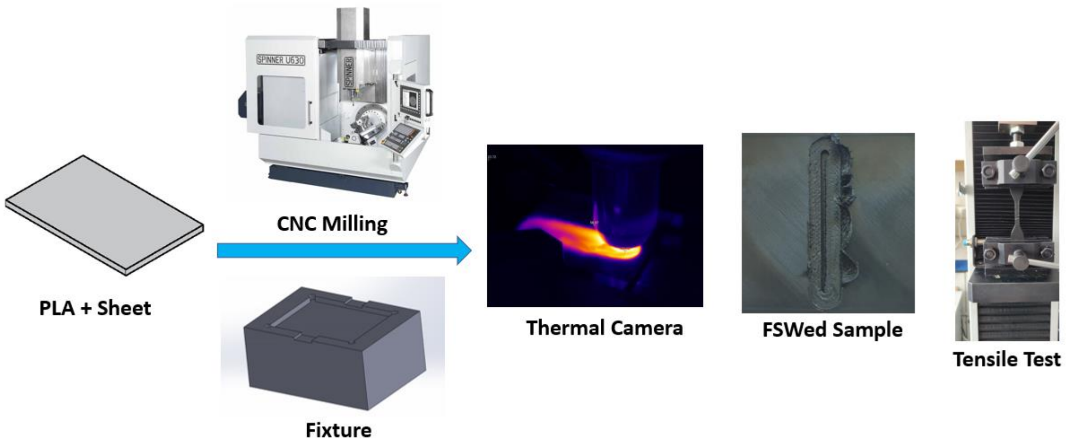


Figure 4. Overview of the FSW process (SKK yöntemine genel bakış)

3. RESULTS AND DISCUSSION (BULGULAR ve TARTIŞMA)

The study investigated the weldability of plates obtained from PLA Plus filament using a 3D printer by FSW. PLA Plus plates with five different infill ratios (20%, 40%, 60%, 80%, and 100%) were joined using FSW, with a square pin geometry, two different feed rates (50 mm/min and 100 mm/min), and two different tool rotational speeds (1000 rpm and 1500 rpm). Tensile specimens were extracted from the welded parts to assess the welding qualities. Additionally, the weld zone, heat-affected zone, and base material hardness were measured and compared. Thermal images were captured to evaluate the heat generated during FSW. Finally, visual inspections were conducted on the welded samples to identify welding defects.

3.1. Mechanical Properties of Pla Plus Materials at Different Infill Ratios (Farklı Doluluk Oranlarındaki Pla Plus Malzemelerinin Mekanik Özellikleri)

The stress-strain diagram and elongation values of PLA Plus material at different infill ratios are given in Figure 6. Graphs were drawn from experimental data close to the average UTS and percent elongation value. While the strength at 40% and 60% infill ratio (17.68±1.63 and 17.92±0.96 MPa) tended to increase compared to the strength at 20% infill ratio (15.45±1.42 MPa), the ductility of the material decreased. When the data obtained from the parts with 40% and 60% infill ratios were evaluated together, no significant change was observed in the strength and elongation rates. Evlen et al. [34] stated in their studies that while the tensile strength of the parts increased gradually from 10% infill ratio to 30% infill ratio, the strength decreased at 40% and 50% infill ratio. They stated that this situation results from the inadequate adhesion between the layers in organic materials such as PLA. At 80% and 100% infill ratios, strength (26.16±0.8 and 47.24±1.3 MPa) and elongation values increased significantly depending on the infill ratio.

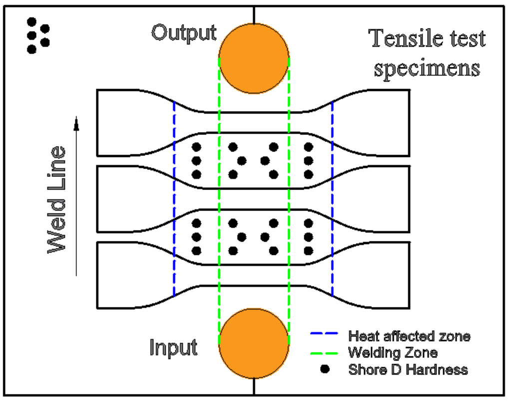


Figure 5. Tensile test samples and hardness measurement locations (Çekme testi numunesi ve sertlik ölçüm noktalarının temsili gösterimi)

