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Optimization of the T-Joint Used in the Interlocking Interface Geometry of Multi-Part Materials Produced by Additive Manufacturing

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Eklemeli İmalatla Üretilen Çok Parçalı Malzemelerin Birbirine Kenetlenen Arayüz Geometrisinde Kullanılan T-Bağlantı Elemanının Optimizasyonu

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Abstract
In the field of Additive Manufacturing (AM), various interlocking methods are used for the detachable assembly of multi-component materials. Although the T-Joint is a widely used interlocking method, the appropriate geometric parameters for this shape are unknown. In this study, the interlocking of multi-component materials produced by AM using T-shaped connecting elements and the optimization of the geometric parameters that constitute them were performed using Response Surface Methodology. A tensile test was simulated using Ansys finite element software, and the von Mises equivalent stress values at the interlocking interfaces of the specimens were examined. Five input parameters and one output parameter, the maximum von Mises equivalent stress value, were determined for RSM optimization. Prior to RSM optimization, a design of experiment was created, and the Box-Benken experimental design method was selected. During the RSM optimization process, the most effective parameters in terms of maximum von Mises equivalent stress were found to be M1P2, M1A1, M1P1, M1A2, and M1P3, respectively. This study has identified more effective and stable geometric interlocking mechanisms. This work provides an important foundation for the optimization of future parametric connection types. However, the findings should be validated through experimental studies, and the optimization process should be expanded to include different material combinations.

Keywords: *Additive Manufacturing, Interlocking Geometry, Response Surface Methodology, Optimization*

Öz
Eklemeli imalat (Eİ) alanında, çok bileşenli malzemelerin sökülebilir montajı için çeşitli kilitleme yöntemleri kullanılmaktadır. T bağlantı elemanı yaygın olarak kullanılan bir kilitleme yöntemi olmasına rağmen, bu şekil için uygun geometrik parametreler bilinmemektedir. Bu çalışmada, Eİ ile üretilen çok bileşenli malzemelerin T şeklindeki bağlantı elemanları kullanılarak kilitlenmesi ve bunları oluşturan geometrik parametrelerin optimizasyonu, Tepki Yüzey Metodolojisi kullanılarak gerçekleştirilmiştir. Ansys sonlu elemanlar yazılımı kullanılarak bir çekme testi simüle edilmiş ve numunelerin birbirine kenetlenme arayüzlerindeki von Mises eşdeğer gerilme değerleri incelenmiştir. RSM optimizasyonu için beş giriş parametresi ve bir çıkış parametresi, yani maksimum von Mises eşdeğer gerilme değeri belirlenmiştir. RSM optimizasyonundan önce, bir deney tasarımı oluşturulmuş ve Box-Benken deney tasarım yöntemi seçilmiştir. RSM optimizasyon süreci sırasında, maksimum von Mises eşdeğer gerilimi açısından en etkili parametrelerin sırasıyla M1P2, M1A1, M1P1, M1A2 ve M1P3 olduğu bulunmuştur. Bu çalışma, daha etkili ve kararlı geometrik kilitleme mekanizmaları belirlemiştir. Bu çalışma, gelecekteki parametrik bağlantı tiplerinin optimizasyonu için önemli bir temel sağlamaktadır. Ancak, bulgular deneysel çalışmalarla doğrulanmalı ve optimizasyon süreci farklı malzeme kombinasyonlarını da içerecek şekilde genişletilmelidir.

Anahtar Kelimeler: *Eklemeli İmalat, Birbirine Kenetlenen Geometri, Tepki Yüzeyi Metodolojisi, Optimizasyon*

1. Introduction

Additive manufacturing (AM) technology is a production method that creates a three-dimensional (3D) physical model by layering molten material based on a digital model of an object. Unlike traditional manufacturing methods, this technology is based on the principle of adding material rather than removing it (e.g., machining). The production process typically begins with the conversion of a computer aided design (CAD) digital file into a physical product using 3D printers (Singh et al. 2019, Karabıyık and Apak 2021, Abdulridha and Abbas 2023).

3D printers, the most common type of AM, are critically important to the manufacturing industry today. In 3D printer manufacturing, Fused Filament Fabrication (FFF), the most common type of AM in fields such as

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automotive, aerospace, and defense, is used. This method plays an important role in industrial production due to the advantages it offers in design flexibility and rapid prototyping (Altunkaynak et al. 2020, Memiş 2024).

