

NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF DISTORTION
AND RESIDUAL STRESS IN 316L STAINLESS STEEL PLATES CAUSED BY
LASER WELDING

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY
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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
METALLURGICAL AND MATERIALS ENGINEERING

MARCH 2025

Approval of the thesis:

**NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF
DISTORTION AND RESIDUAL STRESS IN 316L STAINLESS STEEL
PLATES CAUSED BY LASER WELDING**

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ABSTRACT

NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF DISTORTION AND RESIDUAL STRESS IN 316L STAINLESS STEEL PLATES CAUSED BY LASER WELDING

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March 2025, 154 pages

Welding-induced distortion and residual stress are crucial because they can significantly impact the structural integrity and performance of welded components. The progress of computational power and software has simplified the implementation of the finite element method in the analysis of welding processes, allowing for a deeper understanding of the formation of residual stress and distortion, and thus their minimization. Laser welding joins metal components with a narrower heat-affected zone and less distortion than conventional welding methods like resistance spot welding and TIG/MIG welding. In this study, to optimize laser welding process parameters for better mechanical performance and dimensional stability, the effects of laser power and welding speed on the distortion and residual stress state in the 316L stainless steel plates were investigated using the Simufact Welding software. The simulation results were validated via measurements using height gauge equipment for distortion and the X-ray diffraction method for residual stress.

Keywords; Welding Technologies, Laser Welding of Stainless Steel, Integrated Computational Materials Engineering, Modelling & Simulation, Residual Stress & Distortion



ÖZ

316L PASLANMAZ ÇELİK LEVHALARDA LAZER KAYNAĞINDAN KAYNAKLANAN ÇARPILMA VE KALINTI GERİLİMİN SAYISAL VE DENEYSEL İNCELENMESİ

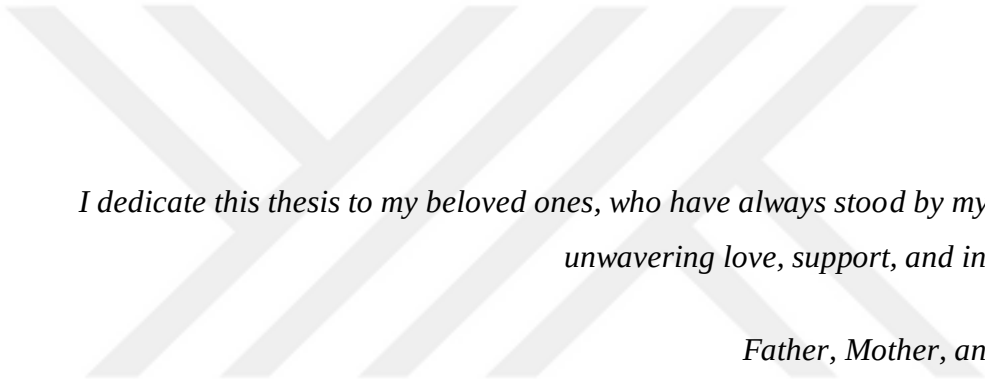
Gökkaya, Emre Denizcan
Yüksek Lisans, Metalurji ve Malzeme Mühendisliği
Tez Yöneticisi: Prof. Dr. Cemil Hakan Gür

Mart 2025, 154 sayfa

Kaynak sebepli çarpılma ve kalıntı gerilim, kaynaklı bileşenlerin yapısal bütünlüğünü ve performansını önemli ölçüde etkileyebilecekleri için kritik öneme sahiptir. Hesaplama gücü ve yazılımdaki ilerlemeler, kaynak süreçlerinin analizinde sonlu elemanlar yönteminin uygulanmasını basitleştirerek, kalıntı gerilim ve çarpılmanın oluşumunun daha iyi anlaşılmasını ve böylece bunların en aza indirilmesini sağlamıştır. Lazer kaynağı, metal bileşenleri direnç nokta kaynağı ve TIG/MIG kaynağı gibi geleneksel kaynak yöntemlerinden daha dar bir ısıdan etkilenen bölge ve daha az çarpılma ile birleştirir. Bu çalışmada, daha iyi mekanik performans ve boyut kararlılığı için lazer kaynak işlemi parametrelerini optimize etmek amacıyla, lazer gücünün ve kaynak hızının 316L paslanmaz çelik plakalardaki çarpılma ve kalıntı gerilim durumu üzerindeki etkileri Simufact Welding yazılımı kullanılarak incelenmiştir. Simülasyon sonuçları, çarpılma için mihengir ve kalıntı gerilim için X-ışını kırınımı yöntemi kullanılarak yapılan ölçümlerle doğrulanmıştır.

Anahtar Kelimeler; Kaynak Teknolojileri, Paslanmaz Çelik Lazer Kaynağı,
Entegre Hesaplamalı Malzeme Mühendisliği, Modelleme ve Simülasyon, Kalıntı
Gerilim & Çarpılma





*I dedicate this thesis to my beloved ones, who have always stood by my side with
unwavering love, support, and inspiration.*

Father, Mother, and Brother

ACKNOWLEDGMENTS

I express my gratitude to Prof. Dr. Cemil Hakan Gür for all his help, patient behavior, guiding attitude, and support. I am much obliged for guiding me with his experience and knowledge in completing this project despite all the difficulties and limitations.

In loving memory of Assoc. Prof. Dr. Caner Şimşir. Always remembered with gratitude.

I greatly appreciate my colleagues Okay Tutar, Metin Bilginay, Egemen Özgenç, Sergen Ünal, Melikşah Ünal, Özlem Gerçek Öksüz, İhsan Ahmet Yüksel, Mustafa Konat, Can Bahadıroğlu, Ahmet Furkan Boncukoğlu, Begüm Erdem, and Deniz Doğan, who gave me great support and help in completing this study.

I would also like to thank my ICME research group, Mehmet Şamil Dinçer, and Cem Diyarbakır for their experienced guidance and advice.

I am beyond grateful to my source of happiness, Elif Buse Sungur, who never left me alone in this hard time and gave me inspiration and dedication, with all my heart.

Finally, from the bottom of my heart, I would like to thank my precious family for supporting me in completing this work and supporting me throughout every period of my life.

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LIST OF ABBREVIATIONS

ABBREVIATIONS

AISI	:	American Iron and Steel Institute
ASME	:	American Society of Mechanical Engineers
ASTM	:	American Society for Testing and Materials
AWS	:	American Welding Society
EDS	:	Energy Dispersive Spectroscopy
FCC	:	Face Centered Cubic
GTAW	:	Gas Tungsten Arc Welding
HAZ	:	Heat Affected Zone
HB	:	Brinell Hardness
HLM	:	Hybrid Laser-MIG
HLT	:	Hybrid Laser-TIG
HRC	:	Rockwell Hardness (Scale C)
HTB	:	High Temperature Brazing
HV	:	Vickers Hardness
ISO	:	International Organization for Standardization
LASER	:	Light Amplification by Stimulated Emission of Radiation
MAG	:	Metal Active Gas
MIG	:	Metal Inert Gas
NDT	:	Non-Destructive Testing
OES	:	Optical Emission Spectroscopy
SAW	:	Submerged Arc Welding
TIG	:	Tungsten Inert Gas
UTS	:	Ultimate Tensile Strength

LIST OF SYMBOLS

SYMBOLS

cm	:	Centimeter
J	:	Joule
kN	:	Kilonewton
m	:	Meter
mm	:	Milimeter
MPa	:	Megapascal
sec	:	Second
μm	:	Micrometer
W	:	Watt
σ	:	Stress

CHAPTER 1

INTRODUCTION

Welding is defined by the American Welding Society (AWS) as the process of joining metals or nonmetals together in a predefined area with the use of heat to melt the base metal to welding temperatures, which is known as fusion of materials [1]. In other words, welding is combining two separate materials into one piece when enough heat is applied to soften or melt the separate pieces together. Additive materials as filler are not a must in this process. Welding has many uses, such as ships, buildings, aircraft, and automobiles.

There are different types of welding as follows:

- Resistance welding
- Gas welding
- Arc welding
- SAW, TIG, and MIG/MAG welding
- Electron Beam welding
- Laser welding

The basic welding techniques were all developed during World War I, and their industrial uses started in World War II in the aircraft industry [2]. Laser welding operation has advantages such as different kinds of materials, such as different metals and plastic, even glass that can be joined with automatic or half-automatic robotic laser weld equipment. The environment of laser welding for protecting the fusion zone to minimize oxidation can be enabled by using Helium (He) or Argon (Ar). Nevertheless, it can be used without protecting the atmosphere, in other words, an open atmosphere. The important characteristics of laser welding can be shortly described as a high-quality fusion zone and precise dimensions after

welding due to low distortion. However, it is important to understand the material's behavior under different welding parameters since weld penetration, welding defects, and cooling behavior after welding are general issues for a welding operation [3]. The main two parameters in a general welding operation that should be considered are the residual stresses after welding and distortion since the former may cause premature defects or cracks with cyclic loads, which is the common load type in airframe structures. Due to the long-life use of the load-carrying structures, it is crucial to take into account the fatigue behavior of the weld zone. The latter can cause the failure in the assembly of the part with other frame structures or with fasteners [4]. Grade 316L Stainless Steel has enormous advantages; firstly, it has excellent corrosion resistance, which is a critical threshold for engineering applications. The corrosion resistance of the stainless material is an important threshold because some structural materials are present on the product without being changed throughout the product's life cycle, and a fault in this structural material can cause a catastrophic result. For different environments: gas-containing (CO_2 , SO_2), acid-containing (Sulfuric Acid), salt-containing (NaCl), etc. Grade 316L Stainless Steel has excellence in corrosion resistance due to the presence of molybdenum content [5]. Since Grade 316L Stainless Steel material is in a stainless material group included in the austenitic class, it is also chosen as the material in fasteners such as nuts and bolts, which are frequently used in corrosive environments. Also, the welding behavior of Grade 316L Stainless Steel is a criterion for selection in the welded structures, since Grade 316L Stainless Steel does not undergo phase transformation during welding, which is a crucial factor that can increase the distortion or residual stresses. In this thesis study, it is planned to Grade 316L Stainless Steel, thermomechanical analysis, compare it with real laser welding results, and verify real laser welding results with simulation. The weld zone of real laser welding results and simulation should be similar in terms of dimensional and shape. The configuration in the simulation must be the same as the actual laser source configuration, in terms of

clamping, laser weld line, laser welding parameters etc. The thesis study consists of 3 parts:

In the first part, mechanical, microstructure, and chemical tests and dimensional measurements of the base metal plate in C_0 configuration (To avoid confusion, it is named C_0 configuration from now on) without laser welding will be carried out. Also, the simulation of the welding will be performed before starting real-world welding experiments with Simufact Welding software. To identify the weld pool of the selected parameters, the trial&error method will be used. To perform welding simulations, weld pools must be defined (pool diameter and pool depth). Before running the welding operation on real coupons, the welding parameters will be tested on a trial coupon, and the weld pools will be examined macroscopically. For this adjustment, thermal analysis will be conducted. After heat source parameters are adjusted, for the distortion and residual stress analysis, thermomechanical simulations will be conducted.

- Mechanical tests include tensile tests and hardness tests.
- Microstructure examination will be carried out with an optical microscope.
- Chemical tests, including chemical analysis and elemental analysis will be performed with optical emission spectroscopy.
- Dimensional measurements will be carried out with a height gauge.

In the second part, 100x100x0.9 mm plates will be welded at 2 different welding speeds and 2 different laser powers. In the account of the design of the experiment conducted with Minitab software, for 2 factors (Welding Speed, Laser Power) and 2 levels, 4 samples should be prepared. After welding with different laser welding powers and different laser welding speeds, mechanical tests and microstructural examinations will be carried out.

- Mechanical tests include tensile tests and hardness tests for all 4 samples.
- Microstructure examination will be carried out with an optical microscope after welding for all 4 samples to observe the fusion zone in welding.
- Dimensional measurements will be carried out with a height gauge.

Chemical tests will not be carried out since no filler material will be used during laser welding operations.

In the last part, the validation of the simulation welding test results with experimental work will be performed with a comparison of distortion & residual stress values. The distortion values of the simulation will be compared with height gauge measurements. The residual stress results will be obtained with XRD for the highest residual stress specimen that is two-side clamped, and the highest distortion specimen that has the highest J/cm value will be used to identify the residual stress; also, the highest distortion specimen will be used for clarifying the zero residual stress by selecting an area that is not in thermal stress due to the weld and the obtained XRD results of residual stresses will be compared to the simulation residual stress results, and the relation between them will be compared.

CHAPTER 2

LITERATURE REVIEW

2.1 Austenitic Stainless Steels

Stainless Steel holds essential points in the household, transport, food, industrial equipment, aerospace, and defence industry equipment since iron holds the 4th place in the world's most abundant elements [6]. The discovery of the addition of nickel to mild steel improved the tensile properties of steel by Riley of Glasgow in 1889, and in 1905 with the addition of Chromium of more than 9%, the corrosion resistance was enhanced [7, 8]. The factors that should be considered in the selection of stainless steel type should include at least the corrosion resistance, mechanical properties, creep resistance, and fabrication characteristics (machinable). There are different types of stainless steel according to their metallurgical structure. Austenitic stainless steel contains 18-25 wt. % Cr and 8-20 wt. % Ni elements. Among the stainless steels used in industry, austenitic stainless steel covers 65-70 percent; the high amount of their usage is related to their high-temperature performance, excellence in corrosive environments and stability at cryogenic temperatures [7]. General types of austenitic stainless steels used in industry are given in the below Figure 1.

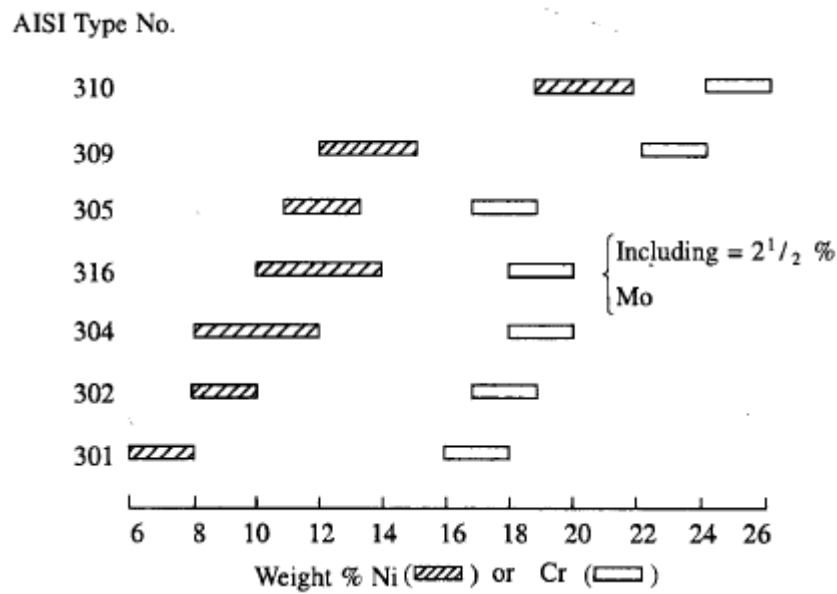


Figure 1 Austenitic Stainless Steel Types [7]

Alloying elements have an incremental effect on the strength of the austenitic stainless steel. These substitutional/interstitial alloying elements include carbon, nitrogen, silicon, chromium, molybdenum, etc. The empirical formula of yield strength contribution by these substitutional alloying elements has been developed by Pickering [9]. Where d is the mean grain diameter.

$$Y_{0.2} \% (\text{MPa}) = 15.4 [4.4. + 23(\text{C}) + 32(\text{N}) + 1.3(\text{Si}) + 0.24 (\text{Cr}) + 0.94 (\text{Mo}) + 1.2(\text{V}) + 0.29 (\text{W}) + 2.6 (\text{Nb}) + 0.16 (\% \text{ferrite}) + 0.46 d - 0.5] \quad (1)$$

2.1.1 AISI 316L Austenitic Stainless Steel

As it is widely used in the industry, AISI 316L stainless steel is a well-known austenitic stainless steel with high corrosion resistance and good mechanical properties. Rather than other stainless steels, the AISI 316L stainless steel stands out with its high amount of Cr and Ni content. The corrosion resistance of the AISI 316L stainless steel is provided by the Cr_2O_3 oxide layer [10, 11, 12]. In comparison with AISI 316 stainless steel, AISI 316L steel is known for its low carbon content, which is a critical parameter in welding applications that reduces

the intergranular corrosion of welds caused by the precipitation of carbides [13]. The primary solidification of the weld is controlled by the chemical composition and cooling rate of the fusion zone. From the thermodynamics of the solidification, with an increase in the time for solidification, the time available for diffusion is efficient; thus, the secondary phase formation is observed. Nevertheless, for welding operations in air, the cooling rate is high, and time for diffusion is not provided. From the work of Ragavendran and Vasudevan in 2020, it is stated that there are four main solidification modes in austenitic stainless steels, which are austenitic (A), austenitic-ferritic (AF), ferritic-austenitic (FA), and ferritic (F), which is determined by the Chromium and Nickel equivalent of the austenitic stainless steel [14]. Below is the relation between the Cr_{eq}/Ni_{eq} ratio and solidification mode.

Table 1 Solidification Mode & Cr_{eq}/Ni_{eq} Ratio Relation

Cr_{eq}/Ni_{eq}	Solidification Mode
< 1.37	A
1.37 to 1.5	AF
1.5 to 2	FA
>2	F

Related Cr_{eq} , Ni_{eq} are calculated according to Hammar and Svensson equation [15].

$$Cr_{eq} = Cr + 1.37Mo + 1.5Si + 2Nb + 3Ti \quad (2)$$

$$Ni_{eq} = Ni + 22C + 14.2N + 0.3Mn + Cu \quad (3)$$

Brooks, Thompson, et al. (1991) worked on the microstructural development and solidification modes of austenitic stainless steel welds; they found that the greater the Cr_{eq}/Ni_{eq} ratio than 1.5, the more it promotes the ferrite solidification [16]. Nevertheless, Tjong, Zhu, et al. (1995) stated that for 316L stainless steel, single-

phase austenitic solidification is the dominant mode [17]. That is related to the undercooling in the tip of the dendrite that the liquid is cooled below the extended austenite liquidus; therefore, the austenitic solidification is favored kinetically [17]. The undercooling arising from welding is related to the cooling rate that is 10^5 - 10^6 K/s for laser welding in the open atmosphere. That affects the solidification mode directly in austenitic mode.

2.1.1.1 Outstanding Properties of 316L Stainless Steel Compared with Other Austenitic Stainless Steels

316L stainless steel is used in industry in many environments with harsh environmental conditions such as high temperature, corrosion, and cryogenics. However, if we examine the features that distinguish 316L from other austenitic stainless steels and make it stand out in engineering use, we see that its corrosion resistance is much higher than 316 and 304 austenitic stainless steels. Zhu et al. (2022) worked on the corrosion resistance of 316L and 304 Stainless Steel in an alkaline environment and found that AISI 316L stainless steel possesses better corrosion resistance compared with AISI 304 stainless steel [18]. Behbahani et al. (2013) worked on the sensitization phenomenon related to the precipitation of chromium carbides at grain boundaries and causing the Chromium depleted areas. In his work, he stated that 316L stainless steel has higher resistance to localized attack compared to 316 stainless steel; also, he stated that the Ti and Nb elements are stabilizing elements of C in a solid solution. Since the 316L stainless steel has a higher C/(Ti + Nb) value compared to 316 stainless steel, the Chromium carbides precipitate less, which leads to higher corrosion resistance in 316L stainless steel and higher sensitization in 316 stainless steel compared to 316L stainless steel [19]. Desu, Krishnamurthy, et al. (2014) studied the mechanical properties of 316L and 304L stainless steels mechanical properties at elevated temperatures, although the 304L stainless steel has higher UTS (Ultimate Tensile Strength) at room temperature and temperatures below 500°C. It was examined that the Ultimate

Tensile Strength value of 316L stainless steel at temperatures above 600°C is higher than that of 304L stainless steel [20].

2.2 Welding Technologies

S. Katayama stated that “Welding is the most versatile and realistic joining method applicable to the construction of products in every industrial field” [3]. With the increasing use of structural and large-sized materials in engineering fields, the welding process has become indispensable for parts that cannot be produced as a result of a single process, and its use in many areas, from automotive to nuclear power plants and the defense industry, is increasing rapidly. Below is a list of, some common welding technologies described briefly:

- Arc Welding: uses an arc to melt the base material and filler rod. The electric arc is created from a power source, and that is a positive voltage applied to an electrode and a negative voltage is applied to the base material.
- Gas Welding: is a type of welding performed using a flammable gas and oxygen source; oxy-acetylene welding type is a type generally used in the industry.
- Energy Beam Welding: these welding types use high-energy electrons or laser light to melt the base material and filler to join materials. This welding method is relatively newer compared to other types of welding.
- Solid-State Welding: unlike fusion welding processes explained above, in this process the materials joined together do not melt; in other words, the temperature is high enough to promote the diffusion or recrystallization but below the melting temperature.