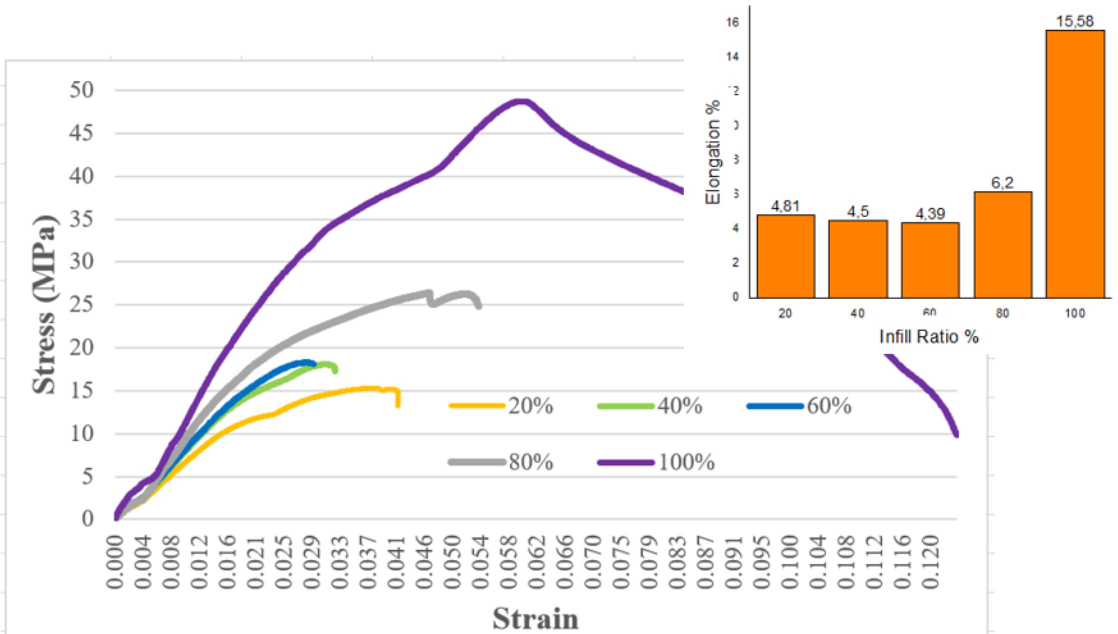


Figure 6. Mechanical properties of PLA Plus material according to different infill ratios (Farklı doluluk oranlarına göre PLA Plus malzemenin mekanik özellikleri)

3.2. General Evaluation of Weld Strengths
(Kaynak Mukavemetinin Genel Değerlendirilmesi)

In Figure 7, the welding strengths (ultimate tensile stress) of the samples with different part infill ratios are given after the FSW process, and in Table 3, the welding efficiencies compared to the reference samples are given. The red columns in Figure 7 show reference values for all part infill ratios. The highest tensile strength value at 20%, 60% and 100% infill ratios were obtained at 100 mm/min feed rate and 1500 rpm rotational speed while it was obtained at 50 mm/min feed rate and 1500 rpm rotational speed at 40% infill ratio. It was obtained at a feed rate of 100 mm/min and a rotational speed of 1000 rpm at 80% infill ratio. Tensile strength was low at 20% and 40% infill ratios, which resulted by the insufficient amount of material to facilitate material flow during FSW. It was observed that the weld strength increased as the infill ratio increased, and the parts were combined with 97.48%, 112.38% and 87.04% efficiency at 60%, 80% and 100% infill ratios, respectively. Especially when joining parts with 80% infill ratio, the weld strength was higher than the reference sample strength. This situation can be explained by the voids in the part balancing the heat generated during welding and preventing excessive plasticization of the material in the welding area. The results have shown that friction stir welding is promising for joining parts with low infill ratios (provided that the infill ratio is determined by optimization).

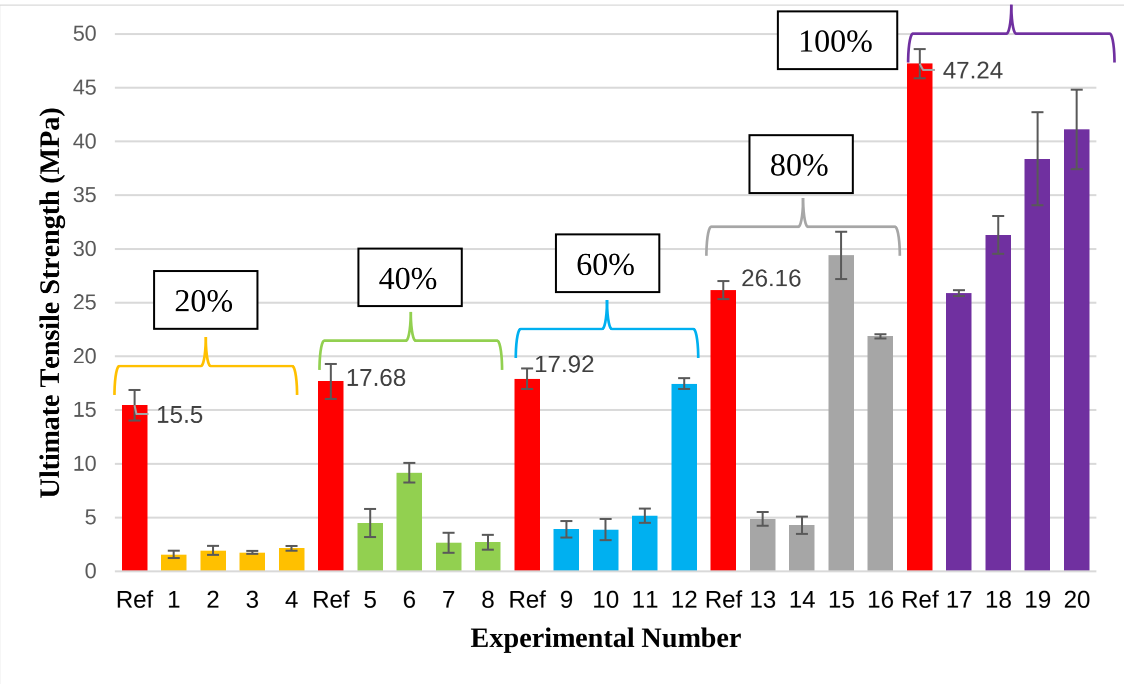
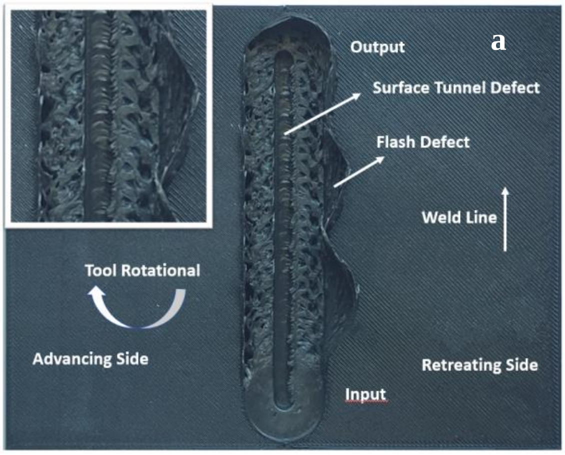