FFF is an innovative manufacturing method used in part production with 3D printers, where 3D parts are produced by adding layers of molten material filaments at high temperatures. This method is based on the principle of melting thermoplastic polymers and depositing them in layers, enabling the production of geometrically complex objects. While biodegradable bioplastics produced from renewable sources were commonly used in the early days, today the range of applications has expanded with the introduction of different materials (metal, composite, etc.). Bioplastics, which are advantageous in terms of environmental sustainability, contain components such as Polylactic Acid (PLA), which is synthesized from various bio-based raw materials, primarily corn starch and sugar cane, and is the most widely used. Due to these characteristics, components produced using the FFF method exhibit sustainable qualities that are compatible with ecological balance and have the potential to compost in biological environments (Sürmen 2019, Shanmugam et al. 2021, İncesu 2023, Wang et al. 2023). In this method, which is carried out using a 3D printer, the internal and external structural geometries of the part can be produced with the desired level of complexity. Considering the mechanical strength values of the part, the importance of the 3D printer's printing parameters increases (Patan 2019, Wang et al. 2019, Karagöz et al. Tuna 2021, Akbulut 2022).

Mechanical strength is a critical factor in the reliability of structures and products. Examining how materials behave within specified boundary conditions and desired parameters is of great importance in evaluating their performance. The mechanical properties of a workpiece under load, such as deformation, fracture, and fatigue, can be measured and analyzed using various strength tests. The data obtained from these tests guides optimization and quality control processes, while simulations performed prior to testing using the Finite Element Method (FEM) enable predictions to be made. FEM is a method that provides numerical analysis and solutions to engineering problems and has been applied in many fields since the mid-20th century, particularly in machinery, automotive, aerospace, and space industries. This method, which reduces the need for experimental testing and helps obtain results close to real-world conditions in a digital environment, is a critical tool that enables evaluations based on analysis results and optimization steps (Ay 2019, Eser 2021, Turan et al. 2022, Özden and Gökçe 2023).

In recent years, when mechanical and functional optimization has been targeted in manufactured parts, the production of multi-material parts using AM methods has become widespread. In this regard, multi-material additive manufacturing (MMAM) has brought numerous topological, mechanical, and physical advantages. Although weight reduction and durability have often been the criteria in many studies since the introduction of the MMAM method, its importance has been increasing with its use in areas such as biomedical applications and tissue engineering. FFF, the most common method used in MMAM, allows the production of materials with different properties or different geometries. Today, 3D printers enable the application of this method through flexible production processes such as single nozzle or multi-nozzle printing (Ribeiro et al. 2019, Mustafa and Kwok 2022).

This new technology, MMAM, is currently being tested for various types of multi-part prints with optimization goals in mind, and research and development activities are ongoing. The main connection types used for the interlocking of multiple parts produced with MMAM and the optimization of these interlocking interfaces are U, Dovetail, and T (Mihalache et al. 2022, Altuntaş 2024, Liu et al. 2024). When examining studies on interlocking interface geometries, the advantages of T and Dovetail connections over others stand out in many aspects. In their study on U, T, and Dovetail interface interlockings in the MMAM field, Ribeiro et al. (2019) evaluated their performance under mechanical behaviors such as Young's modulus, fracture strength, and fracture strain, revealing that the T interface geometry exhibited superior performance compared to the others. Frascio et al. (2024) compared T and Mickey-Mouse interface geometries in similar studies and observed that the T interface geometry exhibited better mechanical behavior.

To maximize the mechanical performance of multi-material or interlocking connection interfaces produced using additive manufacturing technologies, FEM-based numerical simulations and parametric optimization processes are widely used (Peralta Marino et al. 2022). This simulation-based parametric optimization, combined with DOE approaches, enables the mathematical modeling (e.g., using second-degree polynomial equations, machine learning) of the relationships between production geometric parameters and mechanical strength (stress, deformation, etc.) (Mihalache et al. 2022). This analytical framework, which allows for the detailed investigation of linear or non-linear mechanical behavior under boundary conditions, provides a rational and scientific basis for determining the optimal interface design that maximizes macroscopic locking between different polymer pairs with weak chemical affinity (Frascio et al. 2024).

While studies comparing the geometries of interlocking interfaces exist in literature, there are no studies on the parameters that constitute geometry. In fact, it is thought that the parameters that form geometry play an active role in the joints. In this study, the optimization of the parameters that form the T-shape, one of the joint interfaces used in the MMAM field, was performed in the ANSYS Workbench 2025 R1 program and the mechanical effects of the parameters on the joined parts were revealed. Additionally, it is intended to determine the most suitable geometric parameters that target the maximum stress generated in the bonding interface for this purpose and to statistically examine the correlations between the input and output parameters.

2. Materials and Methods

2.1 Material Selection

PLA, a rigid biodegradable thermoplastic polymer with isotropic elasticity properties, was used as the material for the optimization process.