In the 1880s, the patent for arc welding, which used carbon electrodes, was taken by Nikolay Benardos and Stanislaw Olszewski; nevertheless, as stated in

Radhakrishnan's work, "Welding had its ancient origins in the fires of blacksmiths, who could forge two white-hot pieces of metal together with hammer blows and patience "[21].

2.2.1 Introduction to Laser Welding Technology

The use of laser power on materials began with the invention of the fiber laser by Elias Snitzer in 1963, 3 years after the invention of the laser. However, laser power is initially at milliwatt levels that have not even reached watt levels. The use of a 100-watt laser was introduced to the market in early 2000 [22]. The growth in the car market and the increase in the use of welding in the assembly process of the body in white parts have been a process that triggered the use of laser welding in the automotive industry. As Chao stated, there are between 2000 and 5000 resistance spot welding parts in a vehicle [23]. However, resistance spot welding causes the used consumable electrode to wear in galvanized steel and creates costs. Due to the switch to light alloys in the automotive industry for less fuel consumption and higher range with the same fuel, the use of aluminum in body parts has increased since the density of steel is approximately 2.5 times that of aluminum. However, the consumable electrode used in resistance spot welding wears out much faster than galvanized steel, which is compared to steel; aluminum requires almost three times higher electric current [24].

2.2.1.1 Definition of Laser Welding

The word "Laser" named by Mr. Gordon Gould, stands for "Light Amplification by Stimulated Emission of Radiation" as described in the name, the process consists of the light irradiation or emission principle. Laser is not a form of matter that exists on earth; it is artificially made light of electromagnetic waves [25]. In general, as described in Katayama's Handbook of Laser Welding Technologies

book, there exist 6 different types of laser welding technologies, as given in below Figure 2.

Types of laser	Laser characteristics
CO ₂ laser	Wavelength: 10.6 μm ; far-infrared ray Laser media: CO ₂ -N ₂ -He mixed gas (gas) Average power [CW]: 50 kW (Maximum) (Normal): 1–15 kW
Lamp-pumped YAG laser	Wavelength: 1.06 μm ; near-infrared ray Laser media: Nd ³⁺ :Y ₃ Al ₅ O ₁₂ garnet (solid) Average power [CW]: 10 kW (cascade-type max & fiber-coupling max) (Normal): 50 W–7 kW (Efficiency: 1–4%)
Laser diode (LD)	Wavelength: 0.8–1.1 μm ; near-infrared ray Laser media: InGaAsP, etc. (solid) Average power [CW]: 10 kW (stack-type max.), 15 kW (fiber-delivery max.) Merits: Compact, and high efficiency (20–60%)
LD-pumped solid-state laser	Wavelength: about 1 μm ; near-infrared ray Laser media: Nd ³⁺ :Y ₃ Al ₅ O ₁₂ garnet (solid), etc. Average power [CW]: 13.5 kW (fiber-coupling max.) [PW]: 6 kW (slab-type max.)
Disk laser	Wavelength: 1.03 μm ; near-infrared ray Laser media: Yb ³⁺ :YAG or YVO ₄ (solid), etc. Average power [CW]: 16 kW (cascade-type Max.) Merits: Fiber delivery, high brightness, high efficiency (15–25%)
Fiber laser	Wavelength: 1.07 μm ; near-infrared ray Laser media: Yb ³⁺ :SiO ₂ (solid), etc. Average power [CW]: 100 kW (fiber-coupling max.) Merits: Fiber delivery, high brightness, high efficiency (20–30%)

Figure 2 Types and Characteristics of Laser Welding [3]

2.2.1.2 Advantages & Disadvantages of Laser Welding

As stated by Quintino et al. (2013), there exist two different modes of laser welding: conduction mode and keyhole mode. The difference between them can be described shortly as the power density of the laser beam applied to the workpiece.

In keyhole mode, the base metal is vaporized during welding, and penetration to deeper zones is enabled. However, this fluctuation in the vaporized base metal may cause porosities and irregularities in the weldment's fusion zone [26]. Li, Gobbi, et al. (1997) worked on laser welding of Titanium alloys; in their work, they mentioned the difficulty of laser butt welding since the welding edge in butt welding should be precisely aligned; otherwise, the undercut in laser butt welding is inevitable. The undercut is an undesirable consequence of welding since under cyclic loads the fatigue life will be diminished due to stress concentration points in the undercut. [27]. Another drawback of laser welding is the high first setup cost for high-power laser welding equipment. Those are laser weld sources and workstations, which are a must for welding operations. Although the energy consumption is lower than other welding processes, the energy efficiency of laser welding is relatively low [28]. Although laser welding is a new process and has some shortcomings, laser welding is characterized by its high energy focusability, enabling precision and clean welds with significant penetration depth. Laser welding enables the use of a wide range of weld power for different materials, to say, for plastic materials, low welding power in watts can be used. Also, the high welding power can be applied to thick metallic materials without preparation of the weld edge in the fusion zone, which is a general problem for weld preparation of complex metallic geometries since machining of complex geometries can be costly and may cause a formation of stress concentration points. This reduces heat-induced distortion and minimizes post-welding machining. A key benefit of laser welding is its suitability for automated welding of large or intricate structures. Laser beam welding is suitable for certain dissimilar metals and alloys. The capability to weld thick sections in a single pass can significantly reduce the amount of consumables needed and lower hazardous emissions. Additionally, low heat input can enhance grain structures in the heat-affected zone and sometimes in the fusion zone, leading to improved mechanical properties. [28-31].

2.2.1.3 Nd:YAG Laser Welding

Karagiannis and Chryssolouris et al. (2003) explained the general overview of recent developments on Nd:YAG Laser Welding in terms of a limited heat-affected zone compared to other welding technologies. They emphasized the superiorities of Nd:YAG Laser Welding in terms of limited heat-affected zone, good surface quality at the weld zone, and less affected mechanical properties of base metal after welding. They compared the general properties of laser welding, electron beam welding, resistance spot welding, and gas tungsten arc welding given in the below Figure 3 [32].

Characteristics	Laser	Electron Beam	Resistance Spot	Gas-tungsten arc
Heat generation	Low	Moderate	Moderate	Very High
Weld quality	Excellent	Excellent	Good	Excellent
Weld speed	Moderate	High	Low	Low
Initial cost	Moderate	High	Low	Low
Operating/maintenance costs	Low	Moderate	Low	Low
Tooling costs	Low	High	High	Moderate
Controllability	Very Good	Good	Low	Fair
Range of dissimilar materials	Very wide	Wide	Narrow	Narrow

Figure 3 Comparison of Welding Processes [32]

Jandaghi et al. (2008) worked on the alloying element loss due to laser welding of 316 stainless steel. In his work, he compared the Quick Calculus software; the model results correlate with measured EDS analysis for depleting elements calculation. For both analyses in the fusion zone, there was loss of manganese and chromium due to vaporization [33].

2.2.1.4 Challenges in Laser Welding

Although Laser welding is a promising joining method, it has some disadvantages due to its nature; since the power of welding is limited, it is not an appropriate method for thick materials such as >100 mm, which is required for applications in nuclear power and shipbuilding that are beyond the current capability of lasers [22]. As stated in the Advanced Welding Technologies book, the faster heating and cooling rates may cause the formation of intermetallic compounds or micro-cracks due to the rapid solidification rate [34]. Nielsen et al. (2015) worked on high-power laser-hybrid welding; in his work, he stated that for thick materials, defect control should be taken into consideration since the cracks and porosities are possible discontinuities for high-power laser welding, which can be eliminated by relevant filler materials or optimum joint geometries [35]. Due to the keyhole effect in the laser welding in high laser welding powers, the welding power and welding environment are the essential factors to consider; otherwise, as stated in Figure 4, porosity formation is inevitable:

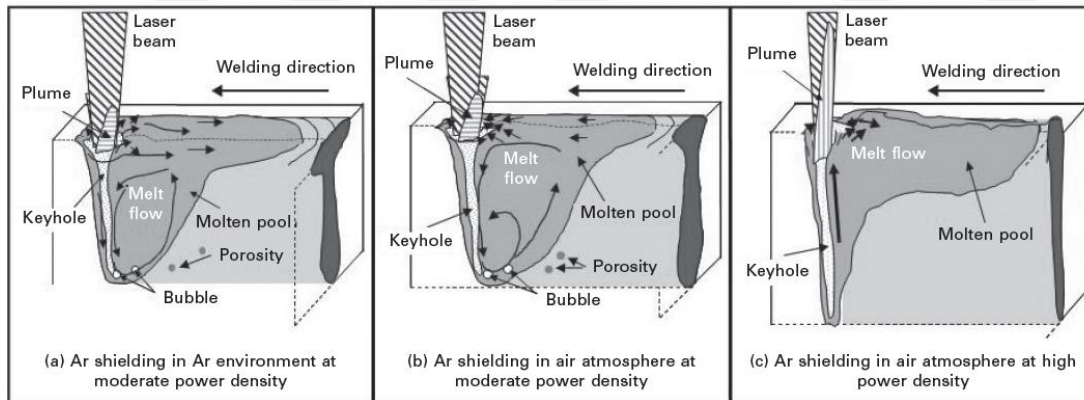


Figure 4 Schematic Representation of Melt Flow in Molten Pool of Laser Welding [25]

2.2.2 Laser Welding of 316L Stainless Steel

Abdel-Monem El Batahgy et al. (1997) worked on the effects of the laser welding parameters on the fusion zone and solidification structure of austenitic stainless steels and concluded that the parameters; laser power, welding speed, defocusing distance, and type of shielding gas affects the weld pool. In his work, Batahgy stated that due to the good crack resistance of the base metal, no welding cracks or porosities were observed. The substances worked on in his experiment consisted of 304L, 316L, and 347 stainless steels [36]. Yan, Meng, et al. (2022) stated that the large thermal expansion coefficient and low thermal conductivity of austenitic stainless steels contribute to the formation of residual stress and distortion [37]. Ventrella, Berretta, et al. (2010) worked on 316L stainless steel thin foils, and they focused on the pulse energy parameter, and the results showed that the pulse energy has a direct effect on discontinuities in the weld zone [38]. Soltani, Tayebi, et al. (2018) emphasized that austenitic stainless steels are not sensible to cold-cracking due to the stable austenitic phase, and the heat treatment after welding is not required. Nevertheless, the main problem for welding the austenitic stainless steels is the precipitation of carbides, which is caused by the formation of chromium carbide at the 425-870°C temperature range. These carbides are formed in the grain boundaries, thus decreasing the corrosion resistance of the parent metal [39]. Ragavendran and Vasudevan et al. (2020) underlined that for laser welding, compared to hybrid welding of laser, the dendrites are finer due to the high power density of the laser, which results in a higher cooling rate [14].

2.3 Mechanical Experiments

Tjon, Zhu et al. (1995) worked on the hardness and creep behavior of electron beam and laser welded specimens of 316L stainless steel. They have conducted hardness tests after welding; the test results showed that higher hardness values

were observed at the fusion zone compared to the base metal, which is due to high cooling rates from the liquid state, which promotes the formation of fine grains [17]. Köse et al. (2022) have considered the effect of laser welding heat input on the mechanical properties of AISI 317L austenitic stainless steel. Like Tjon and Zhu's work, he has found that the hardness value taken of the fusion zone is greater than the base metal, which he stated is related to a fine grain microstructure. In addition to the hardness test, Köse also applied a tensile test to the weld samples created with different heat inputs and observed that the tensile strength decreased in the samples with an increment in the heat input, which in turn provides a higher solidification time for solidified grains in the fusion zone. As expected, coarser grains in higher heat input specimens resulted in lower tensile strength; fine grain size was observed due to faster cooling in samples with low heat input, and higher tensile strength is obtained [40]. Jung, Park, et al. (2019) worked on the effect of welding speed on the mechanical properties of laser-welded AISI 304 stainless steel. They have found that with an increase in welding speed, the hardness value at the fusion zone increased. They have related the higher hardness values results to obtaining finer grain sizes with an increase in weld speed [41]. Zhang, Buchanan et al. (2021) considered the effects of laser parameters on mechanical properties and microstructure on the additively manufactured 316L stainless steel plates. The conclusion of this work can be listed as: with an increase in the energy input of the laser, the width of the weld and the heat-affected zone increases. As a result, weld strength is observed to decrease due to coarse grains in the heat-affected zone [42]. In general, as stated by the Hall-Petch equation, with a decrease in grain size, the tensile strength increases as given in the equation below [43].

$$\sigma_0 = \sigma_y \frac{-k_y}{\sqrt{d}} \quad (4)$$

Where: σ_0 = materials constant for the starting stress for dislocation movement, σ_y = the yield stress, k_y = the strengthening coefficient, and d = average grain diameter.

2.3.1 Hardness Test Experiments

Yilbas et al. (2013) worked on the residual stress and microhardness of AISI 316 stainless steel that are laser beam welded with a CO₂ laser weld, and he validated the experimental test results with a simulation, and he concluded that the high welding speed resulted in rapid recrystallization. In the fusion zone, significant grain refinement was observed, leading to increased hardness in the welded region compared to the base material [44]. Chatterjee et al. (2020) worked on laser beam welding of AISI 316 and Ti6Al4V with Nd:YAG laser weld method. In his work, he concluded that the base material (BM) shows the lowest hardness value compared to the heat-affected zone (HAZ) and the fusion zone (FZ). The HAZ has the highest hardness value due to its fine grain structure [45]. Zhang, Lu et al. (2012) studied a comparative work with laser welding technologies on AISI 304 stainless steel; fiber laser, CO₂ laser, and Nd:YAG laser. In his work he observed that the microhardness of the laser welding zone is higher than that of the base metal because the alloy elements do not have enough time to form a second phase and precipitate due to the high cooling speed. These elements remain largely dissolved, leading to solid solution strengthening after the laser welding process [46]. Torkamany et al. (2011) worked on laser welding of dissimilar materials that are low carbon steel and AISI 304L stainless steel. In his work, the hardness test results for 304L stainless steel showed 1.5 higher values for the fusion zone than the base metal [47].

2.3.2 Tensile Test Experiments

Kumar et al. (2016) studied the effect of laser welding parameters on the mechanical properties of 316 SS and 304 SS. In his work, the variables under examination were laser power, welding speed, and pulse width. He examined the effect of variations in laser welding parameters on tensile properties and microhardness values of specimens. In his work, he concluded that faster welding

speed results in a faster cooling rate, leading to the fine grain structure, which is obtained, and higher micro-hardness values are observed [48]. Saravanan, Raghukandan et al. (2017) worked on the parametric optimization to enhance the tensile strength of AISI 316 stainless steel. In their work, which is different from previous work results obtained by Kumar, they have found that with an increase in welding speed, the tensile strength is reduced. Nevertheless, when they observed the weld pool in the fusion zone, they found that there was incomplete penetration in the fusion zone when the welding speed was increased sharply [49-50]. Benyounis et al. (2006) worked on the parametric optimization of laser welding parameters for the tensile strength behavior of austenitic stainless steel. In his work, he focused on the laser weld power, welding speed, and focus distance parameters. He concluded that a high laser power and low welding speed combination or a low laser power and high welding speed is not recommended since high laser power and low welding speed will cause undesirable residual tensile stresses. Likewise, low laser power and high welding speed will end up with incomplete penetration [51]. Venkatesu et al. (2018) worked on the laser beam welding, gas tungsten arc welding (GTAW), and high-temperature brazing (HTB) of AISI 316 stainless steel and compared these three different joining operations in terms of mechanical strength comparison and concluded that the laser beam welding has higher tensile strength and ductility compared to GTAW and HTB processes. He sums up the reasoning of these test results with finer grains in laser-welded specimens, elongated grains in GTAW, and dendritic-structured grains in the HTB process [52]. Prabakaran et al. (2018) studied the optimization of CO₂ laser beam welding of AISI 316 and AISI 1018 stainless steels in terms of mechanical properties by adjustment in laser power, focal distance, and welding speed. Similar to Benyounis' works, he observed that weld strength can be increased by using either low laser power with low welding speed or high power with high welding speed [53].

2.4 Optical Microscope Analysis

Saha, Waghmara et al. (2020) worked on parametric optimization with AISI 316 stainless steel on autogenous laser beam welding; they underlined that, after the welding, the microstructure of the base material consists of a fully austenitic structure with equiaxed grains and annealing twins. Also, when they increased the laser power without any change in other parameters, it resulted in grain coarsening in the fusion zone of the weld microstructure. Also, within the experiments with different welding parameters, they observed that the welding speed decrease led to a coarser dendritic structure. Which is the expected result since the decrease in welding speed will cause the decrease in cooling rate. Thus, the welding speed decrease will cause the grain coarsening and coarser dendritic structure since the time allowed for solidification and grain growth is increased [54]. Prabakaran et al. (2022) worked on the effects of laser welding parameters on low carbon steel and AISI 316 stainless steel. In his work, he found that a small amount of carbide precipitation was observed in the grains and along the grain boundaries of the welded stainless steel's heat-affected zone (HAZ). No phase transformation occurred in the HAZ of the stainless steel because austenitic stainless steel is non-transformable [55]. Prabakaran et al. (2020) found that the solidification after welding completion is composed of nucleated grains through the fusion line, which grew towards the center of the molten pool. In other words, the grain growth takes place along the weld line [56]. Farid, Molian et al. (2000) worked on the AISI 316 stainless steel. In their work, they have found that there was no crack occurrence due to hot cracking, which in high cooling rates, is a significant problem for welding austenitic stainless steels. Furthermore, the dendritic zones are equally distributed and homogeneous through the fusion zone, which is related to high G/R ratios (G = temperature gradient, R = growth rate). That phenomenon occurs in high cooling rates/rapid solidifications. [57].

2.5 Dimensional Experiments

Derakshan et al. (2018) worked on the distortion and residual stress analysis with three different welding methods: laser welding, submerged arc welding, and hybrid laser arc welding. In his work, he stated that as expected, laser welding showed the least amount of distortion among other welding processes. Because the laser welding has lower heat input among them, a consequently narrower HAZ occurred. Nevertheless, submerged arc welding showed the most significant distortion after welding was completed because of its higher heat input, which led to a wider HAZ. In general, it can be said that the higher heat input through the weld zone causes a higher heat-affected zone and greater distortion through the weldment [58]. Xu, Guo et al. (2019) investigated the impact of laser power on the welding deformation of an ultra-thin steel plate in the pulsed laser welding method. In their work, they used both numerical simulation and a real-world experimental dataset. The experiment includes AISI 316 stainless steel plates that have a thickness below 0.1 mm; they changed the laser power through different levels and observed the distortion. They have observed that the final welding deformation of the ultra-thin plate showed two different deformation types. With low heat input, the specimen displayed a convex shape deformation within the axis of the weld zone, in other words, the plate deformed in the -y direction. Oppositely, with a high input of laser power, the weld zone displayed a concave shape in the +y direction [59]. Ragavendran et al. (2021) compared the effect of different welding processes on distortion and residual stress of welded AISI 316L (N) stainless steels. The work includes a comparison of three different welding methods: the hybrid laser-MIG (HLM), hybrid laser-TIG (HLT), and laser welding processes. All three different weld processes were applied to the weldment with the same welding position and configuration. After welding was completed, he measured the weldments perpendicular to the weld direction; the measurements were taken with a height gauge on a granite table. As given in Figure 5, he found that distortion in the joint is directly proportional to the heat input into the test plates and the volume of weld

metal produced after welding, in other words, the fusion zone of the weld through the welding [60]. Derakshan et al. (2018) worked on the distortion and residual stress analysis with three different welding methods: laser welding, submerged arc welding, and hybrid laser arc welding. In his work, he stated that as expected, laser welding showed the least amount of distortion among other welding processes. Because the laser welding has lower heat input among them, a consequently narrower HAZ occurred. Nevertheless, submerged arc welding showed the most significant distortion after welding was completed because of its higher heat input, which led to a wider HAZ. In general, it can be said that the higher heat input through the weld zone causes a higher heat-affected zone and greater distortion through the weldment [58]. Xu, Guo et al. (2019) investigated the impact of laser power on the welding deformation of an ultra-thin steel plate in the pulsed laser welding method. In their work, they used both numerical simulation and a real-world experimental dataset. The experiment includes AISI 316 stainless steel plates that have a thickness below 0.1 mm; they changed the laser power through different levels and observed the distortion. They have observed that the final welding deformation of the ultra-thin plate showed two different deformation types. With low heat input, the specimen displayed a convex shape deformation within the axis of the weld zone; in other words, the plate deformed in the -y direction. Oppositely, with a high input of laser power, the weld zone displayed a concave shape in the +y direction [59]. Ragavendran et al. (2021) compared the effect of different welding processes on distortion and residual stress of welded AISI 316L (N) stainless steels. The work includes a comparison of three different welding methods: the hybrid laser-MIG (HLM), hybrid laser-TIG (HLT), and laser welding processes. All three different weld processes were applied to the weldment with the same welding position and configuration. After welding was completed, he measured the weldments perpendicular to the weld direction; the measurements were taken with a height gauge on a granite table. As given in Figure 5, he found that distortion in the joint is directly proportional to the heat input into the test

plates and the volume of weld metal produced after welding, in other words, the fusion zone of the weld through the welding [60].