Figure 7. Weld strengths after FSW process (SKK işleminden sonra kaynak kalitesi)

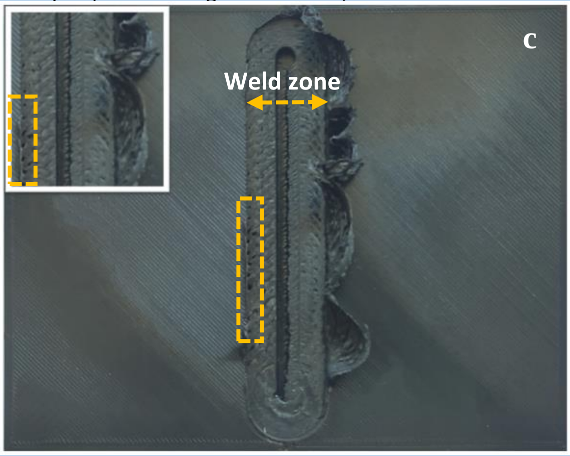
Figure 8 shows the basic concepts of FSW (tool entry and exit points, welding direction, tool rotational direction, advancing side (AS), retreating side (RS) and welding defects). Additionally, in Figure 8, sample images with the best and worst welding strengths after FSW are given for infill ratios of 20%, 40%, and 60%, while in Figure 9, the samples are presented for infill ratios of 80% and 100%. In all samples, a flash defect was observed at the end of the tool shoulder. Surface tunnel defects along the weld line occurred at infill ratios of 20%, 40%, and 60%. It is believed that this condition is attributed to the low infill ratio, leading to insufficient material in the weld zone and causing the surface tunnel defect. Surface tunnel defects did not occur at 80% infill ratio. In samples with poor weld quality at 100% infill ratio, surface tunnel defects were observed, while in samples with good weld quality at 100% infill ratio, no surface tunnel defects were observed. The reason for the occurrence of surface tunnel defects in samples with 100% infill ratio can be explained by insufficient material flow due to inappropriate process parameters. When Figure 8 a is compared with Figure 8b, it is determined that in Figure 8 a, due to inappropriate process parameters, voids occur in the weld zone on both the AS and RS sides compared to the sample in Figure 8b. When comparing Figure 8 c and Figure 8 d for the 40% infill ratio, it can be observed that in the sample with lower welding strength (Figure 8 c), there are voids at the edges of the tool shoulder area. These voids have adversely affected the welding strength. For the 60% infill ratio (Figure 8 e), the low feed rate and high rotational speed have led to excessive plasticization of the material, causing it to overflow from the weld zone.

Figure 9 a and Figure 9 b show images of the best and worst welded samples for 80% infill ratio. In Figure 9 b, it is understood that the weld lines resulting from the tool rotation form a continuous structure, and the material flow is uninterrupted. In Figure 9a, the defect occurring along the weld line indicates that the material flow is interrupted, and the selected parameters are inappropriate. In Figure 9c, material flow negatively affecting the weld quality has been observed. When examining the weld lines in Figure 9d, it was determined that the weld seam is well-formed.