Table 1. PLA General Material Properties

Feature	Unit	Value
Density	kg/m³	1250
Young's Modulus	MPa	3450
Poisson Ratio	-	0,39
Volume Module	MPa	5220
Shear Modulus	MPa	1240

2.2 T-Shaped Connection Geometry

Among the many connection shapes with interlocking interface geometries used in the MMAM field, the T-shaped connection was selected due to its mechanical performance advantage. The ASTM D638-14 Type III sample was used (Test Method for Tensile Properties of Plastics 2014). The geometric parameters of the T-shaped connection are shown in Figure 1.

The T-shape geometry of the test sample is formed by the interlocking of M1 (material 1 - male part) and M2 (material 2 - female part). It consists of the parameters M1P1 (material 1 parameter 1), M1P2, M1P3, M1A1 (material 1 angle 1), and M1A2. Changing these parameters automatically updates the parameters of the female form belonging to material 2. Changing the angle values of M1A1 and M1A2 changes the geometric form of the T-shape connection to a certain extent.

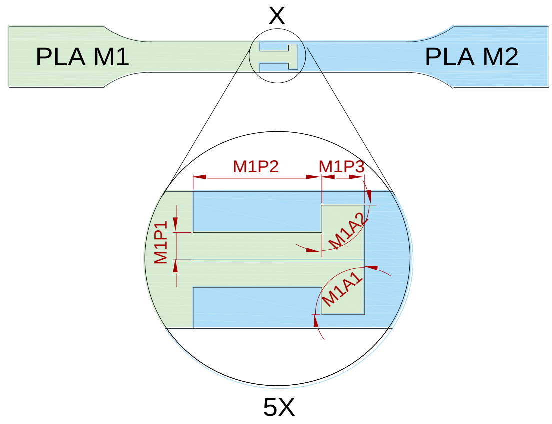

Figure 1. T-shape geometry and parameters

2.3 T-Shaped Connection Parameters and RSM

The boundary conditions for the five parameters of the T-shaped connection have been determined. The values were examined at three levels with equal total increments. The parameters and their corresponding levels are shown in Table 2. The lower and upper values of the geometric parameters selected in the study were determined by considering production constraints, weak geometric forms, stress concentrations, etc., during the formation of the interlocking interfaces of the parts in the MMAM field.

Table 2. T-Shaped Connection Parameter Boundary Conditions

Parameter	L1	L2	L3
M1P1 (mm)	2	3	4
M1P2 (mm)	4	7	10
M1P3 (mm)	1,5	3	4,5
M1A1 (°)	90	112,5	135
M1A2 (°)	90	112,5	135

L-Level

In this study, stress values formed on the clamping interface geometry were determined as output based on the input parameters specified in Table 2. Within this scope, experimental designs (DOE - Design of Experiments) were created in the ANSYS RSM module to establish statistical relationships between parameters. There are many DOE types within ANSYS RSM. Considering the large number of parameters in our study and the limited number of experiments, the Box-Behnken DOE type was selected. A Box-Behnken DOE design with 5 input and 1 output parameters, consisting of 42 experiments, is shown in Table 3.

Table 3. Box-Behnken experimental design input and output parameters

Test No	**M1A1** (°)	**M1A2** (°)	**M1P1** (mm)	**M1P3** (mm)	**M1P2** (mm)	**von-Mises Stress** (MPa)
1	90	90	4	3,2	9	89,82
2	112,5	112,5	3	3	7	68,59
3	90	90	3	3	7	81,17
4	135	90	3	3	7	72,26
5	90	135	3	3	7	73,69
6	135	135	3	3	7	66,42
7	112,5	112,5	2	1,5	7	68,08
8	112,5	112,5	4	1,5	7	94,67
9	112,5	112,5	2	4,5	7	61,61
10	112,5	112,5	4	4,5	7	77,61
11	112,5	90	3	3	4	72,86
12	112,5	135	3	3	4	78,14
13	112,5	90	3	3	10	72,71
14	112,5	135	3	3	10	74,34
15	90	112,5	2	3	7	69,54
16	135	112,5	2	3	7	65,12
17	90	112,5	4	3	7	77,73
18	135	112,5	4	3	7	74,15
19	112,5	112,5	3	1,5	4	78,44
20	112,5	112,5	3	4,5	4	72,60
21	112,5	112,5	3	1,5	10	84,30
22	112,5	112,5	3	4,5	10	63,50
23	112,5	90	2	3	7	76,15
24	112,5	135	2	3	7	67,01
25	112,5	90	4	3	7	85,18
26	112,5	135	4	3	7	81,48
27	90	112,5	3	1,5	7	89,11
28	135	112,5	3	1,5	7	69,50
29	90	112,5	3	4,5	7	65,37
30	135	112,5	3	4,5	7	62,21
31	112,5	112,5	2	3	4	68,78
32	112,5	112,5	4	3	4	86,57
33	112,5	112,5	2	3	10	74,05
34	112,5	112,5	4	3	10	82,06
35	90	112,5	3	3	4	74,15
36	135	112,5	3	3	4	73,14
37	90	112,5	3	3	10	74,02
38	135	112,5	3	3	10	66,04
39	112,5	90	3	1,5	7	100,63
40	112,5	135	3	1,5	7	83,58
41	112,5	90	3	4,5	7	68,67
42	112,5	135	3	4,5	7	64,56
43*	118,74	90,45	4,00	1,50	9,82	96,66
44*	122,40	90,17	4,00	1,50	9,70	109,05
45*	119,19	90,75	3,99	1,51	10,00	100,04
46*	125,13	90,09	4,00	1,51	9,85	103,57