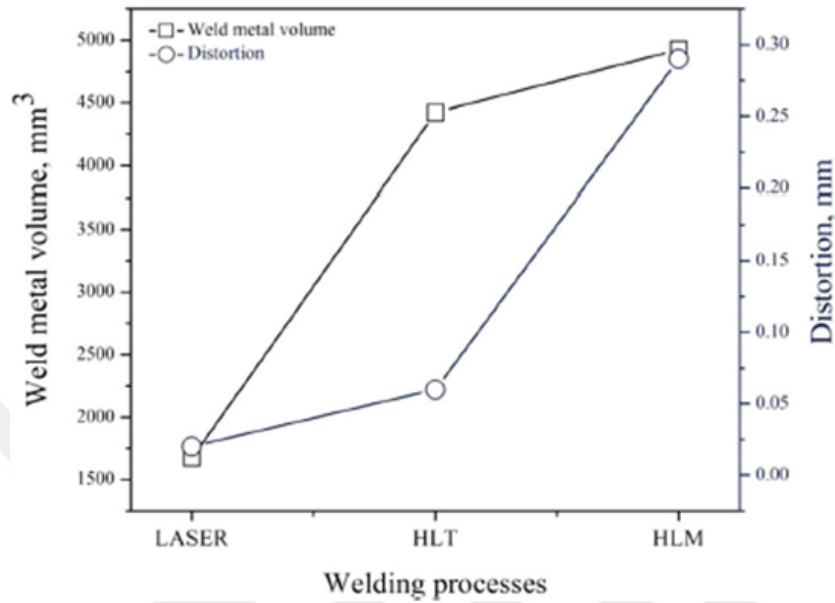


Figure 5 Weld Metal Volume versus Distortion for Different Welding Processes [60]

2.6 Simulation of Laser Welding

Dal, Fabbro et al. (2016) focused on the art of state in laser welding simulation; in this work, they emphasized that the literature work includes two types of models: thermo-mechanical simulations and multi-physical simulations. The former aims to determine the mechanical stress and strain resulting from welding and is usually simplified to reduce the simulation size. The latter computes thermal and velocity fields more accurately [61]. Labeas et al. (2013) identified the modeling process in two main steps as given in Figure 6 [62]. As indicated, the first part of the simulation consists of thermal analysis, and subsequently the mechanical analysis is performed.

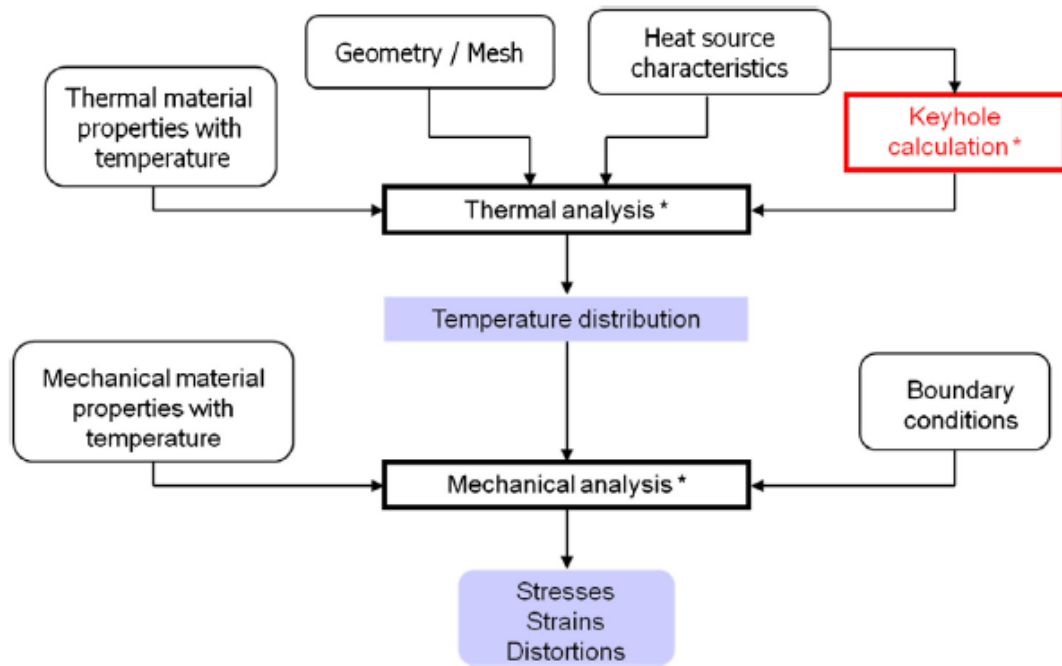


Figure 6 Flow Chart of Laser Beam Welding Simulation Process [62]

2.6.1 Simufact Welding

Chukkan, Vasudevan et al. (2014) worked on the prediction of residual stress and distortion by using three different heat source models on Simufact Welding that are 3D conical, 3D conical with double ellipsoidal, and 3D conical with cylindrical shell. In their work, they validated their simulation results with experimental measurements. They have concluded on all three models; the peak temperature simulation is close to real experimental data; residual stress shows good agreement with experimental data. Nevertheless, for distortion calculation, the 3D conical with cylinder heat source model showed the closest results to the experimental data [63]. Schönegger, Mosching et al. (2024) studied the calibration of the heat source model to the experimental fusion zone microstructure, which is an essential work for all simulation validation experiments. In their experimental work, they have used the plasma wire arc additive manufacturing method, and for the heat source parameter calibration, they have used the trial-and-error method. In this method,

they have conducted 27 thermal simulations for molten volume agreement in simulation with experiment [64]. Similar to Schöneegger, Mosching's work Kik stated that incorrectly performed heat source calibration may lead to a significant difference in experimental work and simulation [65]. Danielewski, Skrzypczyk et al. (2020) emphasized the effect of mesh convergence. In their work, they have performed the simulations with 0.5, 0.25, 0.125, and 0.0625 mm mesh sizes. For 0.0625 and 0.125 mm mesh sizes, no difference is observed in HAZ geometry; nevertheless, they have seen different HAZ geometries for 0.25 mm mesh size and 0.5 mm mesh size [66]. Perret, Thater et al. (2011) worked on the simulation of automotive industry body parts and validation of experimental data. In their work, they have conducted the below workflow diagram:

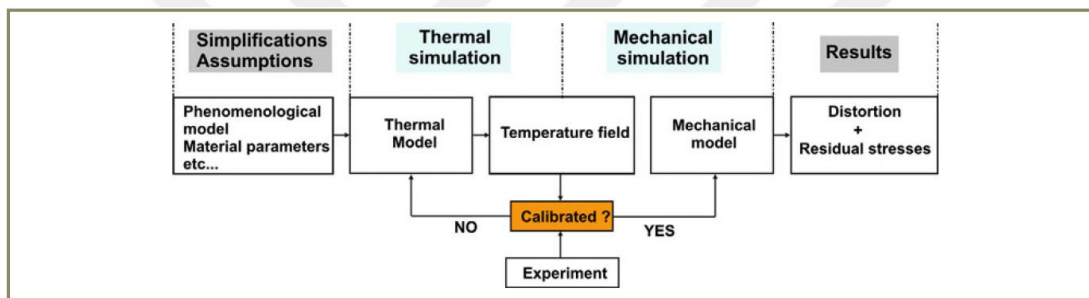


Figure 7 Workflow Diagram for Structural Welding Simulation

As indicated in Figure 7, they have mentioned the simplifications, the calibration of the heat source model, and the validation of the mechanical simulation with experimental data [67].

2.6.1.1 Numerical Approaches for Predicting Residual Stress & Distortion

Numerical approaches for predicting the distortion & residual stress can be divided into three parts for this work. It is essential to verify the real-world tests performed with simulation. It can be observed that the parametric inputs determined through simulation verifications enable the application of pre-heating or pre-bending operations to eliminate distortions that will occur in the welding of complex

geometries. Lindgren et al. (2001) state that the simulation of most of the analysis consists of two steps, which are thermal analysis and mechanical analysis, as given in Figure 8. Most of the thermo-mechanical analysis consists of these two steps. This approach is known as the staggered approach. In which the thermal dilatation is the driving force and the geometry is updated in subsequent mechanical analysis [68].

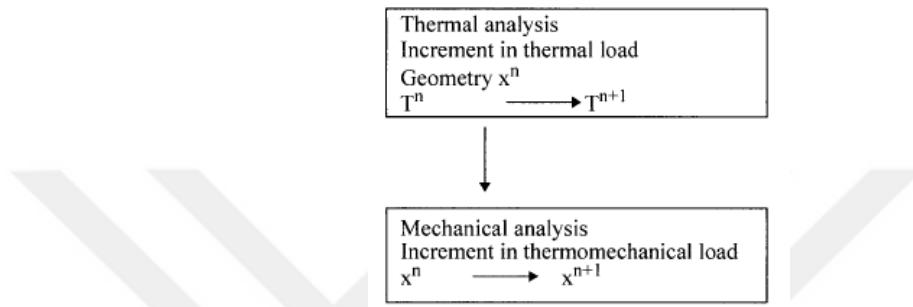


Figure 8 Thermo-Mechanical Analysis Steps

Schoinochoritis, Chantzis et al. (2017) worked on the simulation of residual stresses and pointed out that for real part geometries, it is not recommended to model the part as micro-scale since the time needed for computation will take enormous times [69].

2.6.1.1.1 Thermal Modelling

Rosenthal (1941) worked on the field of welding, an approach to understand the heat flow in the welding process with a conduction heat transfer model in two-dimensional and three-dimensional states [70]. Furthermore, Goldak et al. (1984) were the first to introduce a heat source model called the ellipsoidal heat source model, which is the simulation approach used for arc welding methods today [71]. In contrast to volumetric models commonly used in arc welding simulations, Goldak's model uses two equations that independently show different sections of the ellipsoid shape. His establishment of his work is used in studies of welding techniques involving energy levels, like laser welding or electron beam welding, as

well as plasma welding methods. In their research, Kik and colleagues (2020) studied the complexities of heat source models in simulations of laser welding, suggesting adjustments to these models and techniques for simulation of heat input in welded materials for welding simulation applications with solid-state and high-power diode lasers [65, 72, 73, 74]. Zhan, Mi et al. (2016) developed a heat source model to simulate the laser beam welding of a 1060 steel plate. In their work, they underlined that for carbon steels, two types of weld bead types were observed, “nail” type and “hourglass” type. Thus, they challenge themselves to simulate the latter one with different welding parameters. Also, they emphasized that with a conical heat source of Gaussian distribution heat flux that is mostly used for simulation of laser welding is not an appropriate method to simulate the hourglass shape weld bead in the bottom of the weld bead [75].

2.6.1.1.2 Thermo-Mechanical Modelling

For thermo-mechanical modeling of the phase-changing materials during welding, as stated by Lindgren et al. (2006) in his work on improved material modeling, phase changes should be considered for different mechanical properties [76].

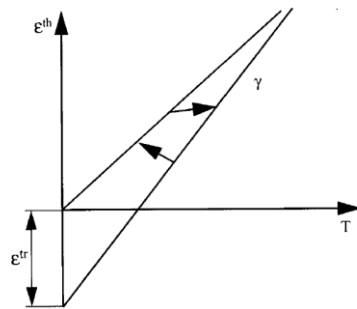


Figure 9 Properties of Different Phases

Nagel, Simon et al. (2014) worked on the optimization strategies for laser welding of high alloy steel sheets by using simulation software. In their work, they explained the yielding mechanism:

$$f = \sigma_{eq} - K - \sigma_y = 0 \quad (5)$$

Where σ_{eq} is Von Mises equivalent stress, σ_y is the initial yield stress, and K is the degree of strain hardening.

The strain calculated in material model is identified as:

$$\epsilon = \epsilon_i + \epsilon_e + \epsilon_p + \epsilon_{th} \quad (6)$$

Where ϵ_i the initial strain, ϵ_e is the elastic strain, ϵ_p is the plastic strain and ϵ_{th} is defined as thermal strain [77]. Bielik et al. (2020) worked on thermomechanical modeling of the additive manufacturing process. In his work, he stated that the deformation mechanism in Simufact Welding includes a Cauchy's equation for static problems, where in Simufact Welding, Cauchy's equation is used in multiplicative plasticity. That consists of being particularly suitable for modeling the evolution of internal variables and the effects of these variables on material behavior. In non-linear mechanical analysis, which is considered a quasi-static incremental analysis, the stress equation can be expressed as:

$$\nabla \cdot \sigma + f_{int} = 0 \quad (7)$$

Where σ is the stress tensor and f_{int} is the internal force vector.

This equation can be expressed when expanding the stress tensor for elastic behavior:

$$\sigma = C \epsilon^e \quad (8)$$

Where C is the stiffness tensor that is a fourth-degree tensor (where material shows anisotropic behavior) and ϵ^e is the elastic strain tensor. The total strain tensor ϵ can also be expressed as:

$$\epsilon = \epsilon^e + \epsilon^p + \epsilon^{th} \quad (9)$$

Where ϵ^e is the elastic strain, ϵ_p is the plastic strain, and ϵ_{th} is defined as the thermal strain. Since the stress tensor includes ϵ^e , the elastic strain is expressed as:

$$\epsilon^e = \frac{1}{E} \sigma - \frac{\nu}{E} \text{tr}(\sigma) \quad (10)$$

Where E is the Young's Modulus, σ is the stress tensor, ν is the Poisson's Ratio, $\text{tr}(\sigma)$ is the trace of the stress tensor that is the sum of diagonal elements in stress tensor that is; $\text{tr}(\sigma) = \sigma_{xx} + \sigma_{yy} + \sigma_{zz}$ which described as normal stress components [78].

2.6.1.1.3 Finite Element Method

Montalvo, Akbay et al. (2009) have underlined that the adaptive mesh method enables approximating the time-dependent thermal process in terms of heat-affected zone, temperature, and distortion. Their work includes the refinement of meshing in the laser beam applied section and gradually coarsening the mesh to the original size, as given in Figure 10 [79].

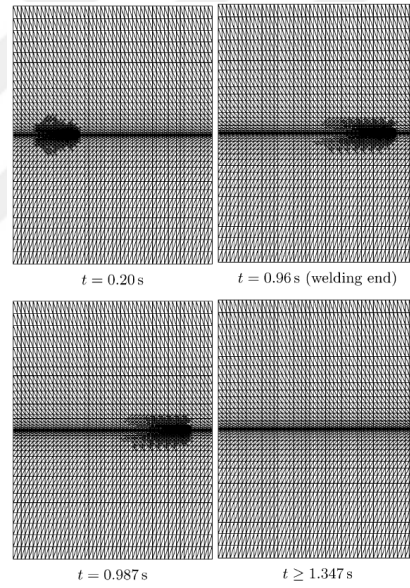


Figure 10 Refinement and Coarsening of Meshes with Heat Applied [79]

Casalino et al. (2015) studied the simulation of the laser-welded titanium plates in a butt welding configuration, stating that the calibration of the heat source model and heat distribution along the weld zone according to thermocouples placed on experimental work [80]. Lindgren et al. (2001) present a literature review of the simulation studies carried out so far and future studies that can be carried out in the

article “Finite Element Modeling and Simulation of Welding Part 3: Efficiency and Integration.”. In his work, he emphasized the reduction in the computing time by adaptive meshing up to 60%. Also, he underlined that with development in computational technologies, the real-time simulations may be possible [81]. He et al. (2012) presented the latest developments in finite element analysis for laser welding applications. His work includes the modeling of materials and meshing procedure [82].

2.7 Residual Stress Measurement

Schroepfer et al. (2021) examine the effects of welding temperature control on stresses during welding and subsequent PWHT processes and were conducted using a dedicated 3D testing facility under realistic constraints and heat dissipation conditions. In his work, he worked with the submerged arc welding process with wire feeding; he used a low-alloyed creep-resistant steel 13CrMoV9-10, which has a thickness of 50 mm. In his work, he concluded on how restraints affected the intensity of the residual stress [83].

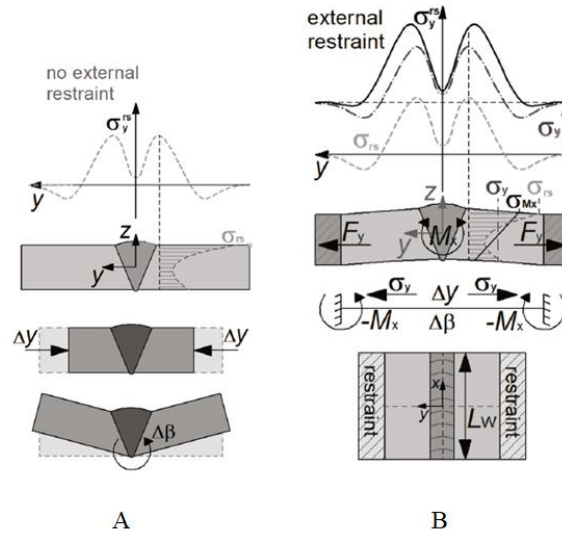


Figure 11 Transverse Residual Stress without Restraint (A) and with Restraint (B) [83]

Deng et al. (2007) welded two 100x100x1 mm low-carbon plates in a butt welding configuration with the GMAW method and observed their distortion and residual stress distributions using FEM and experimental data. In this study, he compared two different theories and observed that the large deformation theory gave results closer to the experimental data results than the small deformation theory. Large deformation theory is based on a non-linear behavior, and this theory has shown results closer to real data. The figures below show the results of large deformation theory and small deformation theory [84].

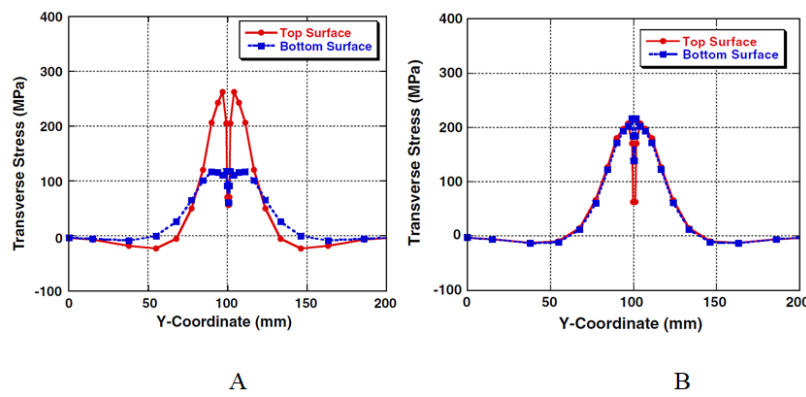


Figure 12 Transverse Residual Stress Distribution According to Large(A) and Small (B) Deformation Theory [84]

CHAPTER 3

EXPERIMENTAL PROCEDURE

The experimental procedure of this work can be divided into 3 main headings: the experiments conducted before the welding operation, the experiments conducted in the welding operation, and the experiments conducted after the welding operation was completed. The flowchart of this work is given below for these three different steps.