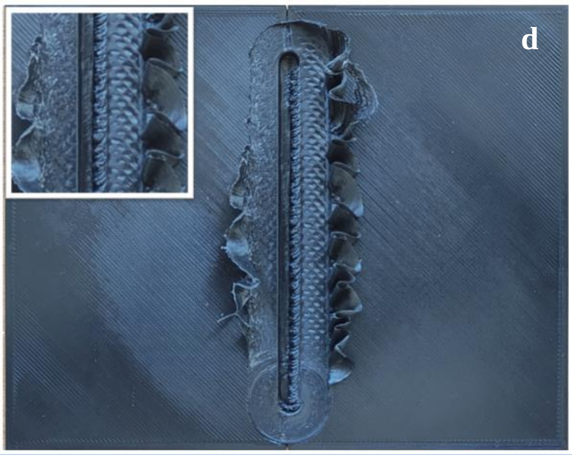


Infill Ratio:20%, Feed Rate: 100 mm/min, Rotational Speed: 1500 rpm (Weld Strength: 1.58 MPa)

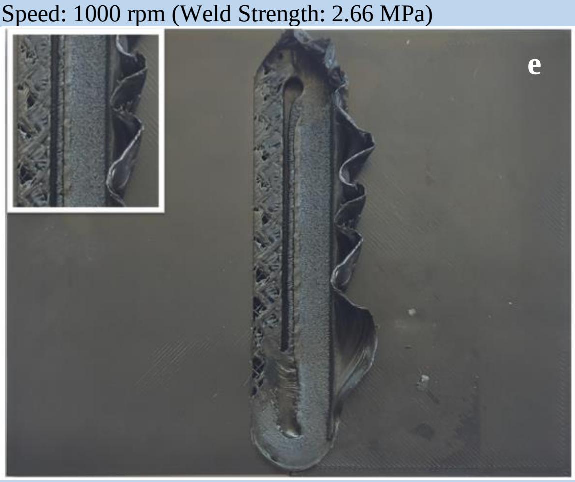
Infill Ratio:20%, Feed Rate: 100 mm/ min, Rotational Speed: 1500 rpm (Weld Strength: 2.14 MPa)



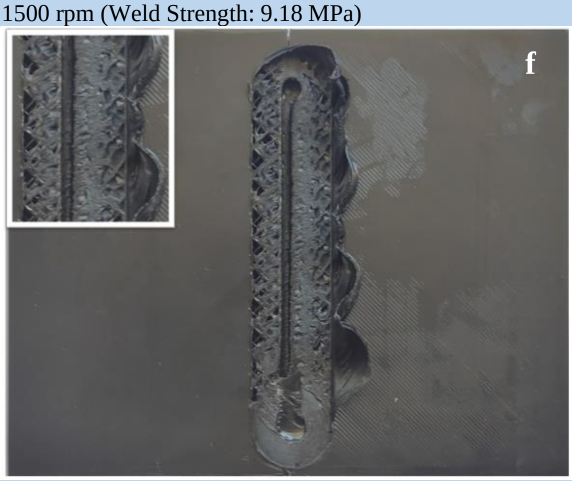
Infill Ratio:40%, Feed Rate: 100 mm/ min, Rotational Speed: 1000 rpm (Weld Strength: 2.66 MPa)



Infill Ratio:40%, Feed Rate: 50 mm/ min, Rotational Speed: 1500 rpm (Weld Strength: 9.18 MPa)

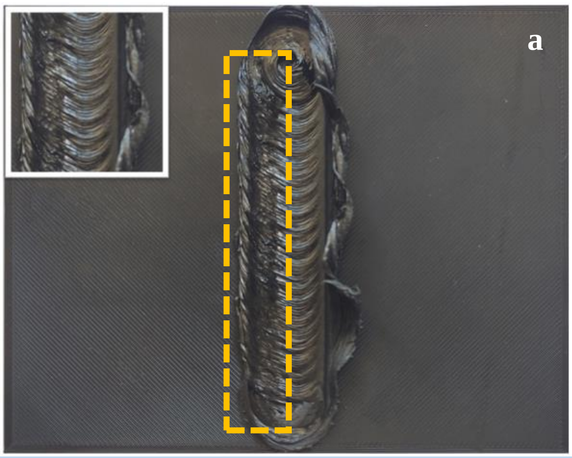


Infill Ratio:60%, Feed Rate: 50 mm/ min, Rotational Speed: 1500 rpm (Weld Strength: 3.88 MPa)

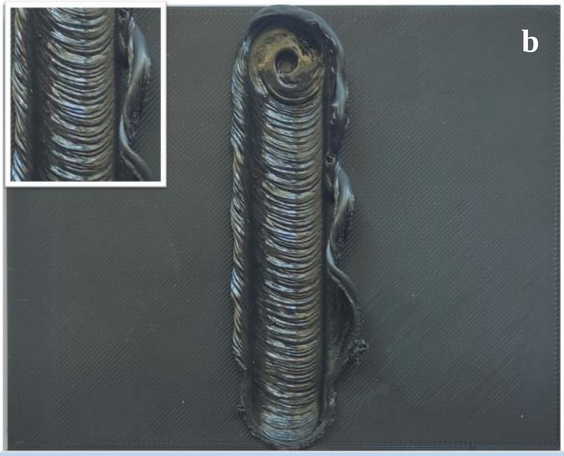


Infill Ratio 60%, Feed Rate: 100 mm/ min, Rotational Speed: 1500 rpm (Weld Strength: 17.47 MPa)