*Generated from optimization

2.4 FEM Boundary Conditions and Analysis

The connection regions formed at the bonding interface of two PLA materials are comprehensively defined by a three-stage boundary condition; specifically, Contacts 1, 2, and 3 are defined as distinct friction surfaces with varying friction coefficients of 0.01, 0.3, and 0.3, respectively (Figure 2.) (Pawlak et al. 2019). This nuanced contact formulation is essential for accurately capturing the mechanical behavior during the physical interaction. The localized region inside the sphere with a 25 mm radius, which covers the clamping interface area used for the tensile test simulation, is refined to have a mesh size of 1 mm, while the remaining global regions of the sample piece have a coarser mesh size of 2 mm to optimize computational efficiency. The specific mesh body method applied throughout the geometry is Quad Dominant (Quadrilateral Weighted), and the elements are mathematically defined as tet10 (ten-node parabolic quadrilateral) structures. Consequently, the final discretized model of the mesh consists of 122,862 nodes and 83,871 elements. The overall structural integrity is confirmed, as the mesh element quality has an average of 81.4%, indicating a highly robust discretization. The final visual appearance of the test specimen after the complete mesh application is clearly illustrated and shown in Figure 3a.

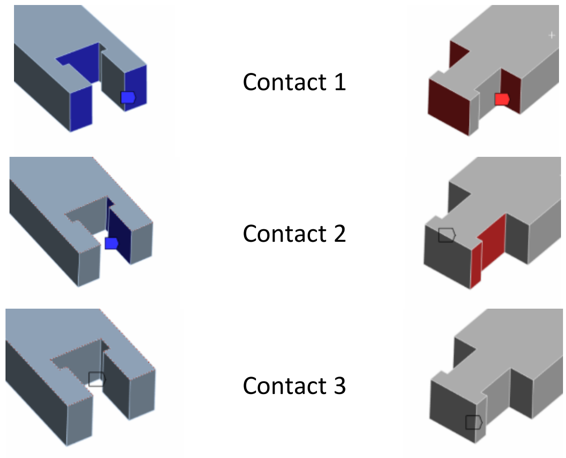

Figure 2. Contact types at the clamping interface

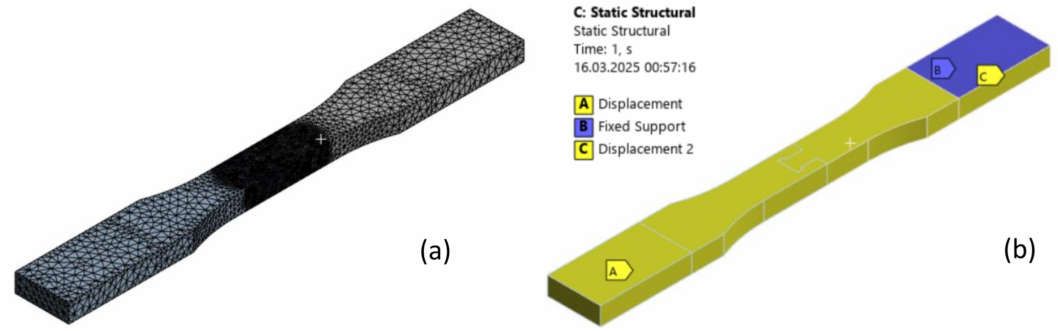

Figure 3. The mesh structure (a) and boundary conditions (b) of the sample

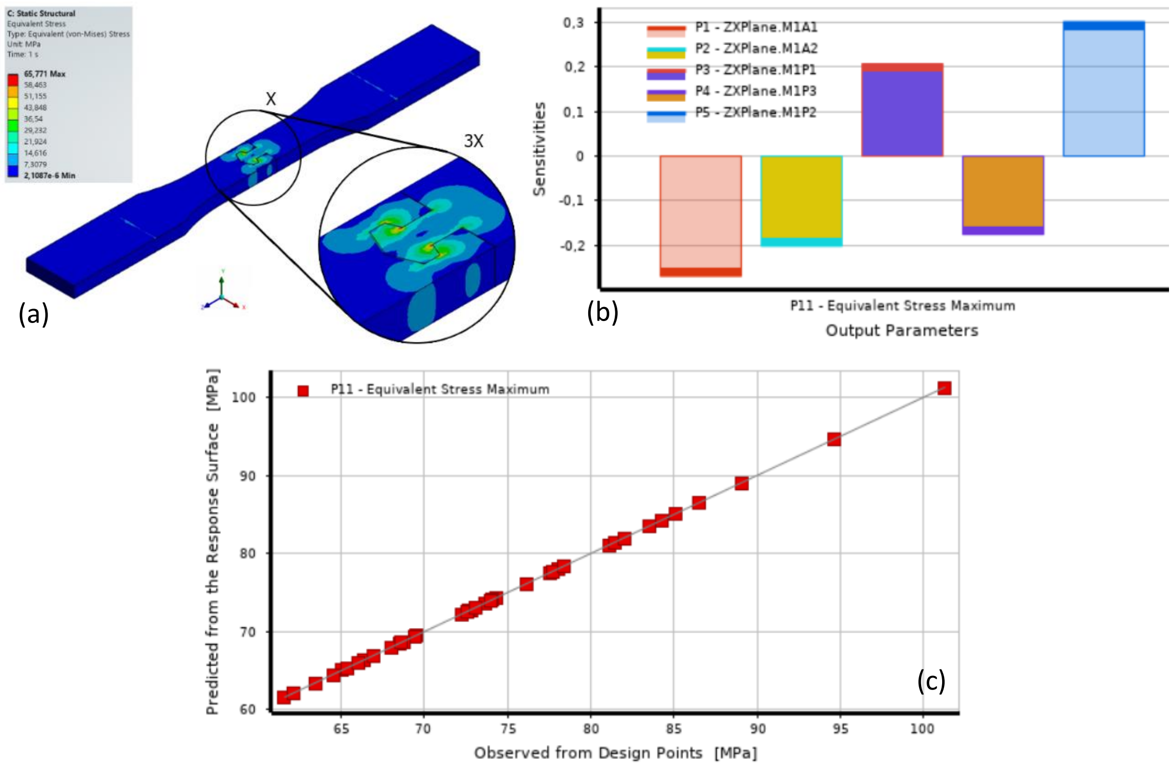