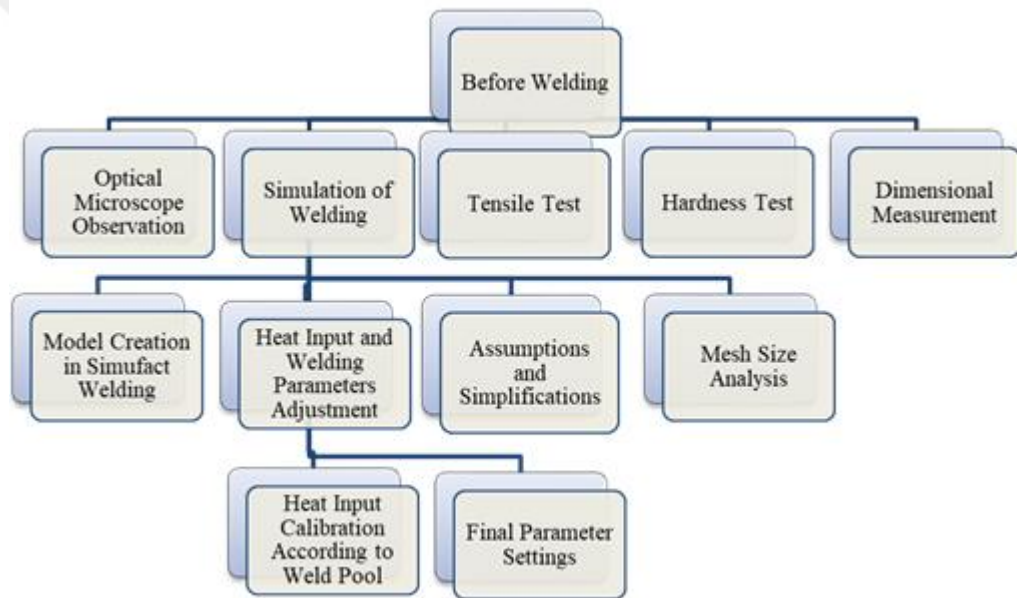


Figure 13 Workflow before Welding Operations

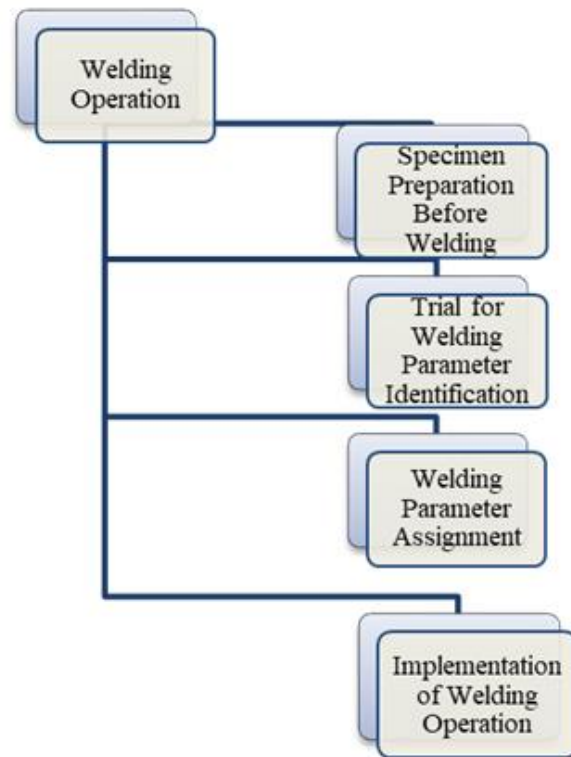


Figure 14 Workflow of Welding Operations

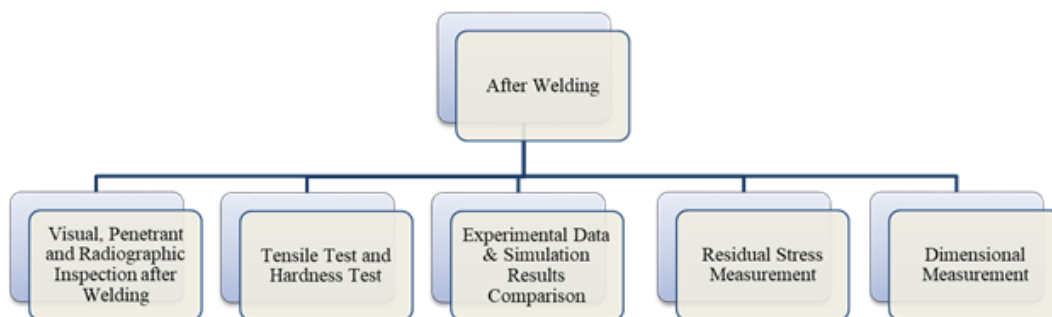


Figure 15 Workflow after Welding Operations

Firstly, before starting the pre-welding tests and post-weld tests, the cold-rolled 0.9 mm thick stainless steel plate with 316L grade was used in tensile testing to get to know the mechanical properties of the plate. The plate subjected to starting tests is given in Figure 16. The main focus of the tensile tests, hardness test, chemical

composition analysis, and optical microscope observations of the base plate is to get to know the starting material and compare it after welding is completed in terms of mechanical properties. 3 tensile test coupons were taken from this plate called the C_0 configuration as indicated in Figure 17. Since one of the tensile test specimens may give an irrelevant result, the test specimen number taken is 3, which is also indicated in the ASTM E8 “Standard Test Methods for Tension Testing of Metallic Materials” standard.



Figure 16 C_0 Configuration Pre-Welding Test Plate

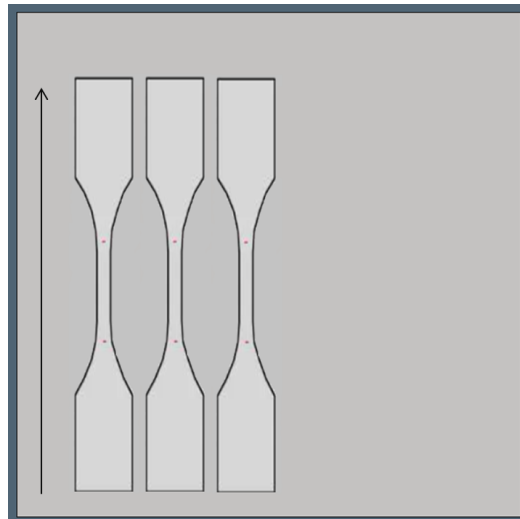


Figure 17 Representative C_0 Configuration Plate and Direction of Tensile Test Specimens

The test equipment used for the tensile test and detailed explanation is defined under the Mechanical Tests heading. The remaining material from the coupons removed from the plate for the tensile test was used for the hardness test. The hardness test was taken as microhardness, and since the material was an austenitic stainless steel and a relatively soft material, the Vickers hardness value was examined. Test specimens taken into bakelite are given in Figure 18. The test equipment and detailed description used for the hardness test are defined under the heading Mechanical Tests.

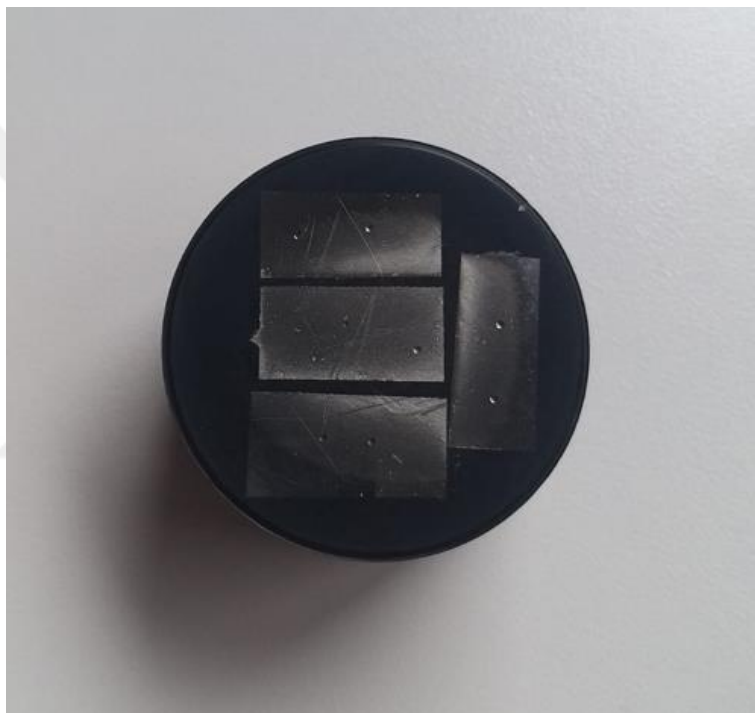


Figure 18 Hardness Test Specimen Taken into Bakelite

After the hardness test and tensile test samples were removed, a small-sized chemical analysis sample was removed from the remaining part of the plate. Chemical analysis was performed by optical emission spectroscopy. The test equipment and detailed description used for the chemical analysis are defined under the heading Characterization Techniques.

After the chemical analysis sample, tensile test sample, and hardness test sample were removed, an optical microscope sample was taken from the remaining part of

the plate for microstructure examination, and the taken sample was subjected to grinding and etching operations and examined with an optical microscope. The sample was taken into bakelite, as shown in Figure 19. The test equipment and details used for the microstructure examination are defined under the heading Optical Microscopy.



Figure 19 Optical Microscope Specimen taken into Bakelite

After the tests designed with the C_0 configuration plate are completed, 4 test coupons that have a dimension of 100x100x0.9 mm will be measured in terms of their parallelism with a height gauge before the welding operation as defined in the Dimensional Measurement heading. To observe the effect of the welding parameters on the distortion of the plate, the pre-measurement of parallelism is required. Because after the welding is completed, the parallelism measurements for 4 coupons will be repeated. Pre-measurement and post-measurement values will be distracted, and the total amount of distortion caused by the laser welding operation will be calculated as the total sum-up distortion value due to the laser welding operation. The laser welding operation in simulation will be carried out with one bearing and one clamp as defined in Figure 20 and Figure 21. Similar to the simulation the welding operation will be carried out with a clamping block of

Mitutoyo that holds the welding coupons parallel to the laser source. A detailed explanation is given in the Specimen Preparation heading. Except for the four test coupons, 1 test coupon will be tested in a way that two Mitutoyo blocks rigidly hold the specimen, not to enable a distortion after welding is completed, as given in Figure 22. This specimen will be used to compare the residual stress results. Similar to four test coupons, pre-welding and post-welding distortion measurements of this coupon will be taken with a height gauge. This coupon will be welded with parameters selected for C_{125.7-1.75} since the maximum energy per centimeter is given with this parameter set, and the maximum residual stress is desired to be obtained from this two-side clamped specimen. This specimen will be named C_{125.7-1.75}TSC, the TSC abbreviation is defined as two-side clamped. Detailed explanation for residual stress test coupon welding and measurement configuration is given in Specimen Preparation heading. The welding operation will take place in a way that passes through the middle area of the plate for 4 welding samples with a thickness of 100x100x0.9 mm. The parameters to be used during laser welding are defined in the heading Material.

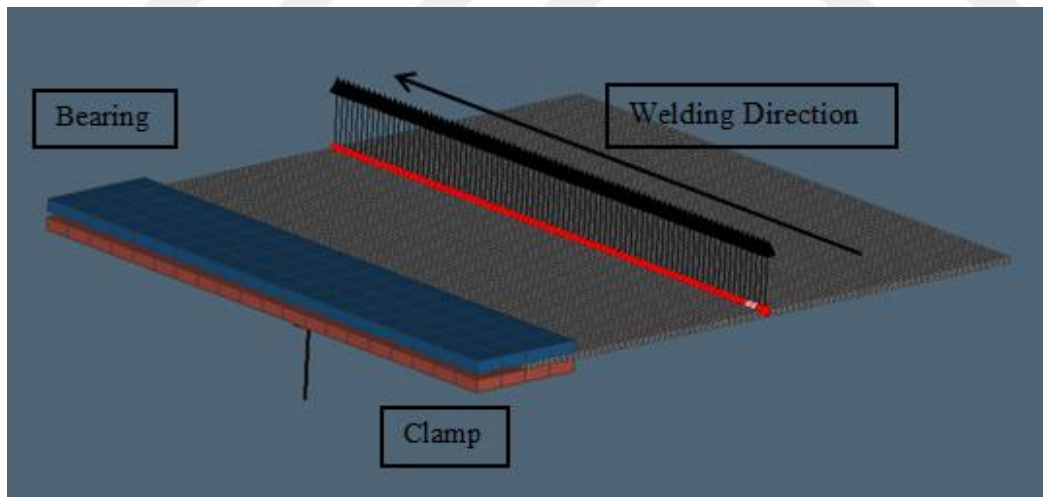


Figure 20 Weld Position and Direction

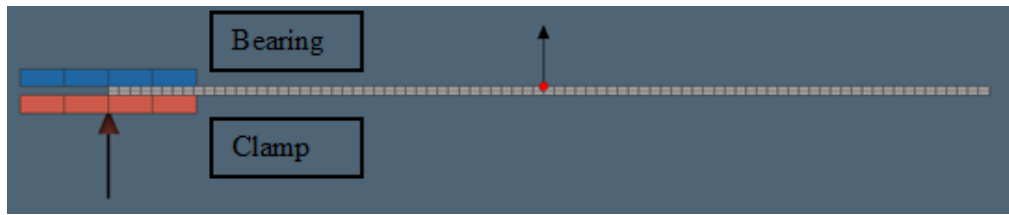


Figure 21 Clamp and Bearing Position

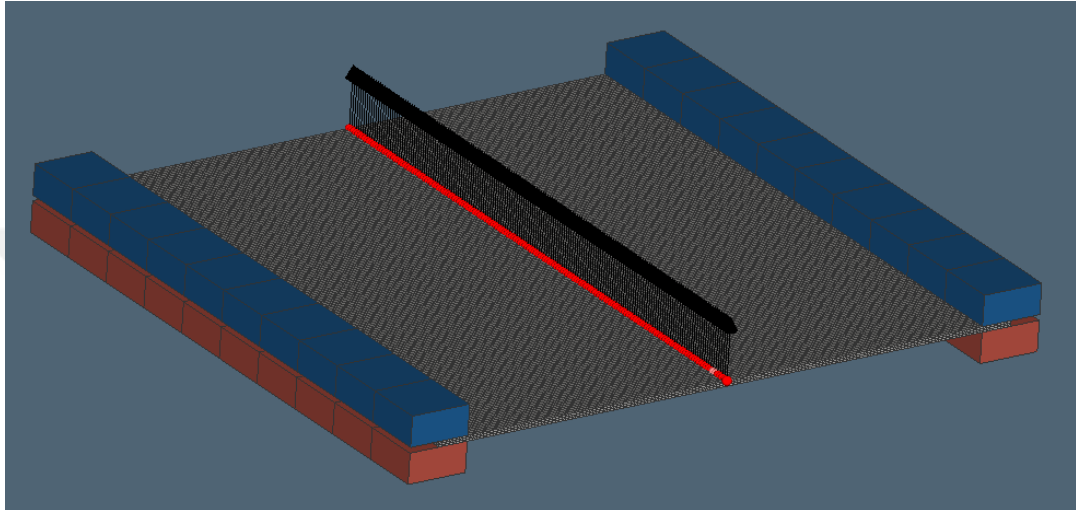


Figure 22 Two Side Clamped Weld Plate

The situation to be observed as a result of this experiment will have an effect on the distortion and mechanical properties of the 316L material at different laser welding parameters. Two different plates will not be welded together, and wire feeding will not be applied during laser welding. Argon gas will be used as a protective gas to prevent oxidation at high temperatures in the fusion zone where laser welding is applied. Detailed information about the amount/bar of argon gas used, the focus distance of the laser source, and the application method is defined in the Material and Specimen Preparation headings. Laser source coupons are named as $C_{112.1-1.75}$, $C_{112.1-2.00}$, $C_{125.7-1.75}$, and $C_{125.7-2.00}$. The 112.1 and 1.75 expressions defined here express the laser source wattage and laser source travel speed in mm/sec. In addition to the four coupons, welds will be placed on a different coupon with four parameters defined to determine the weld pool in the simulation, and after welding, this coupon will be taken into bakelite and weld pool measurements will be taken.

From the four coupons, only tensile coupons and hardness coupons will be removed. Four test coupons that have completed laser welding operations with different parameters; firstly, parallelism measurements will be measured with the help of a height gauge as discussed before. The measurement plan for the measurements to be made after welding is defined under the heading Dimensional Measurement. After parallelism measurement, to make certain that plates do not have any micro-cracks or porosities after welding operation, NDT (Non-Destructive Testing) with radiography and liquid penetrant test will be applied.

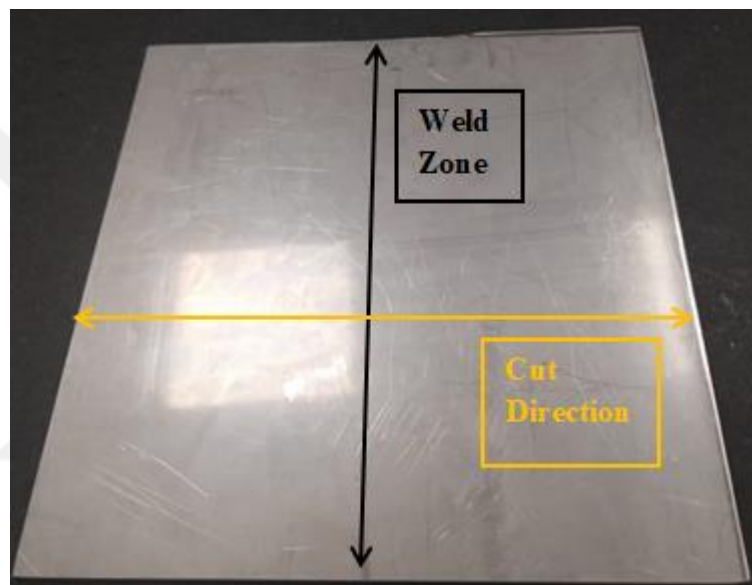
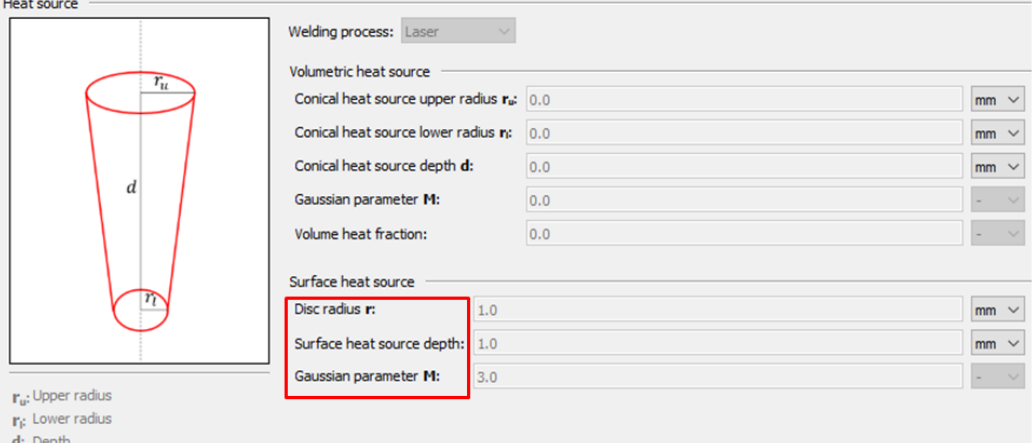


Figure 23 Cut Direction for Optical Microscope after Welding Process

Then, to observe the effect of different laser welding parameters on mechanical properties, tensile coupons and hardness test coupons will be removed, as described in Figure 23. To validate the simulation with real experiments, the 4 test coupons weld pools should be identified in Simufact Welding. Thus, a coupon including 4 welding parameters will be observed under the optical microscope, and the fusion zone's radius and the fusion zone's depth will be calibrated with thermal analysis. This operation will be carried out by the trial and error method by adjusting the Gaussian parameter (M) value, surface heat source depth value, and disc radius (r) value of the heat source as shown in Figure 24. After reaching the same weld pool geometry in simulation with the coupon that has 4 different welding parameters,

the simulations of the experiment will be carried out by adjusting the same welding power (W) and the same welding speeds (mm/sec) values in the laser welding operation. Details regarding validation are defined in the Adjustment of the Dataset for Simufact Welding heading and its subheadings. After the simulation is complete, the simulation values in terms of distortion & residual stress will be compared to the real-world experiment coupons that are $C_{112.1-1.75}$, $C_{112.1-2.00}$, $C_{125.7-1.75}$, and $C_{125.7-2.00}$. These comparisons will include the comparison of the height gauge measurement of real-world experiments and the simulation distortion values. Also, the residual stress results of real-world experiments and simulation residual stress values will be compared. An explanation for the specimen/test detail is given below for each specimen.