Figure 8. The view of parts with 20%, 40%, and 60% infill ratios after FSW (SKK sonrası %20, %40 ve %60 doluluk oranlarındaki parçalar)



Infill Ratio: 80%, Feed Rate: 100 mm/ min, Rotational Speed: 1000 rpm (Weld Strength: 16.39 MPa)



Infill Ratio: 80%, Feed Rate: 100 mm/ min, Rotational Speed: 1000 rpm (Weld Strength: 83.56 MPa)

Infill Ratio:100%, Feed Rate: 50 mm/ min, Rotational Speed: 1000 rpm (Weld Strength: 54.78 MPa)

Infill Ratio:100%, Feed Rate: 100 mm/ min, Rotational Speed: 1500 rpm (Weld Strength: 87.04 MPa)

Figure 9. The view of parts with 80% and 100% infill ratios after FSW (SKK sonrası %80ve %100 doluluk oranlarındaki parçalar)

3.3. Evaluation of Weld Strength Based on Tool Rotational Speed (Takım Dönüş Hızına Bağlı Kaynak Dayanımının Değerlendirilmesi)

Figure 10 illustrates the variation in weld strength based on rotational speed. It has been determined that the weld quality is not affected by the rotational speed for infill ratios of 20% and 40% at a 100 mm/min feed rate. At 100% infill ratio, weld strength increased with the increase of rotational speed at both feed rates (50 and 100 mm/min). It is seen that the effect of 100 mm/min feed rate increases significantly after 60% infill ratio. While the weld strength increased with increasing rotational speed at 60% and 100% infill ratio, the weld strength decreased with the increase of rotational speed for both feed rates at 80% infill ratio. As a result, it can be said that the low infill ratio makes it difficult to join the parts and limits the effects of the process parameters.

3.4. Evaluation of Weld Strength According to Tool Feed Rate (Takım İlerleme Hızına Göre Kaynak Dayanımının Değerlendirilmesi)

Figure 11 shows the welding strength according to the feed rate. Although the feed rate changed at 1000 rpm rotational speed, the weld strength did not change up to 80% infill ratio. Welding strength increased significantly at 100 mm/min feed rate at 80% infill ratio, and weld quality increased with the increase in feed rate at 100% infill ratio. There was an increase in weld strength at 1500 rpm rotational speed, 50 mm/min at 40% infill ratio, and 100 mm/min feed rate at 60% and 80% infill ratio. It has been determined that the effect of feed rate increases especially at 80% and 100% infill ratios. As a result, it was determined that the feed rate had a greater effect on the weld quality. It can be said that after 60% infill ratio, the feed rate has an impact on the weld quality and has a positive effect. In the FSW process, overheating in the welding area negatively affects the weld quality. Increasing the feed rate during the FSW process will prevent the weld zone from overheating.

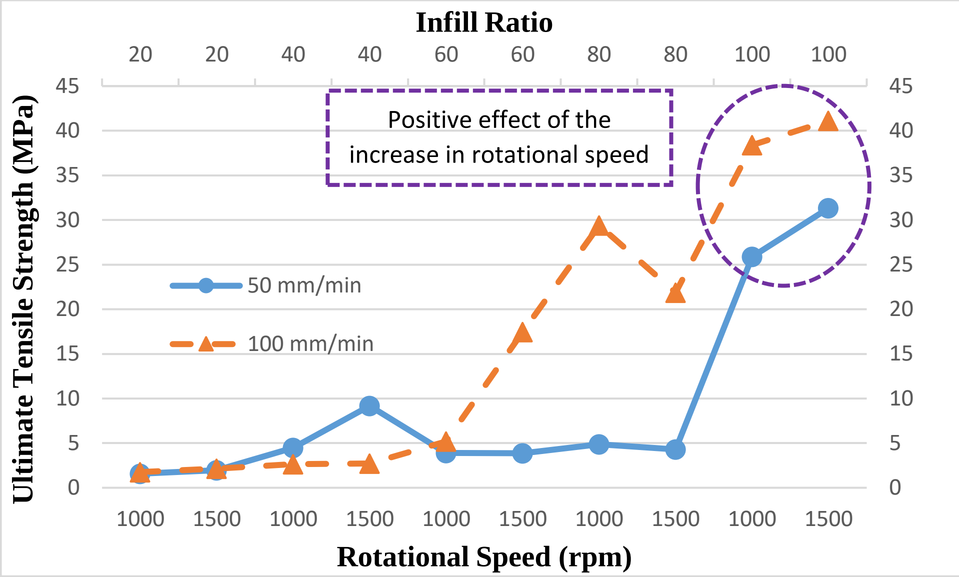


Figure 10. Weld strength depending on rotational speed (Takım dönme hızına bağlı kaynak dayanımı)