Figure 4. a) von Mises equivalent stress values on the specimen according to the results of the static tensile test performed with FEM, (b) Sensitivity of the parameters used in RSM optimization on the von Mises equivalent stress formed on the part, (c) Accuracy of the response surface model (R^2 graph - Goodness of Fit)

In accordance with the working principle of the tensile testing machine, one end of the test specimen (Figure 3b-B surface) was held stationary, and the other end (Figure 3b – A surface) was subjected to a displacement of 0.35

mm in the axial direction. Furthermore, during the analysis, the axial movement of the part was free, while movements in the other coordinates (x and y) were constrained. The defined boundary conditions are shown in Figure 3b. During the analysis, the parts were modeled as homogeneous, isotropic, and linearly elastic (ElHassan *et al.* 2024).

3. Results

Based on the preliminary static analysis results obtained prior to RSM optimization, the maximum von Mises stress value was determined to be 66.771 MPa (Figure 4a). The geometric parameter values used in the analysis were taken as averages (Table 2-L2). Looking at the results obtained, it can be seen that stress concentration occurs at sharp corners where stresses in opposite directions are present at the bonding interfaces. The static analysis result shows where stress concentrations occur and where damage will occur in the later stages of the tensile test process. In addition, the stress values obtained from the static analysis results were used for comparison purposes during the optimization process. Each T-shaped connection parameter has different sensitivity on stress. Figure 4b shows the sensitivity of these parameters on von Mises equivalent stress.