Heat source

Welding process: Laser

Volumetric heat source

Conical heat source upper radius r_u : 0.0 mm

Conical heat source lower radius r_l : 0.0 mm

Conical heat source depth d : 0.0 mm

Gaussian parameter M : 0.0

Volume heat fraction: 0.0

Surface heat source

Disc radius r : 1.0 mm

Surface heat source depth: 1.0 mm

Gaussian parameter M : 3.0

r_u : Upper radius
 r_l : Lower radius
 d : Depth

Figure 24 Surface Heat Source Parameter User Interface in Simufact Welding

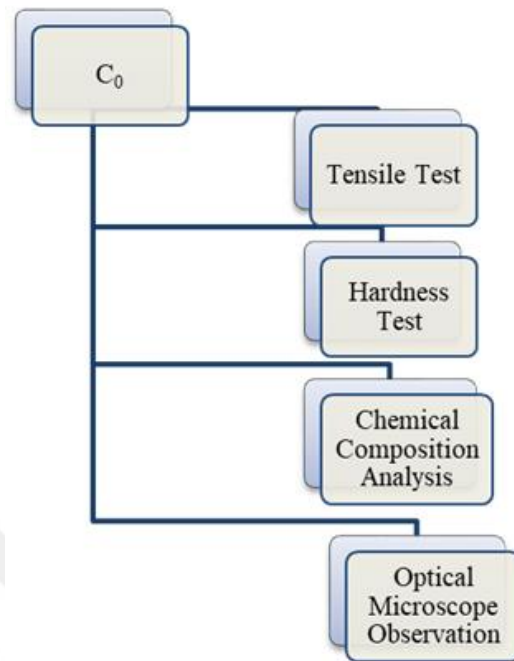


Figure 25 C_0 Configuration Test Plan

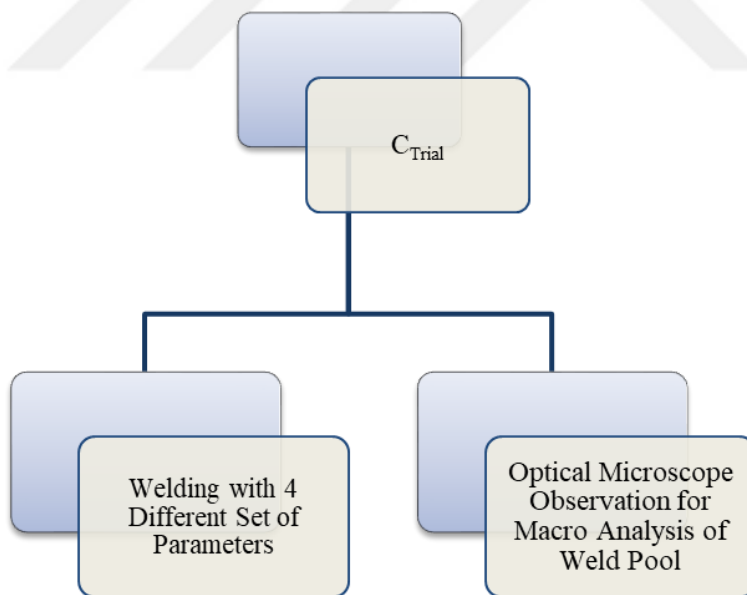


Figure 26 C_{Trial} Configuration Test Plan

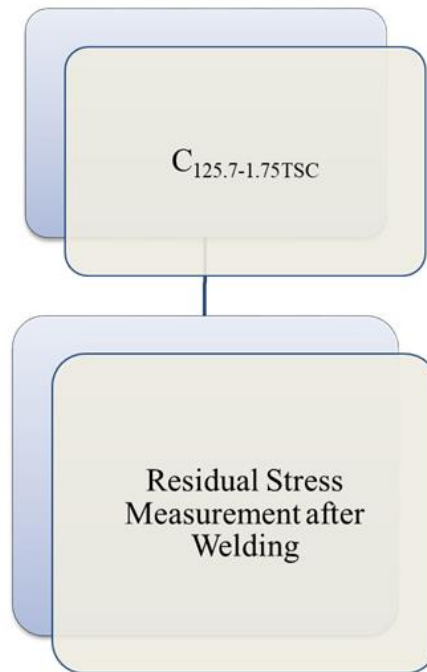


Figure 27 C_{125.7-1.75TSC} Configuration Test Plan

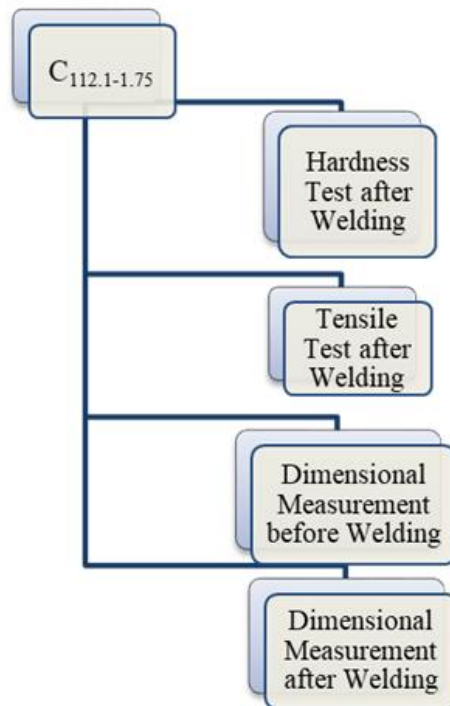


Figure 28 C_{112.1-1.75} Configuration Test Plan

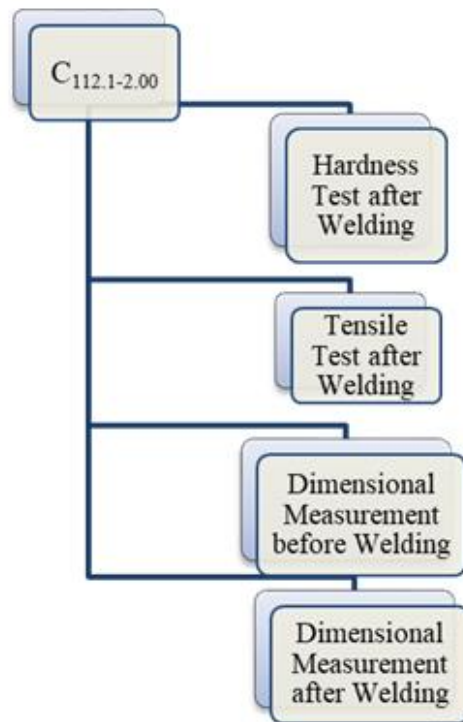


Figure 29 C_{112.1-2.00} Configuration Test Plan

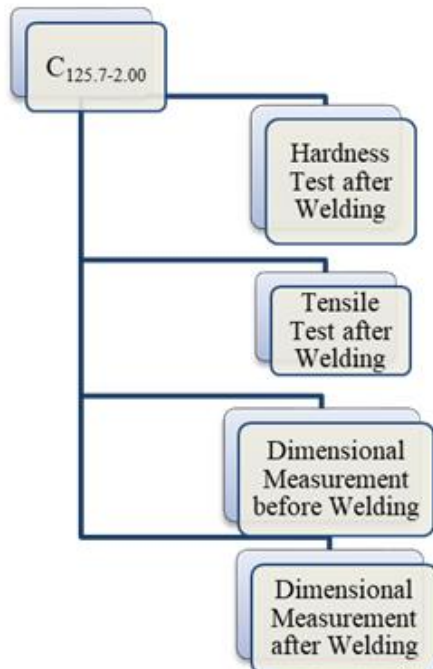


Figure 30 C_{125.7-2.00} Configuration Test Plan

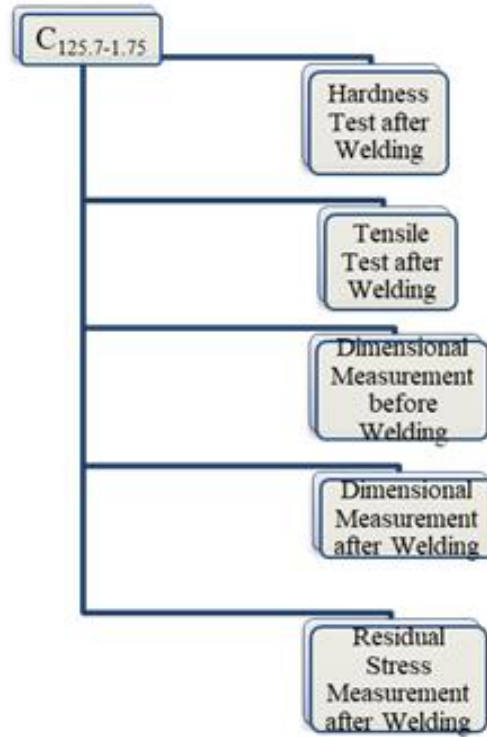


Figure 31 C_{125.7-1.75} Configuration Test Plan

As described in the above; Figure 25, Figure 26, Figure 27, Figure 28, Figure 29, Figure 30, and Figure 31, 7 specimens are used for this work that includes base plate operations, welding operations, and after welding operations. The residual stress measurement on the C_{125.7-1.75} configuration specimen will include the maximum tensile and compressive residual stress measurements. In addition, the part where the residual stress of this plate is close to zero will be determined from the simulation and will be used to compare with XRD results, whether the residual stress in the experimental condition is close to zero. Furthermore, except for the C_{125.7-1.75} specimen the C_{125.7-1.75TSC} specimen is welded as described above. This plate will be used for comparing the residual stress results of simulation and XRD results with C_{125.7-1.75} specimen. Since this plate is fixed more rigidly than the C_{125.7-1.75} plate, it is expected to observe higher residual stress results in this specimen. For this specimen, as given in Figure 27, only residual stress measurements will be performed since this plate will not be deformed after welding and cooling is completed due to clamping/bearing on both edges. To describe the

situation more clearly, it would be useful to point out that all 7 test coupons were the same size (100x100x0.9 mm), were cut from the same plate (1000x2000x0.9 mm) using the laser cutting method, and were not subjected to any additional operations after cutting. Six of these coupons are used for welding operations, and only the C₀ test coupon is not used in laser welding operations.

3.1 Material

The design of the experiment of this work is planned using the Minitab software, two parameters from the literature view, that is, laser power and welding speed, will be adjusted to 2 different stages, and that is given in the below design of the experiment matrix. A detailed explanation of the configuration is given in Table 2. 4 welding test configurations that are C_{112.1-1.75}, C_{112.1-2.00}, C_{125.7-1.75}, and C_{125.7-2.00} are prepared test samples. Welding tests will be performed with plates that have 100x100x0.9 mm dimensions.

Table 2 Welding Parameters and Configurations

Specimen Code	Laser Power (W)	Welding Speed (mm/sec)	Focus Distance (mm)	Shielding Gas Flow Rate and Pressure (L/min - Bar)	Shielding Gas Distance (mm)	Laser Beam Diameter (mm)
C _{112.1-1.75}	112.1	1.75	-1	14 - 5	25	0.3
C _{112.1-2.00}	112.1	2	-1	14 - 5	25	0.3
C _{125.7-1.75}	125.7	1.75	-1	14 - 5	25	0.3
C _{125.7-2.00}	125.7	2	-1	14 - 5	25	0.3

3.2 Specimen Preparation

For welding operation: the focus distance is selected as -1 mm since higher and lower values of focus distance decrease the efficiency of the laser beam. The Argon gas is used as an inert protective gas; the distance of the Argon gas application to weld the plate is 25 mm. The distance is kept as low as possible, since if the oxidation in the weld pool occurs, that will diminish the mechanical properties. Clamping and bearing of the laser welding sample is carried out as defined in the simulation; the clamping and bearing for experimental work is shown in Figure 32 below by the help of a Mitutoyo clamp that can be adjusted with an Allen wrench.



Figure 32 Fixture used in Welding Operation

The part of the plate fixed during the welding operation was determined as the opposite side of the measured edge; in other words, the opposite side of the X-marked edge is fixed during welding in the given plate image below Figure 34. The fixing of the $C_{125,7-1,75TSC}$ specimen is carried out similarly to one side clamped specimens; that is, the distance of clamping and the used fixture are the same, just two of them are used.



Figure 33 C_{125.7-1.75TSC} Specimen Fixture used in Welding

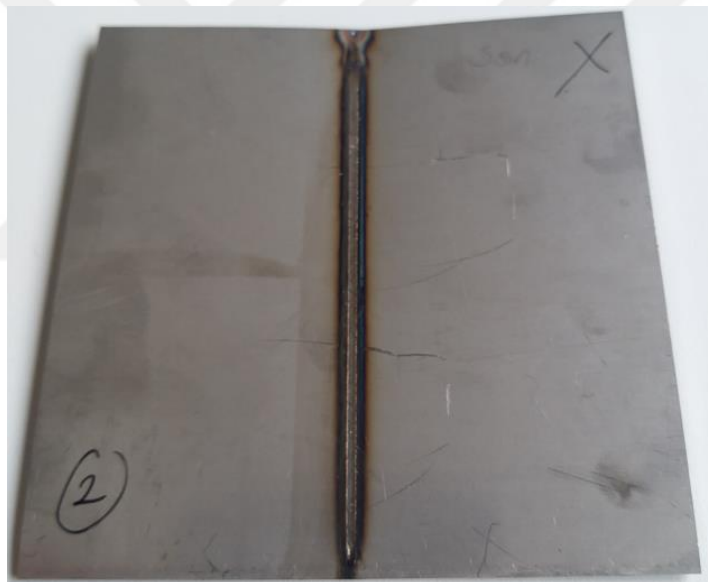


Figure 34 Fixed and Free Region in Welding Operation

The plate fixation was carried out in this way to compare the measurement result on the distorted part after welding with the measurement result before welding. The welding speed of the tray is set and used as automation and is carried out using the speeds given in Table 2. The laser welding operations are performed with the Alpha Laser AL-500, which can create a laser beam up to 500 watts of power. The tray of the laser welding machine can be used in automated mode with up to 5

mm/sec velocity. The tray has a movement capacity in x-y-z coordinates. For this thesis work only, the y-axis is used after setting the z-value to a -1 mm focus distance. Also, the laser welding machine can follow the focus point of the laser beam by microscope and set the starting point by marking the edge or midpoint of the welded plate. Also, the weld path can be imported to software, and the laser beam can follow the weld path by starting with spot welding and continuing with laser welding afterwards. Nevertheless, for this work, the starting edge of the plate is adjusted with a microscope, and automatic welding is performed in the y-axis. Before starting the actual tests, a parameter study was carried out by scrapping a plate in order not to define a high welding power or a low welding speed and to avoid applying high J/cm to the plate. In the study, different welding speeds and welding powers were tested, and other parameters were kept constant. After the parameters were defined, before the welds of the 4 plates to be used in the experiment were removed, the weld area was cleaned with ethyl alcohol to prevent the formation of intermetallic or porosities in the fusion zone caused by foreign materials. Since no preheating operation or post-heat treatment was applied in the simulation, no additional heat input was given to the plates other than the welding operation in real experiments. The welding parameters used in the experiments are listed in Table 2. The jig used to fix the plate in the welding operation has a clamp structure that is given in Figure 35, and a caliper was used to adjust the distance of the plate from the welding axis to a fixed distance.



Figure 35 Mitutoyo Clamp to fix the Weld Plate

Measurement was carried out before welding each plate, and the distance between the beginning and the end was kept within ± 0.3 mm. Also, before starting the experimental work, argon flow, tray movement, focus distance adjustment, and laser welding parameters are checked, and the plates are marked according to parameters given in Table 2. Also, in order to find the midpoint of the weld plates, the midpoint is marked after being measured with a caliper. Since the tray is automatically moved in the y-axis, the trajectory of the weld line is followed in the midpoint axis that is 50 mm to the edge of the plate.

3.3 Characterization Techniques

3.3.1 Optic Emission Spectroscopy

The chemical composition verification of the parent metal is done with optical emission spectroscopy. Single beam SpectroMaxx model Optic Emission Spectroscopy is used [85]. The method used for analysis is appropriate for stainless steels. Chemical composition analysis of the starting material is taken from the

surface of the test plate. Before optical emission spectroscopy, the surface of the material is cleaned of oil, and foreign particles. The test results will be taken according to the standard, which complies with the AISI 316L, which is defined in the norm; from ASTM E 1086 “Standard Test Method for Analysis of Austenitic Stainless Steel by Spark Atomic Emission Spectrometry”.

3.3.2 Mechanical Tests

For hardness testing, the Emcotest Durascan 50 G5 model microhardness testing machine is used. The testing machine can be adjusted to the desired hardness scales with different crossheads: Vickers, Brinell, or Rockwell. Hardness tests will be performed before and after the welding operation, and their comparison will be done. For the C_0 configuration, tests will be carried out from the specimens that are cut parallel to the surface. For $C_{112.1-1.75}$, $C_{112.1-2.00}$, $C_{125.7-1.75}$, and $C_{125.7-2.00}$ configurations, the hardness tests will be carried out perpendicular to the welding operation since the purpose of this test is to find out whether the hardness properties of the 316L stainless steel are affected with different welding parameters. Representative figures for the hardness test points are given in Figure 36.



Figure 36 Hardness Test Points from Weld Plate after Welding Complete

For the tensile testing of specimens, a 300 kN capacity universal tensile testing machine of Instron is used [86]. The extensions in the specimens are observed with a non-contact video extensometer. Similar to the hardness test, tensile tests will be performed before and after the welding operation, and the results will be compared. For the C_0 configuration, tests will be carried out from the specimens that are cut

parallel to the surface. For the $C_{112.1-1.75}$, $C_{112.1-2.00}$, $C_{125.7-1.75}$, and $C_{125.7-2.00}$ configurations, the tensile tests will be carried out from the specimens that are cut perpendicular to the welding operation. As given in the below representative Figure 37. Similar to the C_0 configuration tensile test procedure, 3 tensile testing specimens will be prepared.

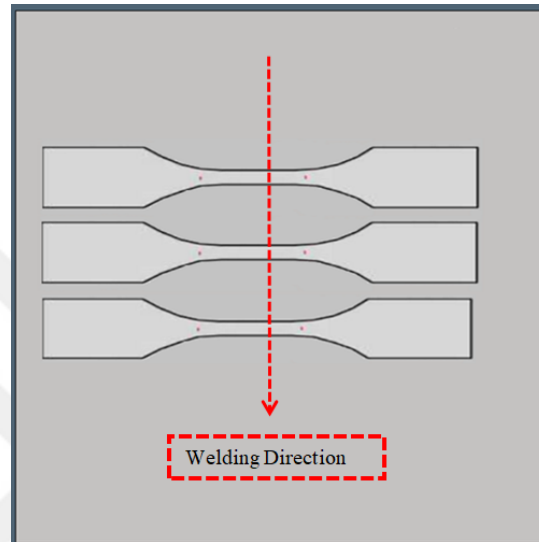


Figure 37 Tensile Test Specimens from Weld Plate after Welding Complete

Test results will enlighten the effect of welding parameters on the tensile strength of the specimens. For mechanical testing of the C_0 configuration of the base plate, 3 tensile testing specimens were cut as given in Figure 38 of the standard. These tensile test specimens were cut according to the ASTM E8 standard. Since the base plate is appropriate for sub-size sheet metal tensile test specimen sizes, its size is taken as the last column in the standard. The tensile tests are conducted according to the ASTM E8 standard too; the testing speed is 5 mm/min. After welding was completed, since the welding specimen sizes are 100x100x0.9 mm, according to ASTM E8 standard, the sub-size sheet metal tensile test specimen size was taken into consideration. Related tensile test specimen sizes for $C_{112.1-1.75}$, $C_{112.1-2.00}$, $C_{125.7-1.75}$, and $C_{125.7-2.00}$ weld specimens are given in Figure 39. The testing speed is an important parameter for tensile testing since increasing the tensile test speed to high levels can change the rupture behavior of the specimen from ductile to brittle.

	Dimensions		
	Standard Specimens		Subsize Specimen
	Plate-Type, 40 mm [1.500 in.] Wide	Sheet-Type, 12.5 mm [0.500 in.] Wide	6 mm [0.250 in.] Wide
	mm [in.]	mm [in.]	mm [in.]
G—Gauge length (Note 1 and Note 2)	200.0 ± 0.2 [8.00 ± 0.01]	50.0 ± 0.1 [2.000 ± 0.005]	25.0 ± 0.1 [1.000 ± 0.003]
W—Width (Note 3 and Note 4)	40.0 ± 2.0 [1.500 ± 0.125, -0.250]	12.5 ± 0.2 [0.500 ± 0.010]	6.0 ± 0.1 [0.250 ± 0.005]
T—Thickness (Note 5)		thickness of material	
R—Radius of fillet, min (Note 6)	25 [1]	12.5 [0.500]	6 [0.250]
L—Overall length, min (Note 2, Note 7, and Note 8)	450 [18]	200 [8]	100 [4]
A—Length of reduced section, min	225 [9]	57 [2.25]	32 [1.25]
B—Length of grip section, min (Note 9)	75 [3]	50 [2]	30 [1.25]
C—Width of grip section, approximate (Note 4 and Note 9)	50 [2]	20 [0.750]	10 [0.375]

Figure 38 ASTM E8 Standard “Standard Test Methods for Tension Testing of Metallic Materials” Specimen Sizes after Welding Operation

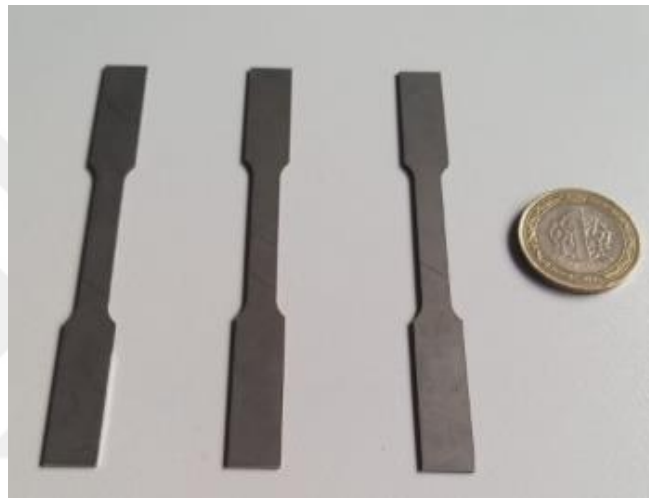


Figure 39 Sub-Size Tensile Test Specimens

3.3.3 Optical Microscopy

For optical microscope examination of the test sample of the base plate, the motivation is to observe the microstructure of the 316L in terms of grain size and grain orientation if it exists and to verify the structure of austenite. Thus, the microstructure test specimen obtained from the test plate is parallel to the surface. Also, before starting the welding operation with experimental test coupons, trial coupons will be used with defined parameters in Table 2. The main concern now is to define the dimensions of the weld pool in terms of pool radius and weld pool depth. After this identification, the fusion zone in Simufact Welding software will be adjusted with the trial & error method for these 4 different coupons. Therefore,

for the trial coupon fusion zone, the heat-affected zone will be observed that is perpendicular to the welding direction, and instead of grain size, the fusion zone measurements will be taken. The model of the optical microscope used for observation is the Nikon Eclipse MA100N inverted microscope [87]. The scale can be adjusted between 5x and 100x zoom.