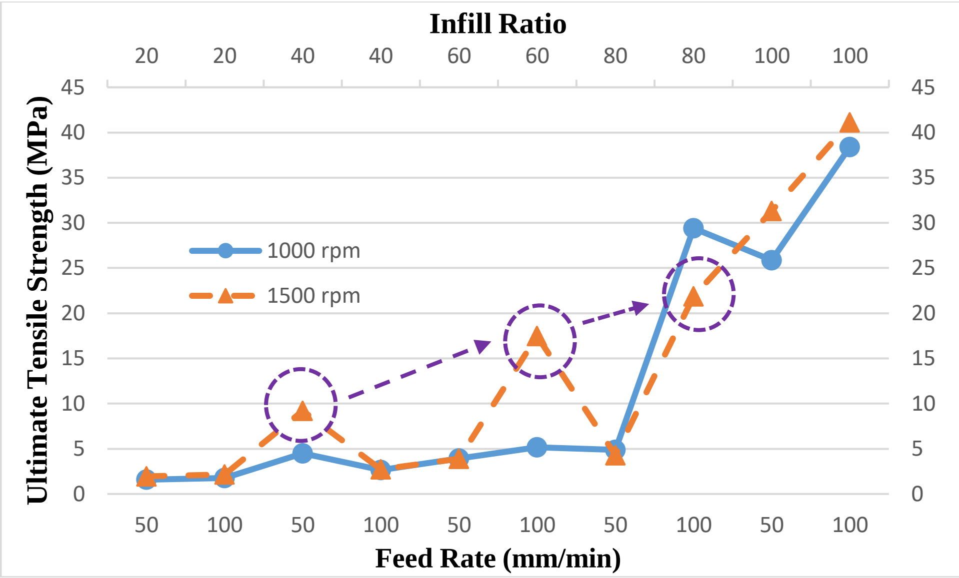


Figure 11. Welding strength depending on feed rate (Takım ilerleme hızına bağlı kaynak dayanımı)

3.5. Evaluation of The Heat Generated During The FSW Process (SKK Sırasında Oluşan Isının Değerlendirilmesi)

The temperatures measured during FSW are given in Figure 12, and the highest, the lowest, and optimum temperature values obtained from thermal images are given in Table 4. When Figure 12 is examined, it is determined that the temperature in the weld zone during FSW was not affected by the process parameters at 20% infill ratio, and the temperature during FSW increased from 40% to 80% infill ratio. The reason for this is that at low infill ratios (20%), the friction of the shoulder against the part is insufficient and therefore negatively affects the welding process (material flow and welding temperature). The increase in the heat generated during the process at 60% and 80% infill ratios is believed to be due to the hindrance caused by the air in the voids within the part's structure, making it difficult for the welding heat to dissipate and leading to its accumulation in the welding area. This phenomenon is supported by the fact that the temperature in the welding area at 100% infill ratio tends to decrease again.

Figure 13 presents thermal camera images of the samples with the highest welding strength obtained when joining parts with different infill ratios FSW. When different infill ratios were considered individually, the temperatures for the highest welding strength were determined as 85.25°C, 118.6°C, 139.95°C, 166.18°C, and 136.18°C, respectively. The temperatures for the lowest welding strength were determined as 96.58°C, 134.88°C, 132.11°C, 175.39°C, and 163.39°C, respectively. The glass transition temperature of

PLA material was 60° C. The temperatures obtained during the FSW process were between 85.25 °C and 189.17 °C, which were above the glass transition temperature. Sharma et al. [9] found the temperature in the weld zone in the range of 75.9-140.7 °C in the images taken with an IR camera in the joining of PLA sheets with FSW. They stated that since the generated welding temperature was above the glass transition temperature, it was easier for the softened polymer to mix with each other, resulting in high-quality welds.

According to the results in Table 4, it has been observed that the temperatures yielding the highest welding strength were within the range of the lowest and highest temperature values. The reason for this is that low temperatures adversely affect material flow, while high temperatures negatively affect welding strength due to excessive plasticization of the material in the weld zone [35,36].