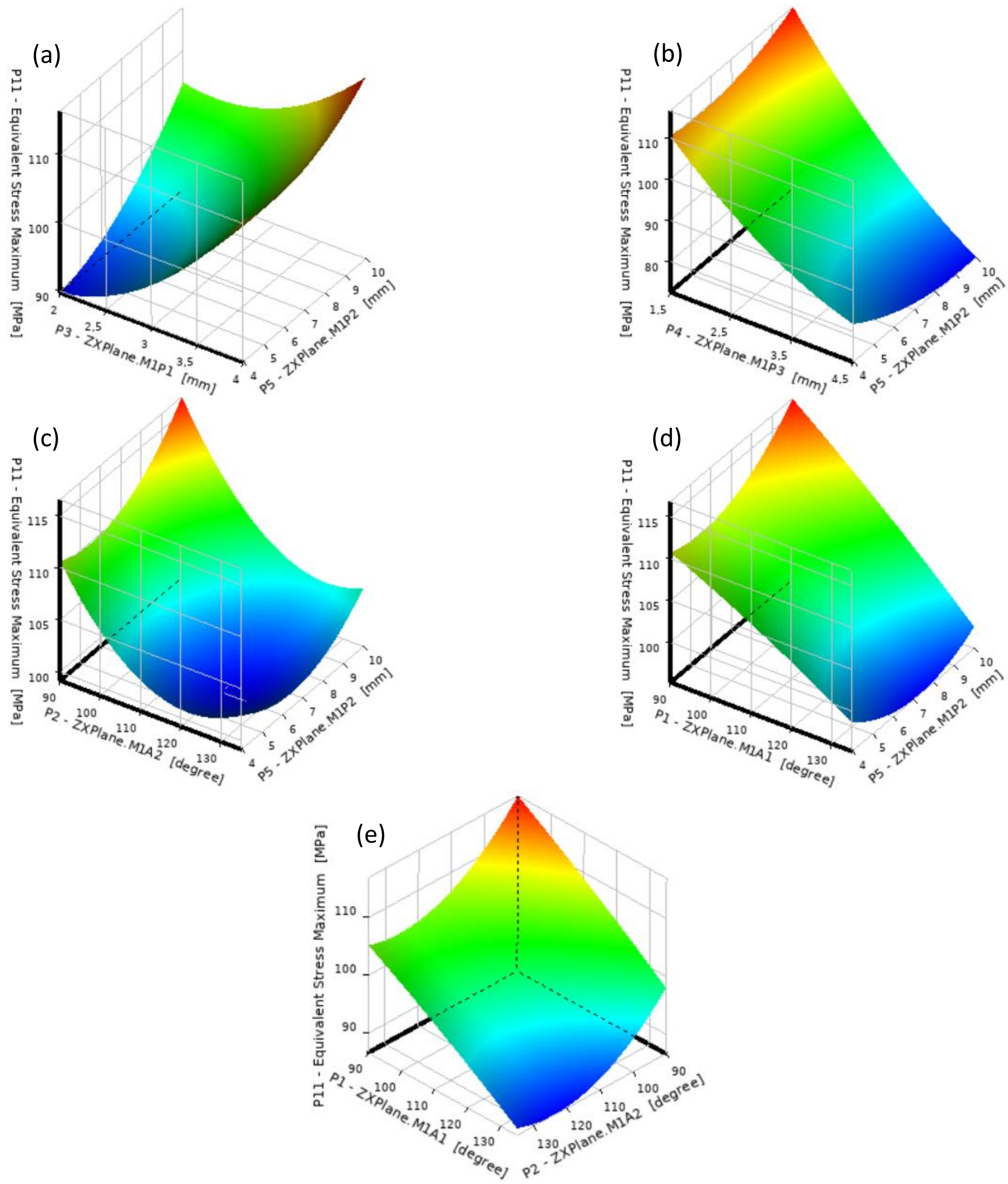

Figure5. 3D graphs showing the relationships between the equivalent stress values of the parameters on the sample according to FEM results (a) M1P2-M1P1, (b) M1P2-M1P3, (c) M1P2-M1A1, (d) M1P2-M1A2, and (e) M1A2-M1A1

Looking at the graph, it can be seen that the parameter with the highest sensitivity is M1P2, and that it has a positive effect on stress. It is understood that as the M1P2 value increases, the stress value also increases. The other sensitivity ratios are listed in descending order as M1A1, M1P1, M1A2, and M1P3. While the M1P1 and M1P2 parameters have a positive effect on the stress value, the M1P3, M1A1, and M1A2 parameters have a negative effect. The predictive capability of the response surface model constructed using deterministic data sets obtained from FEM analysis has been validated using goodness-of-fit metrics. Due to the nature of computer-aided engineering simulations not containing random measurement errors, the model's coefficient of determination (R^2) was calculated as 1.0, indicating perfect fit, and it was demonstrated that lossless interpolation was achieved in the design space (Figure 4c). According to the RSM results, 3D graphs showing the effects of M1P2, the parameter with the highest activity level on equivalent stress, together with other parameters on stress are shown in Figure 5. It was observed that the equivalent stress value increased with the positive increase of the M1P2 and M1P1 parameters (Figure 5a). It was seen that the stress value increased with the increase in the M1P2 parameter and the decrease in the M1P3 parameter (Figure 5b). Here, it was observed that the M1P3 parameter had a negative effect on the stress value. It was seen that the stress value increased with the increase in the M1P2 parameter and the decrease in the M1A1 parameter (Figure 5c), an increase in the M1P2 parameter and a decrease in the M1A2 parameter resulted in an increase in the stress value (Figure 5d), and a decrease in the M1A1 parameter and a decrease in the M1A2 parameter resulted in an increase in the stress value (Figure 5e) were obtained from the graphs.