3.3.4 Dimensional Measurement

The dimensional measurement of the test specimens is carried out with a height gauge before and after the welding operation, since the form of the plates is relatively good and can be measured with a height gauge, which is a faster measurement method. The model of height gauge used for the measurements is Mitutoyo Digimatic Hd-A, which is used with a comparator that is also Mitutoyo, and its model is No.513-415, which has a resolution of 10 micrometers. In other words, a 10-micrometer difference in the measured plane can be detected with this comparator. It is important to emphasize that the touching probe diameter of this comparator is 2 mm, which indicates that an area of 2 mm diameter can be touch-triggered with this probe; this probe diameter will be discussed in the heading Distortion Comparison with Simulation and Measurement Results. Results that will affect the comparison between simulation results and experimental results of distortion. Also, it is important to emphasize that the measurements are taken above a granite table that has a flatness calibration. The height gauge used for this measurement has a sensitivity of 0.01 mm. In other words, with this height gauge, a 10-micron difference in the height can be detected. This measurement can be considered as parallelism to the granite table. The granite table in this situation can be named as the primary datum for this measurement. The main point of this measurement is to compare the simulation test results with real experimental results. The Simufact Welding software gives the “Z Displacement” value, accepting the starting material in perfect form and dimensions. Nevertheless, real starting plates have some form/dimension deviations. Therefore, with a height

gauge, firstly the deflection of the points named as parallelism values will be determined. These parallelism values also can be used as a total deflection of the starting plates in the z direction in the given coordinate system. Since the variation in the start-finish deflection values in the z direction will be compared with the Simufact Welding simulation test results, the deflection values of all plates should be noted before the welding operation, as given in the heading Dimensional Measurement before Welding.

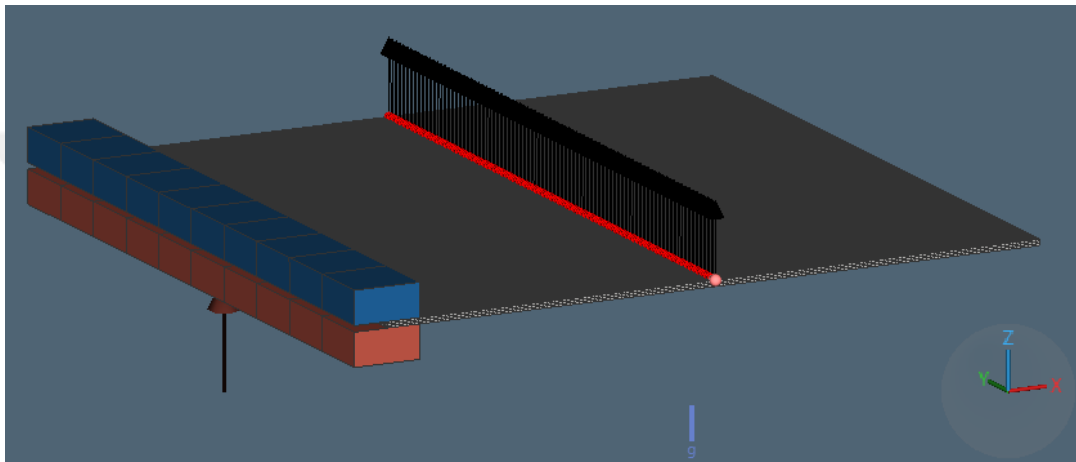


Figure 40 Coordinate System of Plate Measurement

According to ASME B89.7.2, before the measurements of the plates, the measurement plan should be prepared, and this plan should include workpiece identification, determination of measurements to be taken, determination of how measurements will be taken, determination of locations in the workpiece where measurements will be taken, etc. The measurement plan is given in Figure 43. The test sample plates will be placed on the granite table, and with the comparator attached to the height gauge, measurements will be carried out before the welding operation. This granite table is calibrated and has a flatness of 0.0042 mm, which is 4.2 microns. The clamp of Mitutoyo used for measurement has a flatness value of 0.0087 mm, which is 8.7 microns. The measurement uncertainty in measurement repeatability due to the operator is observed as 15 microns for different measurements; this uncertainty is dominantly caused by the touching point of the probe of the comparator. To take into consideration the temperature compensation,

the plates are placed in the laboratory 4 hours earlier to condition before the measurement. The measurements are taken starting from 5 mm inside the edge that will be exposed to the deflection after welding with a spacing of 10 mm. After the welding operation, similar to the pre-welding measurements, the post-welded plates are measured on a granite table of the height gauge. Nevertheless, this operation is performed with clamping of the non-deformed side of the welded plates for accurate measurement since the welded plates do not stand still due to deformation after the welding operation as given in the orange arrows in Figure 41; thus, if not clamped, the measurement is not possible. As a result, factors that affect measurement uncertainty and may affect the results of the plates after the experiment can be listed under the following headings:

- Granite table
- Mitutoyo Clamp
- Comparator
- Operator

Total measurement uncertainty due to these factors is measured as

$u_{\text{Table}} + u_{\text{Clamp}} + u_{\text{Comparator}} + u_{\text{Operator}} = 4.2 \mu\text{m} + 8.7 \mu\text{m} + 10 \mu\text{m} + 15 \mu\text{m} = 37.9 \mu\text{m}$. This value will be used in the error calculations after measurements.

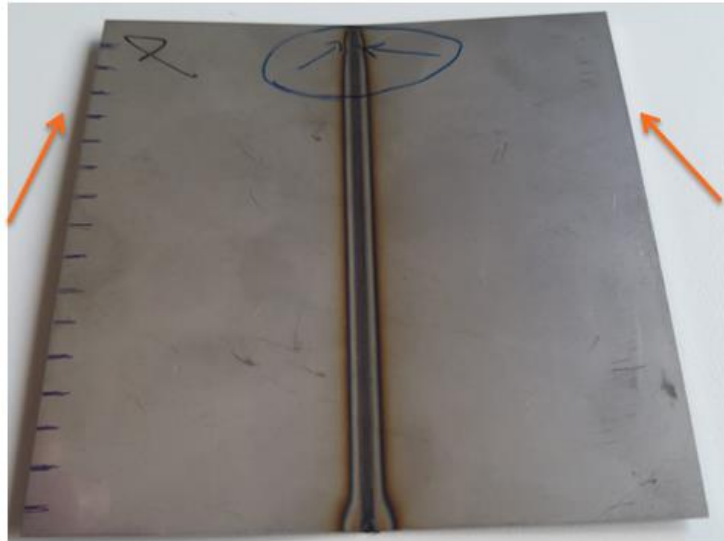


Figure 41 V Shape of the Plate after Welding Operation



Figure 42 Measurement with Height Gauge Equipment

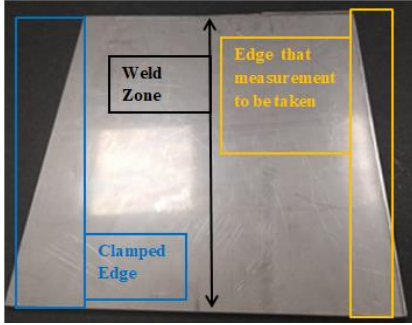
TEST RECORD FORM (GENERAL PURPOSE)		Record No : Test Date : Page No :
Test Step No	Test Step	Measured / Observed Results
1. Paralellism at Edge		
	1.	
	2.	
	3.	
	4.	
	5.	
	6.	
	7.	
	8.	
	9.	
	10.	

Figure 43 Dimensional Measurement Plan at Edge

3.4 Simulation using Simufact Welding Software

Simufact Welding 2024 software will be used to simulate the following comprehensive processes:

- Creation of complex model geometry
- Assignment of appropriate material properties to the defined model
- Application of high-accuracy mesh to the created geometry
- Fixing of the model for welding operations
- Determination of heat transfer

- Welding trajectory assignment
- Definition of welding parameters, welding speed of the robot that will perform the welding, welding geometry, welding power, spot diameter
- Post-welding cooling time
- Comprehensive analysis of stress and distortion distributions in the post-welding geometry

For these processes, the related process tree and the object catalog are used in the figure below.

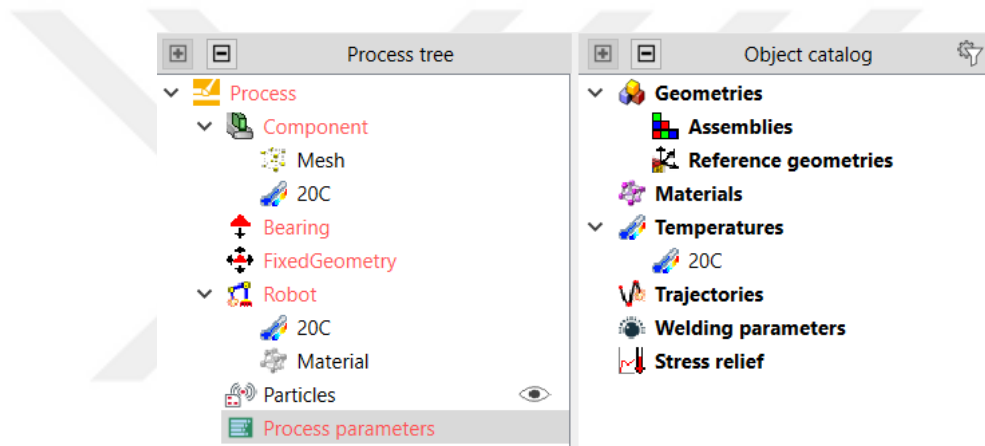


Figure 44 Simufact Welding 2024 Software Guidance User Interface

3.4.1 Model Designation

To simulate the welding operation properly in Simufact Welding, it is critical to define the given parameters;

- Mesh geometry: for mesh geometry, a hexahedral mesh will be used for all simulation operations instead of a tetrahedral mesh since the geometry is relatively basic: the hexahedral mesh is appropriate.

- Mesh size: mesh size will be selected according to mesh convergence analysis taken into consideration, less time-consuming and high accuracy in distortion & stress calculation that is 0.6 mm.
- Total element size of 83667 consisting of 0.6 mm meshes
- Size of the geometry; the size of the geometry will be the same as the size of the plate to be welded, that is; 100x100x0.9 mm.
- Material assigned to the geometry; material assigned to the geometry will be taken from the library of Simufact Welding 2024, and 316L_sw is used for the base metal.
- Bearing of the geometry: bearing of the geometry will be taken as 100x10x5 mm (length x width x thickness); only 5 mm width will be in contact with the weld plate as given in Figure 45.
- Clamping of the geometry: clamping of the geometry will be taken as 100x10x5 (length x width x thickness) mm; that's only 5 mm width will be in contact with the weld plate as given in the below Figure 45.
- Heat transfer: heat transfer will be taken as only radiation & convection to the air since the contact point of the bearing and fixing is negligible in real welding operation.
- Laser beam angle: the laser beam angle will be taken perpendicular to the weld plate, similar to the real welding operation.
- Total weld time: total weld time will be taken as 180 seconds since at the end of 180 seconds the temperature of the weld plate reaches room temperature as given in Figure 46.
- Plasticity solution taken as Multiplicative Plasticity.
- MUMPS (Multifrontal Massively Parallel Solver) is used in the matrix solver.

- Gravity is taken in the z direction as 9.8066 m/s^2 .

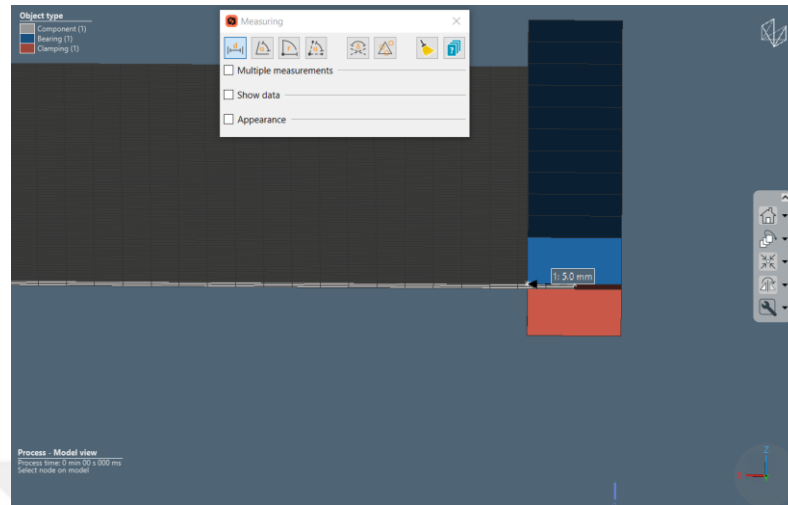


Figure 45 Fixing and Bearing of the Weld Plate in Simufact Welding

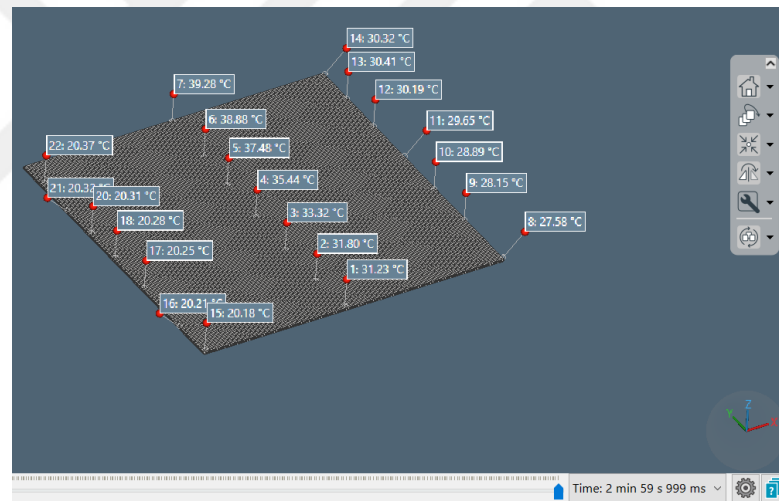


Figure 46 Temperature Distribution after Welding Completed

3.4.2 Mesh Optimization

To optimize the time required for analysis, before starting the simulation with a real experimental data set, it is important to predefine the acceptable mesh size since decreasing the mesh size increases the computational time required for calculations. In this work, the residual stress convergence and distortion

convergence values are taken into consideration. Also, in this work, adaptive mesh is not assigned; adaptive mesh enables concentrating on the points that are under stress or distortion. However, in this work, the total distortion and total Von Mises stress in the welded plate and their relation with mesh size are the work of interest. All of the analyses are run on 8 cores without running different analyses/programs. For simulation analysis, the Simufact Welding software is used.