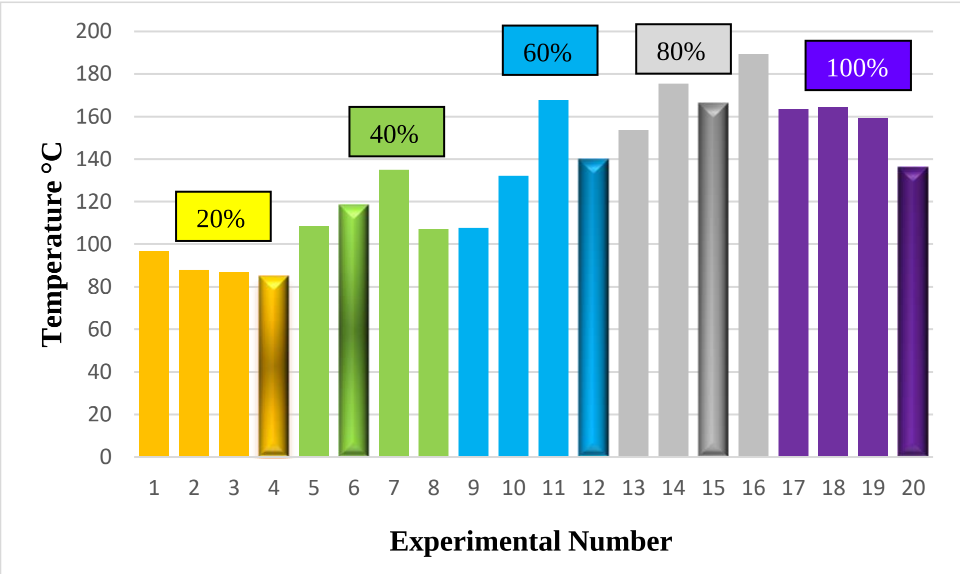
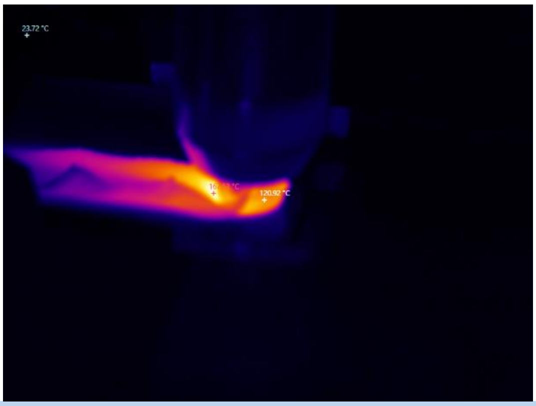


Figure 12. Temperatures measured during the FSW process (SKK işlemi sırasında ölçülen sıcaklıklar)

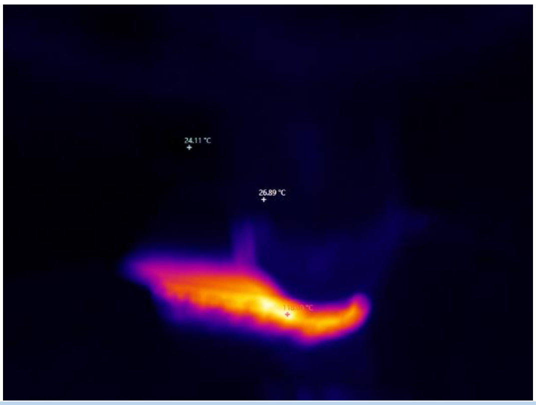
Tablo 4. The highest/lowest/optimum temperature during FSW by different infill ratio

Infill Ratio	Lowest Temperature (°C)	Highest Temperature (°C)	Temperature of Optimum Welding Strength (°C)
20	**85.25** (FR:100 mm/min-RS:1500 rpm)	**96.58** (FR:50 mm/min-RS:1000 rpm)	**85.25** (FR:100 mm/min-RS:1500 rpm)
40	**106.88** (FR:100 mm/min-RS:1500 rpm)	**134.88** (FR:100 mm/min-RS:1000 rpm)	**118.6** (FR:50 mm/min-RS:1500 rpm)
60	**107.66** (FR:50 mm/min-RS:1000 rpm)	**167.53** (FR:100 mm/min-RS:1000 rpm)	**139.95** (FR:100 mm/min-RS:1500 rpm)
80	**153.49** (FR:50 mm/min-RS:1000 rpm)	**189.17** (FR:1000 mm/min-RS:1500 rpm)	**166.18** (FR:100 mm/min-RS:1000 rpm)
100	**136.18** (FR:100 mm/min-RS:1500 rpm)	**164.29** (FR:50 mm/min-RS:1500 rpm)	**136.18** (FR:100 mm/min-RS:1500 rpm)

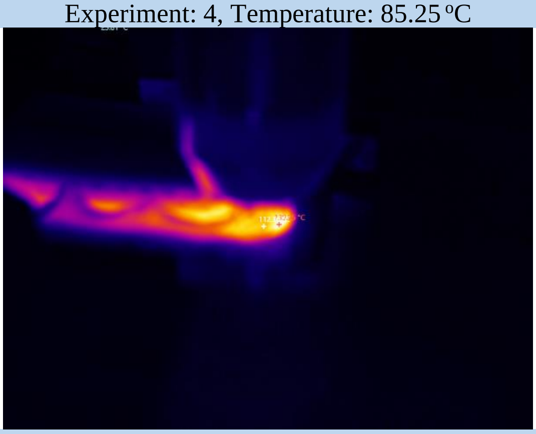
FR: Feed Rate, **RS:** Rotational Speed



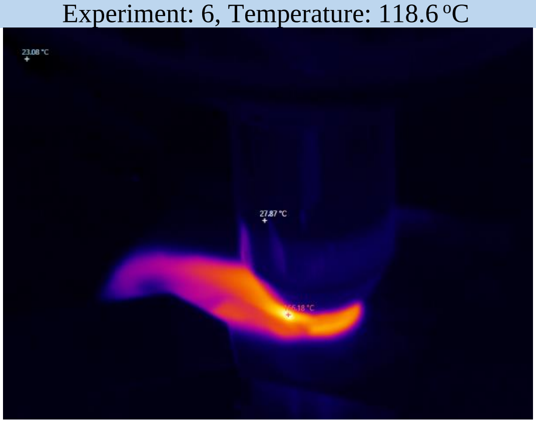
Feed Rate: 100 mm/min, RS: 1500 rpm
Experiment: 4, Temperature: 85.25 °C