When considering the stress changes resulting from the interactions between the parameters used in RSM optimization according to their sensitivity, it is observed that the importance levels of all parameters are close to each other.

4. Discussion and Conclusion

In this study, the optimization of geometric parameters on T-shaped connections used in the detachable assemblies of multi-part structures produced by AM was performed. The results of the study revealed that the M1P2 parameter has a greater effect than the other parameters when considering the stress distributions formed on the clamping surfaces (Figure 4b). A detailed examination of Figure 4b shows that all five input parameters have high sensitivity. Trade-off is a decision support process that systematically shows how much to compromise on which objectives in complex engineering decisions, evaluating both simulation and production constraints together. In the optimization process carried out in this study, 3D Trade-off graphs were created to observe the interaction between geometric parameters and equivalent von Mises stress (Figure 6). The green areas on the graph indicate regions or design points suitable for design. The blue points indicate areas with high stress, while the red points indicate areas with low stress values. Evaluations using trade-off graphs allow for design-oriented interpretations as well as assessments of safety conditions, cost, manufacturability, etc. In the graph in Figure 6a, the M1P2 parameter can be any value between 9.55 and 9.95 mm for a suitable design. However, in the graphs in Figures 6b-d, Upon examination, it is evident that not all values within this range can be selected for an appropriate design. Considering all graphs, it has been determined that the 9.75-9.95 mm value range can be selected for appropriate design points. When considering the M1A1 and M1A2 angle parameters, the most appropriate design points occur when approaching the 90° value (Figure 6e). It has been determined that the von Mises stress values on all graphs vary within a very narrow band (~1 MPa variation). This specific behavior proves that the parameters examined have a similar sensitivity to the maximum stress response and that the developed model exhibits high structural stability against possible manufacturing tolerances or dimensional deviations. The correlations between the input parameters that form the geometric interlocking with the help of RSM and the output parameters that occur on the interlocking and are called equivalent stress are examined in Figure 4b, Figure 5, and Figure 6.

In the study, the Multi-Objective Genetic Algorithm (MOGA) method was used in the RSM optimization process to determine the most suitable parameters based on the maximum equivalent von-Mises stress value formed on the geometric interlocking. The study was examined in a sample space of 5000, and 3 candidate design points were determined after 20 iterations (Figure 7). Looking at this candidate list, it can be seen that the values of the angle parameters M1A1 and M1A2 are close to 90°. It is understood that the M1P1 parameter is close to 3.99 mm, M1P2 is close to 9.95 mm, and the M1P3 parameter is close to 1.5 mm. When data close to the values in the candidate list were entered as input parameters, the equivalent stress was observed to be at its maximum (≈116 MPa).