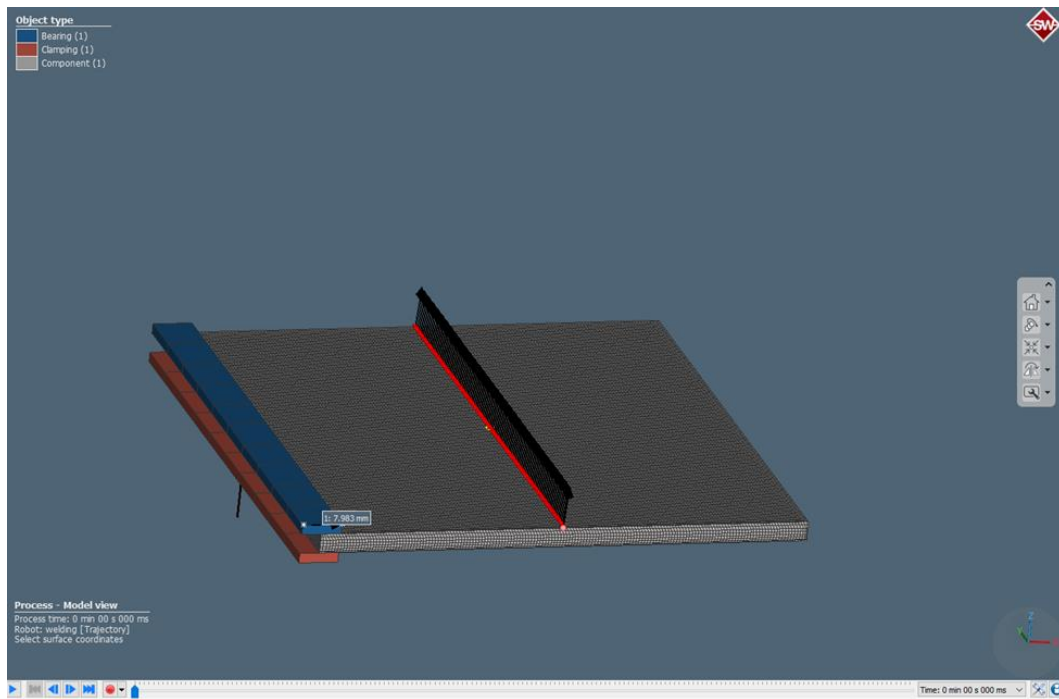


Figure 47 Welding Configuration for Mesh Convergence Analysis

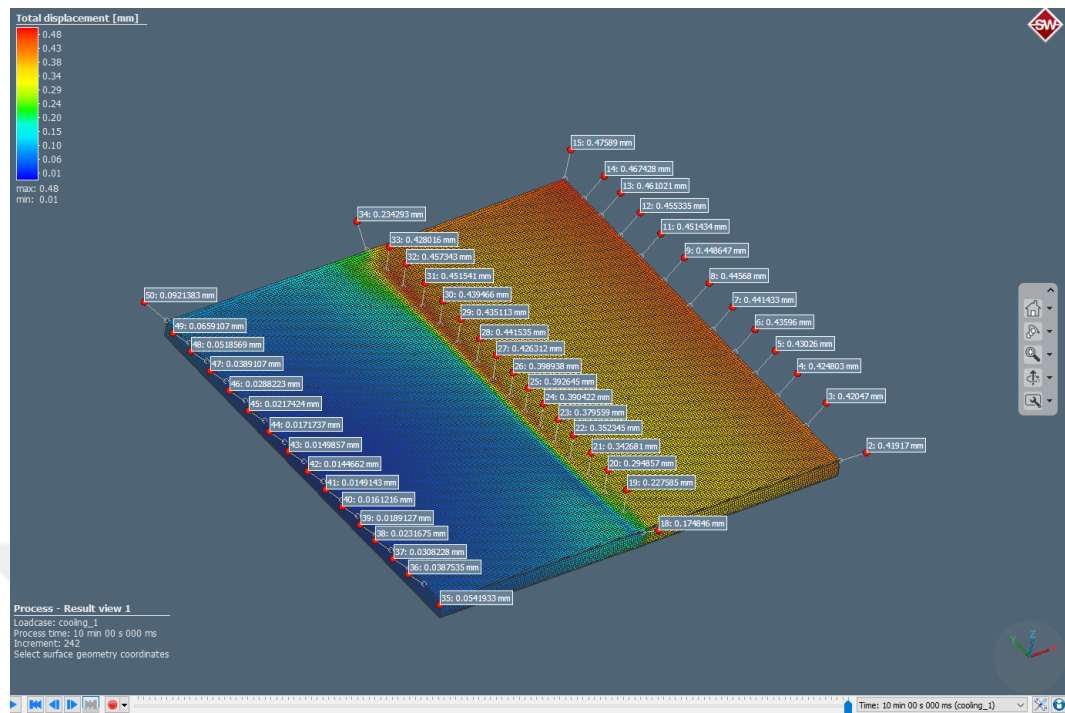


Figure 48 Mesh Convergence Analysis with Simufact Welding

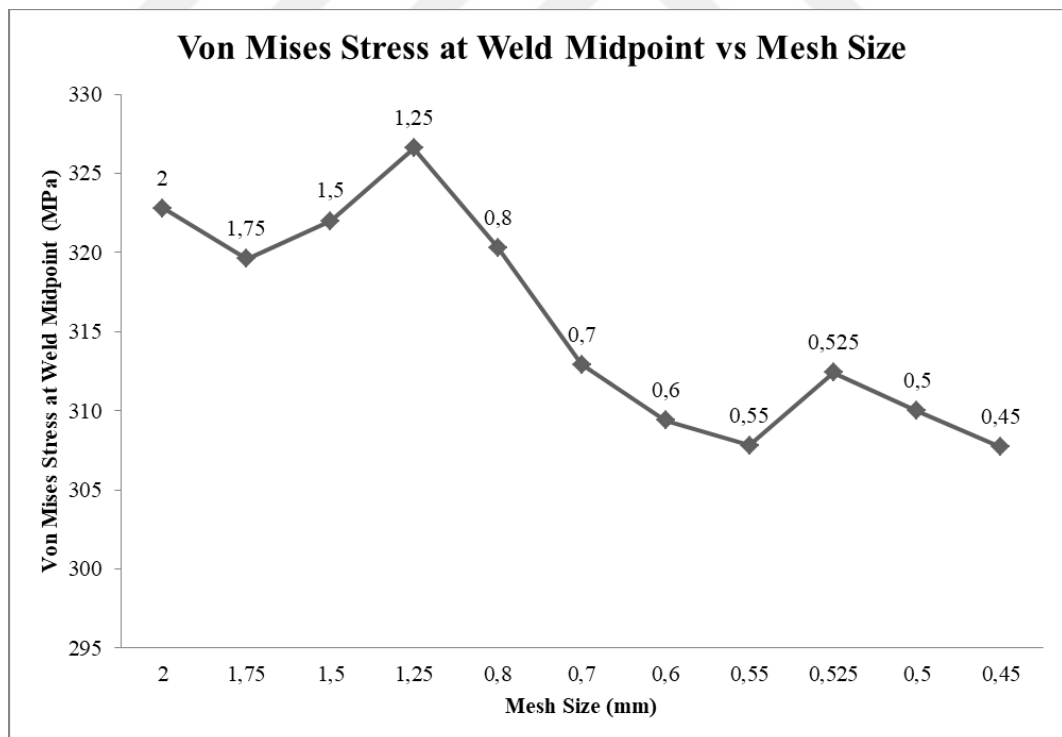


Figure 49 Von Mises Stress at Mid-Point vs Mesh Size

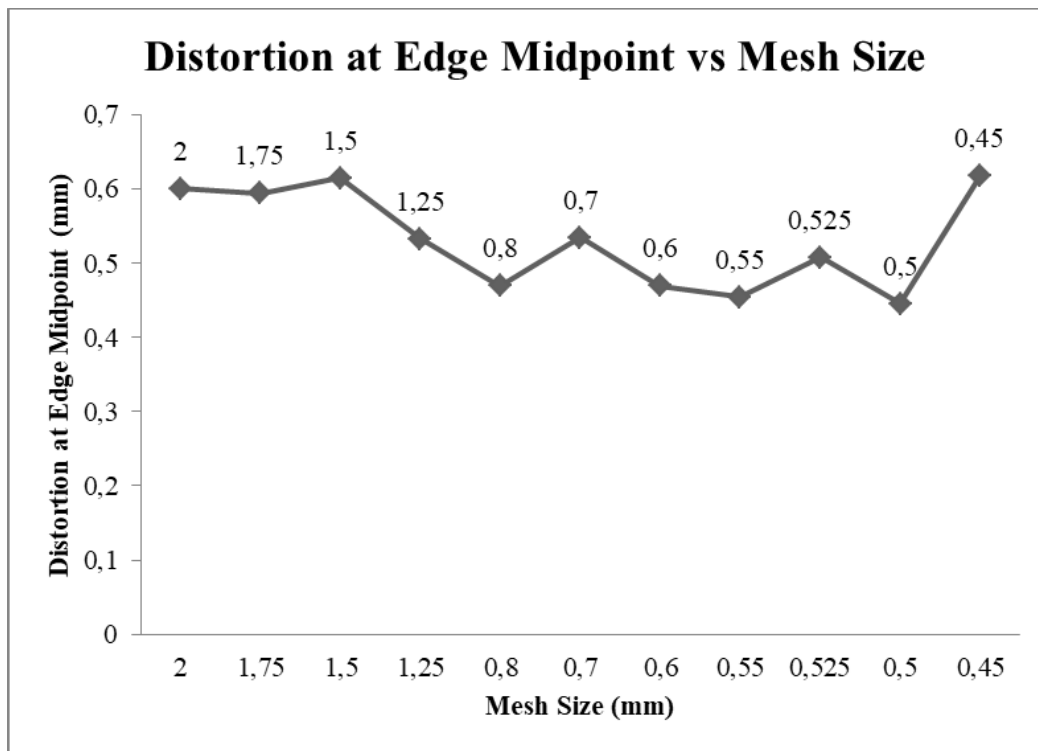


Figure 50 Distortion at Edge Midpoint vs Mesh Size

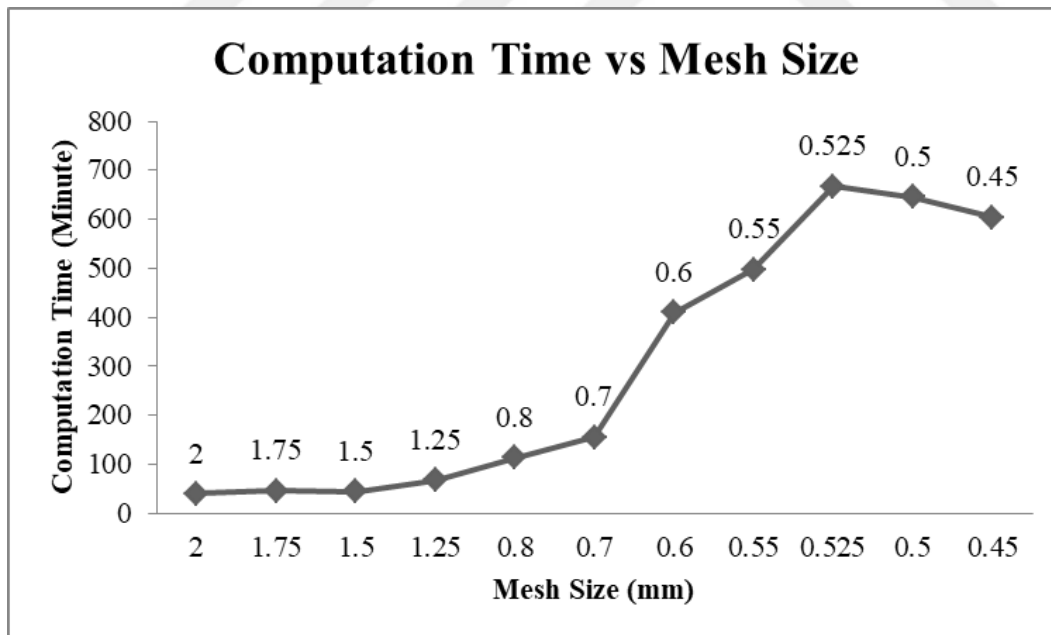


Figure 51 Computation Time vs Mesh Size

For the mesh convergence analysis with Simufact Welding, all parameters, such as bearing size, welding speed, welding power, weld start/finish location at 100x100x4 mm 316L plate, etc. are fixed. The only parameter that differs in the analysis is the different mesh size that is given in Table 3 below.

Table 3 Mesh Convergence Analysis for Von Mises Stress and Distortion

Mesh Size (mm)	Von Mises Stress at weld Midpoint (MPa)	Distortion at Edge Midpoint (mm)	Computation Time (Minute)
2.000	323.0	0.60	40
1.750	320.0	0.59	46
1.500	322.0	0.61	45
1.250	327.0	0.53	67
0.800	320.0	0.46	114
0.700	313.0	0.53	156
0.600	310.0	0.46	410
0.550	308.0	0.45	498
0.525	312.0	0.50	667
0.500	310.0	0.44	646
0.450	308.0	0.61	604

According to the given simulation test results above, the Von Mises Stress converges to ~ 310 MPa and the distortion converges to ~ 0.48 mm, and the computation time increases drastically with decreasing the mesh size below 0.7 mm. Thus, for optimum computation time and more accurate simulation results, a 0.6 mm mesh size is selected.

3.4.3 Assumptions and Simplifications

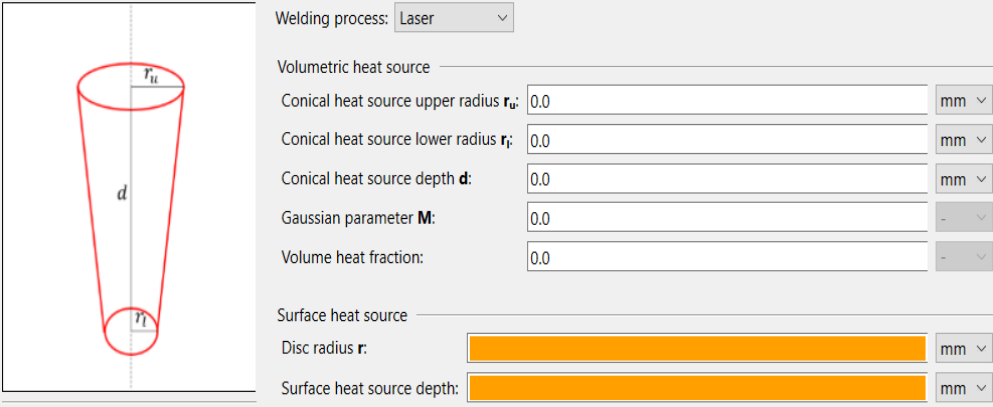
As stated in the above section, Mesh Optimization, to decrease the computation time in simulation, there are some simplifications taken into consideration during mesh convergence simulations, otherwise, the operation time increases dramatically, and the process efficiency decreases;

- 1) Heat transfer between bearing/clamping material and base component is neglected since the interface between them is taken as a small area.
- 2) The mesh analysis of the bearing/clamping is kept as simple as possible since the distortion takes place in the weld zone and the edge opposite to the bearing/clamping side.
- 3) The efficiency of the laser beam is taken as 100%, the effect of the reflection of the laser beam from the base metal and shielding gases is not taken into consideration, which decreases the efficiency of the laser beam.
- 4) The time for simulation is limited to 180 seconds, in other words, after 100 mm of welding of the plate is completed, the remaining section of the welding is comprised of cooling of the weld zone, and then the simulation stops. The total simulation time was determined by examining the cooling behavior of the main material after welding.
- 5) The material used for simulation is taken as isotropic and homogeneous.
- 6) Ideal geometry is selected in terms of dimension and form, in other words, the plate is created as its surfaces are perfectly parallel.
- 7) No defects or imperfections are identified in the plate.
- 8) The material history, i.e., residual stress, is neglected.
- 9) Ideal mechanical boundary conditions are selected, i.e., perfect contact between fixing/bearing and weld plate.

- 10) Up-ramping-Down-ramping through start and finish is disabled, i.e., power is constant at the finish and the start of weld.
- 11) Heat transfer is constant, i.e., steady-state heat transfer is used.

3.4.4 Adjustment of the Dataset for Simufact Welding

The adjustment of the dataset for Simufact Welding will be executed according to parameters defined in Table 2. The parameters defined as mandatory for the heat source to be filled in the Simufact Welding software interface are shown in Figure 52 with orange boxes below. For other parameters, their use can be removed by using the active or deactivated button. The critical operation to be performed here includes the parameters to be defined for the heat source. As described in the Simufact Welding heading, this operation will be performed using the trial and error method.



Heat source

Welding process: Laser

Volumetric heat source

Conical heat source upper radius r_u : 0.0 mm

Conical heat source lower radius r_l : 0.0 mm

Conical heat source depth d : 0.0 mm

Gaussian parameter M : 0.0 -

Volume heat fraction: 0.0 -

Surface heat source

Disc radius r : mm

Surface heat source depth: mm

Gaussian parameter M : 0.0 -

r_u : Upper radius
 r_l : Lower radius
 d : Depth

Figure 52 Heat Source Interface in Simufact Welding

To simulate the real welding conditions, the below table settings will be used, the disc radius, surface heat source depth is adjusted according to trial& error method. The Gaussian parameter M value is taken as 3 for all calculations. The disc radius and surface heat source depth can be seen in Figure 53. Where, disc radius is the

radius of the cylindrical heat source and surface heat source depth is the depth of the defined heat source. Depth of heat source cannot be greater than the total thickness of the weld plate.

Table 4 Heat Source and Process Parameters

Specimen Code	Laser Power (W)	Welding Speed (mm/sec)	Energy Per Length (J/cm)	Disc Radius (mm)	Surface Heat Source Depth (mm)
C _{112.1-1.75}	112.1	1.75	640.5	0.136	0.441
C _{112.1-2.00}	112.1	2	560,5	0.116	0.43
C _{125.7-1.75}	125.7	1.75	718.2	0.22	0.878
C _{125.7-2.00}	125.7	2	628.5	0.177	0.543

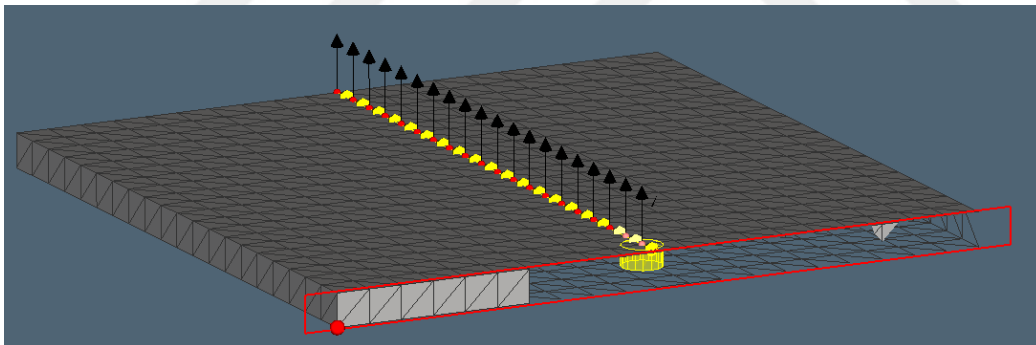


Figure 53 Heat Source given in Yellow Cylindrical Form

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Laser Welding Test Results

After laser welding of the 4 specimens is completed with parameters explained in Table 2, the related images for the 4 specimens are given in the figure chart below. The pass/fail examination for visual inspection of specimens is performed by a Level-2 visual welding inspector according to “ISO 13919-1 Electron and Laser-Beam Welded Joints Requirements and Recommendations on Quality Levels for Imperfections.”. Also, the non-destructive testing of the welded plates is examined according to the AWS D 17.1 Class A standard; related images of radiography and fluorescent liquid penetrant are given in Figure 54. For radiography and fluorescent liquid penetrant inspection, all plates are appropriate according to the AWS D 17.1 Class A standard. Therefore, tensile test specimens can be taken from these plates. All images for samples at weld start, weld end, and wide-angle back and wide-angle front are given below. After welding is completed for four different welding parameters—the weld pool geometry, distortion after welding is completed, and the geometry at the weld start & weld finish points—welding can be distinguished with the naked eye. The images taken after welding are given in Figure 55 and Figure 56.

C_{125.7-2.00}: High Laser Power and High Weld Speed; the result can be identified as a narrow weld bead, low thermal distortion compared to C_{125.7-1.75} welding. Nevertheless, the numerical distortion comparison will be performed under the Dimensional Measurement before Welding heading. No undercut, porosities, and crack & discontinuities were observed at the surface of the weld and the back of the weld zone. A darker, blacker area is seen at the weld start. To determine the focus point of the laser before starting the trajectory of the weld, a short-term welding

process similar to spot welding is performed, which creates a blacker and wider weld pool at the beginning of the welding section. The starting point of the weld line is visible through the microscope, but in order not to damage the equipment, this process was first carried out to fully understand the location of the laser focus point on a point on the plate that is not in a very corner. The reason for the blue/brown color at the end point of the welding operation is due to the deactivation of argon gas when the laser power is cut off at the end point. Since the welding area is still at high temperature, oxidation is observed after the argon gas is cut off. These regions are not important as they will not be evaluated under the title of mechanical tests. Also, the size of this region is higher for the 125.7-watt laser weld power since the fusion zone (liquid area) is greater for higher wattage. At the back of the weld zone, the weld root can be detected with the hand, which means the 125.7 wattage penetrated through the 0.9 mm thickness.

C_{125.7-1.75}: The result can be identified as a wide weld bead and higher thermal distortion compared to C_{125.7-2.00} welding. No undercut, porosities, and crack & discontinuities were observed at the surface of the weld and the back of the weld zone. No spatters were observed on the weld zone surface due to the lower weld speed. Similar to all other specimens, a darker, blacker area is seen at the weld start as described above. At the weld finish point, a similar blue/brown area geometry to the C_{125.7-2.00} specimen is observed since their laser powers are equal. At the back of the weld zone, the weld root can be detected with the hand, which means the 125.7 wattage penetrated through the 0.9 mm thickness.

C_{112.1-2.00}: Low laser power and high weld speed; a shallow and narrow weld seam was observed. Lower thermal distortion compared to C_{112.1-1.75} welding. No undercut, porosities, and crack & discontinuities were observed at the surface of the weld and the back of the weld zone. Similar to all other specimens, a darker, blacker area is seen at the weld start, but due to low laser power, the dark area at the start point is smaller than the 125.7-watt configuration. At the weld finish point, blue/brown area geometry is shown, but again, this area is smaller compared to the C_{125.7-2.00} specimen since the laser power is smaller. At the back of the weld zone, a

bulge due to fusion zone solidification can be detected with the hand, which means the 112.1 wattage penetrated through the 0.9 mm thickness; nevertheless, with the optical microscope observation of the fusion zone, clearer results have been observed.

C_{112.1-1.75}: Low laser power and low weld speed; weld bead of medium depth and width observed. Higher thermal distortion compared to C_{112.1-2.00} welding. No undercut, porosities, and crack & discontinuities were observed at the surface of the weld and the back of the weld zone. No spatters were observed on the weld zone surface due to the lower weld speed. Similar to all other specimens, a darker, blacker area is seen at the weld start, but due to low laser power, the dark area at the start point is smaller than the 125.7-watt configuration. At the weld finish point, blue/brown area geometry is shown, but again, this area is smaller compared to the C_{125.7-2.00} specimen since the laser power is smaller. At the back of the weld zone, a bulge due to fusion zone solidification can be detected with the hand, which means the 112.1 wattage penetrated through the 0.9 mm thickness; nevertheless, with the optical microscope observation of the fusion zone, clearer results have been observed.