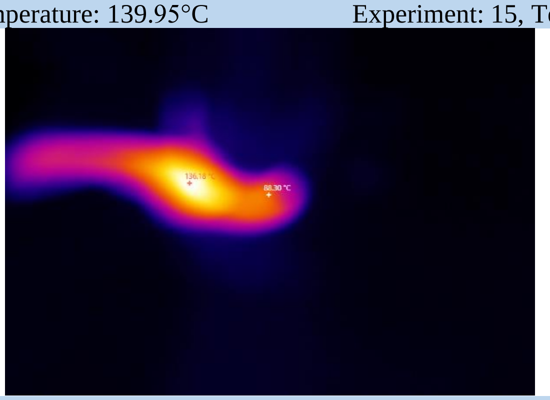
Feed Rate: 50 mm/min, RS: 1500 rpm
Experiment: 6, Temperature: 118.6 °C



Feed Rate: 100 mm/min, RS: 1500 rpm
Experiment: 12, Temperature: 139.95°C



Feed Rate: 100 mm/min, RS: 1000 rpm
Experiment: 15, Temperature: 166.18 °C



Feed Rate: 100 mm/min, RS: 1500 rpm
Experiment: 20, Temperature: 136.18 °C

Figure 13. Thermal imaging of highest welding strength (En yüksek kaynak mukavemetine sahip deneylerden termal görüntüler)

4. CONCLUSIONS (SONUÇLAR)

In the study, the joining behavior of PLA Plus sheets with different infill ratio was examined using FSW. Square pin geometry, two different feed rates (50 and 100 mm/min) and two different tool rotational speeds (1000 and 1500 rpm) were used for welding. The grid pattern was produced as an infill pattern at different infill ratios, and a linear pattern with a 45/-45° angle was produced at 100% infill ratio. The mechanical properties of the PLA Plus material were determined for all infill ratios and the welding efficiency was determined by comparing it with the strength of the welded samples. The weldability of PLA Plus sheets at different infill ratios and the effect of feed rate and rotational speed on the welding process were analyzed experimentally. The key findings of this study are summarized below: Compared to the 20% infill ratio in the reference samples, the strength increased and the % elongation decreased at 40% and 60% infill ratios. At 80% and 100% infill ratios, the strength and % elongation values increased significantly.

The highest tensile strength values for 20%, 60% and 100% infill ratios were obtained at 100 mm/min feed rate and 1500 rpm rotational speed (2.14, 17.47 and 41.12 MPa, respectively), and at 50 mm/min feed rate and 1500 mm/min rpm rotational speed for 40% infill ratio (9.18 MPa). Additionally, the highest tensile strength values were obtained at 100 mm/min feed rate and 1000 rpm rotational speed (29.4 MPa) at 80% infill ratio.

It was determined that the effect of the process parameters on the joining was very low at 20% and 40% infill ratios, and the effect of the process parameters increased as the infill ratio increased.
While flash defect occurred in all samples, surface tunnel defect formation was identified as a result of material insufficiency at 20%, 40% and 60% infilling ratios. When the temperatures occurring during FSW were examined, it was determined that there was an increase from 40% to 80% infill ratio, while there was a decrease in the 100% infill ratio. The insufficient friction during welding at 20% and 40% infill ratios negatively impacts temperature formation, thereby affecting weld quality negatively. On the other hand, it is presumed that temperatures increased at 60% and 80% infill ratios due to the air in the voids, making heat diffusion difficult. In future studies, the part infill ratios can be changed in the range of 70%-100% and their combinability with FSW can be examined. In addition, the effects of infill ratios on FSW process in dissimilar materials can be examined.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Nergizhan ANAÇ*:** She conducted the experiments, analyzed the results and performed the writing process.
Deneyleri yapmış, sonuçlarını analiz etmiş ve makalenin yazım işlemini gerçekleştirmiştir.

Oğuz KOÇAR: He conducted the experiments, analyzed the results and performed the writing process.
Deneyleri yapmış, sonuçlarını analiz etmiş ve makalenin yazım işlemini gerçekleştirmiştir.

Cihan ALTUOK: He conducted the experiments and analyzed the results and performed the writing process.
Deneyleri yapmış, sonuçlarını analiz etmiş ve makalenin yazım işlemini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

NOMENCLATURE (KISALTMA)

3D	3 Dimensions
FR	Feed Rate
FSW	Friction Stir Welding
PLA	Polylactic Acid
RS	Rotational Speed

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