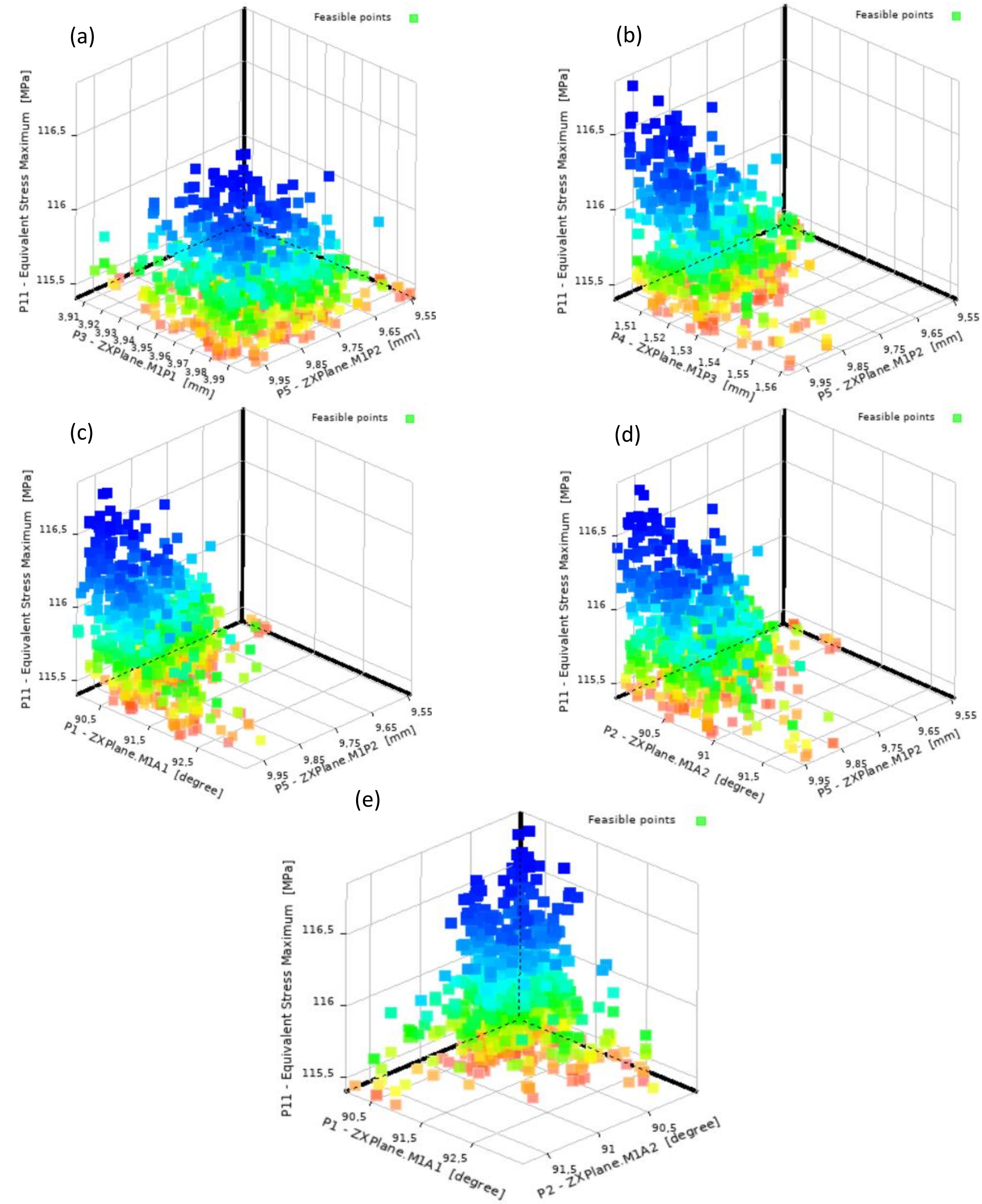

Figure 6. 3D Trade-off graphs of geometric parameters based on von-Mises equivalent stress values formed on the sample; (a) M1P2-M1P1, (b) M1P2-M1P3, (c) M1P2-M1A1, (d) M1P2-M1A2, and (e) M1A2-M1A1

Candidate Points	Candidate Point 1	Candidate Point 1 (verified)	Candidate Point 2	Candidate Point 2 (verified)	Candidate Point 3	Candidate Point 3 (verified)
P1 - ZXPlane.M1A1 (degree)	90,552		90,147		91,459	
P2 - ZXPlane.M1A2 (degree)	90,209		90,105		90,398	
P3 - ZXPlane.M1P1 (mm)	3,9964		3,986		3,9975	
P4 - ZXPlane.M1P3 (mm)	1,5056		1,5091		1,5132	
P5 - ZXPlane.M1P2 (mm)	9,991		9,9493		9,9459	
P11 - Equivalent Stress Maximum (MPa)	116,86	129,59	116,74	121,64	116,11	138,23

Figure 7. Candidate list determined based on the maximum equivalent von Mises stress value, which is the output parameter resulting from RSM optimization

In the field of AM, numerous methods and geometric models have been tested in the literature for interlocking different geometric parts (Mihalache et al. 2022, Frascio et al. 2024). These studies have indicated that the T-connection method is superior to other geometric forms. However, the optimizations of the geometric forms themselves and the correlations between the parameters have not been addressed parametrically in this studies. This study aims to address this gap and determine the method. This optimization method, which is addressed theoretically, will be supported by applied and experimental studies in the future.

Declaration of Ethical Standards
The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement
Author-1: Supervision, Conceptualization, Methodology / Study Design, Formal Analysis, Validation, Investigation, Resources, Data Curation, Visualization
Author-2: Methodology / Study design, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Writing – Review and Editing,
Author-3 Conceptualization, Investigation, Resources, Data Curation, Funding Acquisition

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement
All data generated or analyzed during this study are included in this published article.

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