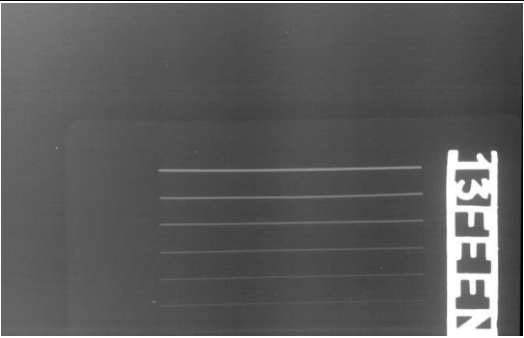
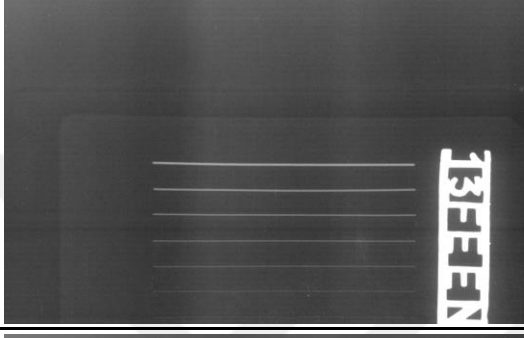
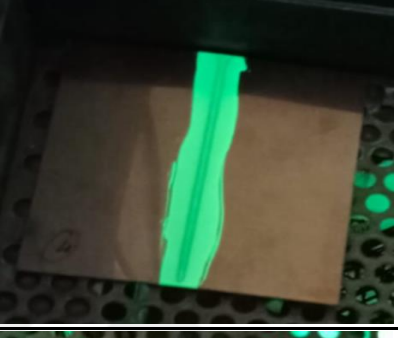
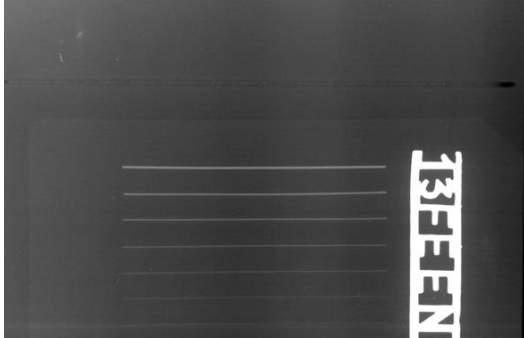
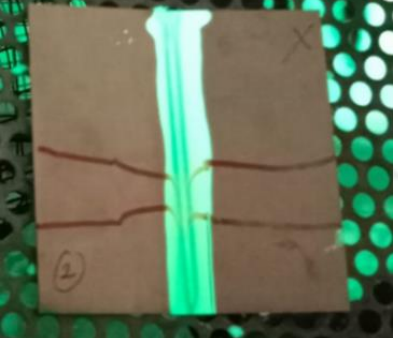
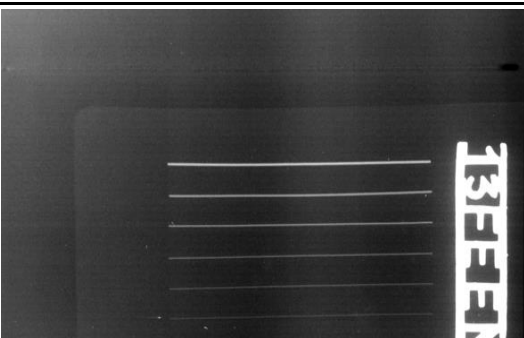
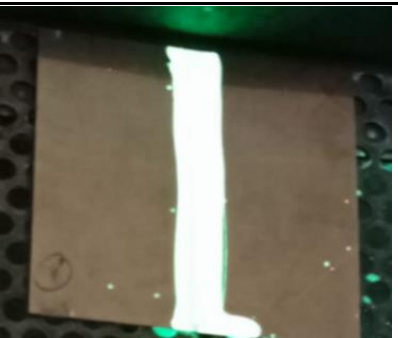
#	Radiography Image	Liquid Penetration Image
C _{112.1-1.75}		
C _{112.1-2.00}		
C _{125.7-1.75}		
C _{125.7-2.00}		

Figure 54 Radiography and Liquid Penetration Test Results

#	Weld Start	Weld Finish
C _{112.1-1.75}		
C _{112.1-2.00}		
C _{125.7-1.75}		
C _{125.7-2.00}		

Figure 55 Weld Start & Finish Points after Welding Completed

#	Wide Angle Front	Wide Angle Back
C _{112.1-1.75}		
C _{112.1-2.00}		
C _{125.7-1.75}		
C _{125.7-2.00}		

Figure 56 Front and Back of the Plates after Welding Completed

4.2 Chemical Composition Analysis with OES

The chemical composition analysis of the C₀ configuration base plate is prepared from the remaining part of the base plate, from which the tensile test coupons were removed. The burn traces are expected since the working principle of optical emission spectroscopy is applying an electrical energy in the form of a spark, which vaporizes the atoms in the surface, thus, in the surface after the test a burned area is observed. For chemical analysis, optical emission spectroscopy is used. Evaluated chemical composition analysis is given below, the values given in Table 5 are mean values taken from the 6 different data sets, and the arithmetic mean of the 6 data sets is calculated. The test results are evaluated according to the ASTM-A276 standard and comply with the ASTM-A276 standard for 316L stainless steel. When we perform a phase analysis considering the Schaeffler diagram for the welded base plate, there is a 10% ferrite and 90% austenite phase as indicated by the red dot in the image below. Relevant calculations were carried out by calculating the Chromium and Nickel equivalents numbered 11 and 12. It would be better to evaluate the post-welding phase analysis and mechanical test results in this context. Within the given Figure 57, Cb stands for columbium, usually called Nb. The Nickel equivalent is calculated as 11.2, and the Chromium equivalent is calculated as 20.2, according to the given equations and the chemical composition given in Table 5.

$$Creq = Cr + Mo + 1.5x Si + 0.5x Nb \quad (11)$$

$$Nieq = Ni + 30x C + 0.5x Mn \quad (12)$$

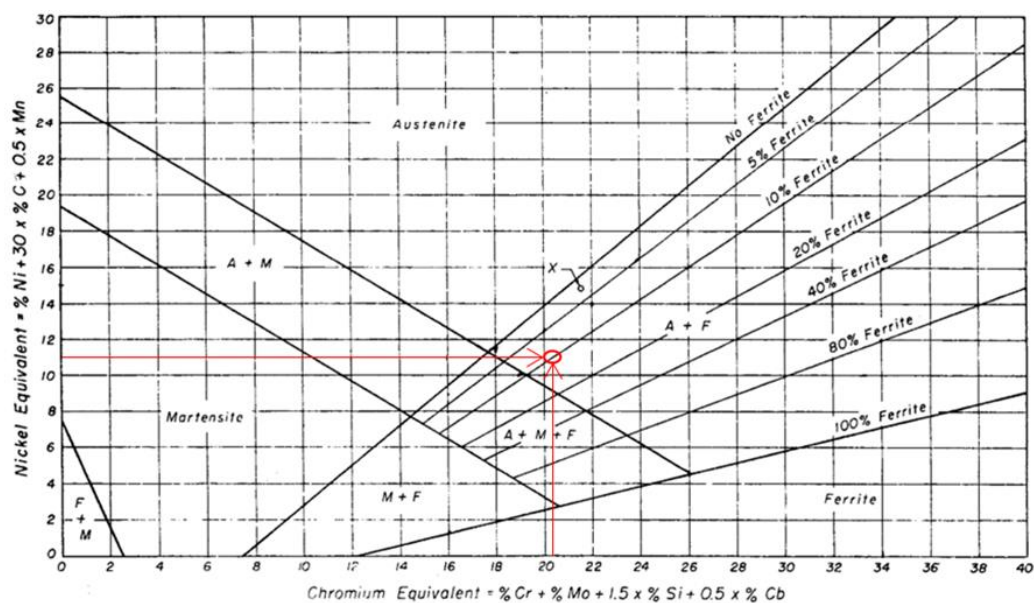


Figure 57 Schaeffler Diagram [88]

Table 5 Chemical Composition of C₀ configuration Stainless Steel Plate

Element	Wt. %
Cr	17,642
Mo	2,130
Mn	1,393
Ni	9,865
C	0,022
Si	0,303
P	0,016
S	0,0005 max
Nb	0.031
Fe	Balance

4.3 Mechanical Tests of Base Metal

4.3.1 Tensile Testing

The test specimens showed ductile fracture mode in tensile testing as indicated in Figure 58. This fracture behavior is also known as cup-on-cone fracture model. Also, it can be understood from the matte fibrous surface.

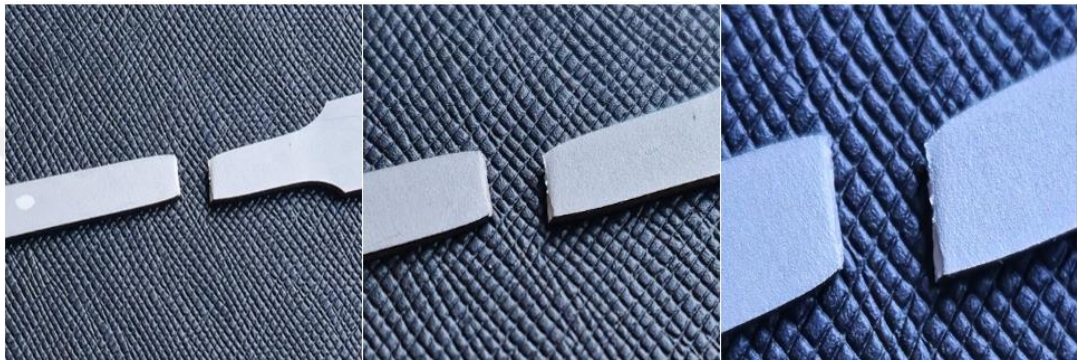


Figure 58 Close-up Image of Test Specimens at Rupture Point of Base Metal

Table 6 Tensile Test Results of Specimens of Base Metal

Specimens (#)	Maximum Force (kN)	Tensile Stress at Maximum Force (MPa)	Tensile Strain at Break (%)	Yield Stress (Offset 0.2 %) (MPa)
1	3.21	627	68.9	289
2	3.20	627	67.9	288
3	3.29	628	67.4	298
Mean	3.23	627	68.0	291

Tensile test results of the specimens show consistency within. Also, as indicated in the ASTM E8 standard, the fracture point of the test specimen is an essential

criterion to evaluate the test results. According to ASTM E8, the fractures that occur outside of the gauge length are not representative of the tested material since the scratch, or micro-crack, may cause the origin of the fracture point. Thus, the torque value for the tested specimen is critical; the specimen should not slip from the crossheads that hold the specimen, nor should it press too much to the test specimen to not create a dent or micro-crack. This behavior is common for brittle materials, composites, or plastic materials; nevertheless, the tested specimen is austenitic stainless steel, and the FCC structure of this material enables it to fracture in a ductile manner. All three specimens are fractured from the gauge length. Therefore, the given test result values can represent the behavior of the non-welded plate 316L stainless steel material.

4.3.2 Hardness Testing

For hardness testing of the C₀ configuration, the remaining part of the base plate, from which the tensile test coupons were removed, was used for the hardness test. The remaining part is taken into Bakelite; it is safer to take a test from the Bakelite since the force applied to the specimen should be perpendicular to the test specimen. Since the tested material, 316L stainless steel, is a relatively soft material, the test results below 20 HRC were obtained with Rockwell HRC, which do not give reasonable values; therefore, it was checked with Vickers hardness. 5 different points are measured from different points; as stated in the Vickers hardness test ASTM E384 (Micro-Hardness) standard, the measurements taken should not be too close to avoid the plastic deformation near the hardness taken point. Test results are taken with 1 kg of force. Test results are given in Table 7; an image of the force-applied area is given in Figure 59. The comparison between base metal hardness and after-welding hardness operation is carried out in the heading of Mechanical Tests after Welding.

Table 7 Vickers Hardness Results of Starting Specimen

Vickers Hardness #	Hardness Value (HV)
1	159
2	163
3	163
4	159
5	161
Average	161

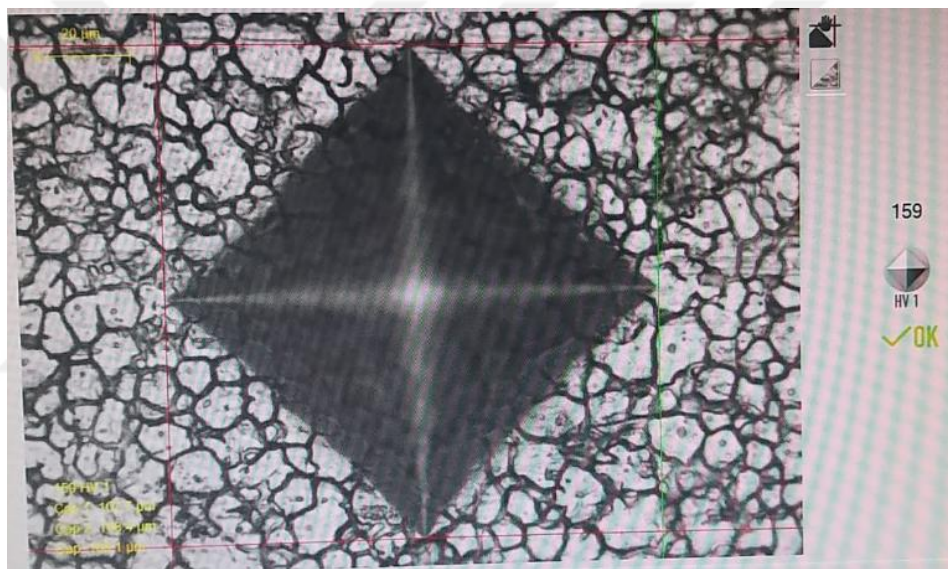


Figure 59 Image of Force Applied Area in Vickers Hardness Test

4.4 Mechanical Tests after Welding

4.4.1 Tensile Testing

After welding was completed, the welded test specimens $C_{125.7-2.00}$, $C_{125.7-1.75}$, $C_{112.1-2.00}$, and $C_{112.1-1.75}$ were cut with EDM (Electrical Discharge Machining) according to the given image below, the numbers marked for the tensile test coupons were made considering the order of welding.

Table 8 Tensile Test Results of Specimens after Welding

Specimens (#)	Maximum Force (kN)	Tensile Stress at Maximum Force (MPa)	Tensile Strain at Break (%)	Yield Stress (Offset 0.2 %) (MPa)
C _{125.7-1.75-1}	3.30	669	61.3	310
C _{125.7-1.75-2}	3.30	677	61.8	314
C _{125.7-1.75-3}	3.30	684	65.2	313
Mean	3.30	676	62.7	312
Range	0.00	15.00	3.90	4.00
St. Dev.	0.00	7.51	2.12	2.08
C _{125.7-2.00-1}	3.22	623	60.8	290
C _{125.7-2.00-2}	3.31	637	59.0	305
C _{125.7-2.00-3}	3.32	630	59.4	302
Mean	3.28	630	59.7	299
Range	0.10	14.00	1.80	15.00
St. Dev.	0.05	7.00	0.95	7.00
C _{112.1-1.75-1}	3.41	702	67.8	337
C _{112.1-1.75-2}	3.41	719	66.6	345
C _{112.1-1.75-3}	3.42	640	69.6	307
Mean	3.41	687	68	329
Range	0.01	62.00	3.00	38.00
St. Dev.	0.00	41.58	1.51	20.03
C _{112.1-2.00-1}	3.41	691	67.0	334
C _{112.1-2.00-2}	3.41	692	67.3	335
C _{112.1-2.00-3}	3.41	690	70.7	332
Mean	3.41	691	68.3	333
Range	0.00	2.00	3.70	3.00
St. Dev.	0.00	1.00	2.05	1.52

When the tensile test results performed after the welding process were compared, it was observed that the yield strength standard deviation was 12 MPa and the tensile strength standard deviation was 8 MPa. The outlier values for C_{112.1-1.75} and C_{112.1-2.00} plates indicate that after welding, the thickness of the plate will become thinner in the region where the weld pool is located, and therefore the tensile and yield strengths will be high. When the force values applied at break are examined, it is seen that there is an increase of around 3 percent. The effect of this value on tensile strength in the same dimensions will be around 20 MPa. Since the wire feeding process is not carried out in the welding operation, the weld pool weld values are lower than the 0.9 mm width value, and it is expected that the yield strength and tensile strength results of the unwelded plate and the post-welded plates will be different. Since the welded plates are austenitic stainless steel, no phase transformation has occurred; therefore, no increase is expected, and since radiographic and liquid penetrant non-destructive examinations are performed after the welding operation, no decrease is expected. The results were as expected in this context.

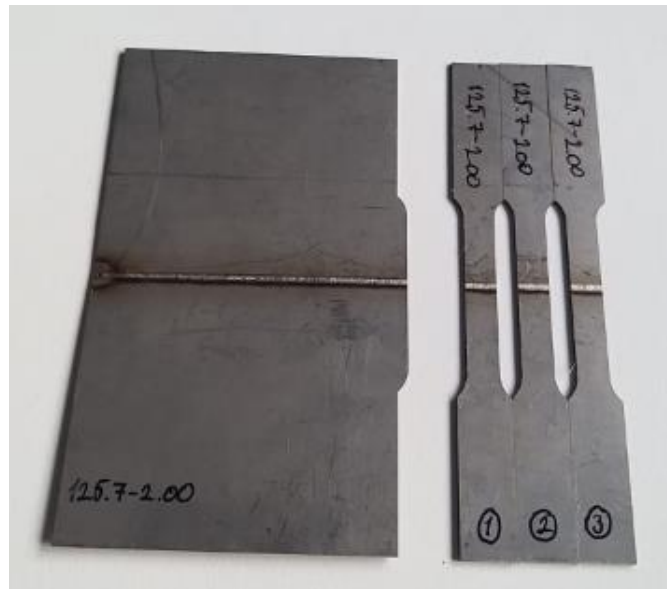


Figure 60 Sub-Size Tensile Test Specimens after Welding Completed

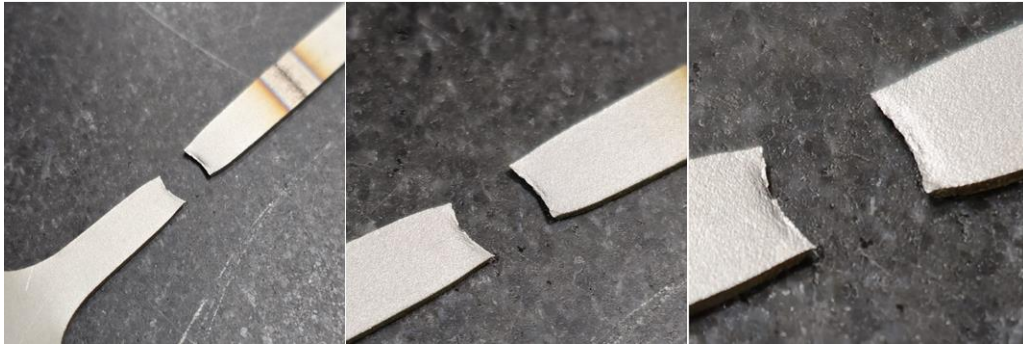


Figure 61 Close-up Image of Test Specimens at Rupture Point after Welding

4.4.2 Hardness Testing

After the test coupon was welded with 4 different parameters and used for examining the weld pools and heat source calibration in the simulation, the etch operation of this coupon was also performed, and this coupon was used for the microhardness test.

#	Vickers Hardness Images
C _{112.1-1.75}	
C _{112.1-2.00}	
C _{125.7-1.75}	
C _{125.7-2.00}	

Figure 62 Images after Vickers Hardness Test

The results of the weld zone and the parent metal are given in Table 9 below. Also, for four test coupons, the standard deviation value is given in the last line, and the range of the measured hardness values is given for the four test specimens. 8 different values are taken as given in Figure 62.

Table 9 Hardness Test Results after Welding

#	C _{125.7-2.00} (HV)	C _{125.7-1.75} (HV)	C _{112.1-2.00} (HV)	C _{112.1-1.75} (HV)
1	179	167	187	171
2	166	162	171	155
3	177	169	186	184
4	169	169	175	163
5	168	163	182	156
6	178	175	187	155
7	168	163	173	166
8	176	176	161	179
Range	13	14	26	29
Average	172.7	168.0	177.8	165.8
Standard Deviation	5.3	5.4	9.4	11.1

Similar to the base metal hardness operation, all hardness tests are conducted with Vickers hardness, and the load is 1 kg/mm². Since the weld material is AISI 316L austenitic stainless steel, no phase transformation to the martensite phase has occurred as expected; average martensitic steel has a Vickers hardness around 400-700 [89]. Additionally, the hardness values within the material itself also show consistent results; it should be considered that the hardness measurement with Vickers hardness may include a measurement uncertainty due to the operator, parallelism of the bakelite, and uncertainty due to the test machine. For lower test forces, the test machine uncertainty decreases up to 1.5% [90]. An additional point

to pay attention to when taking tests is not to take measurements too close to the Bakelite sides. When a comparison is made, the Vickers hardness values taken before and after welding show a slight increase in the average values of post-welding measurements. Since the material used is austenitic stainless steel, no phase transformation took place after welding, and when we consider the standard deviation in the measurements and the measurement method, it is interpreted that this is due to measurement uncertainty. When the measurement values shared in Table 8 are examined, it can be observed that measurements 1, 2, 7, and 8 were taken on the base metal, and these values are similarly slightly higher than the measurements taken from the base metal. The difference between the pre-welding and post-welding hardness measurements is that the hardness values taken from the base metal are taken from the surface parallel to the plate, and the hardness values taken after welding are taken from the section perpendicular to the plate surface.

4.5 Optical Microscope Examination

As stated in the above section, Optical Microscopy, the specimen is taken parallel from the base plate C₀ configuration for the preparation of the test specimen to observe the grain structure and grain size, the following operations are followed:

- Specimen preparation as described in section 3.5
- Take the Bakelite of the cut specimen
- Grinding with an automatic grinder machine from 240 grit to 4000 grit sandpaper
- Polishing of the specimen with 1-6 μm diamond containing solution
- Rinsing the specimen with water and cleaning water droplets with an airgun
- Etching with HCl 50%, C₃H₈O₃ 30%, HNO₃ 20% solution
- Rinsing the surface from the etchant with water and cleaning with an airgun

Etching is performed with a solution given above by the error&trial method, to not burn the surface of the specimen, the specimen is immersed in the solution with 20- a second period and for 6 times, within every trial, the microstructure is observed with a microscope. After these operations, the grain size, grain orientation, and austenite grain structure are examined as given in Figure 63.

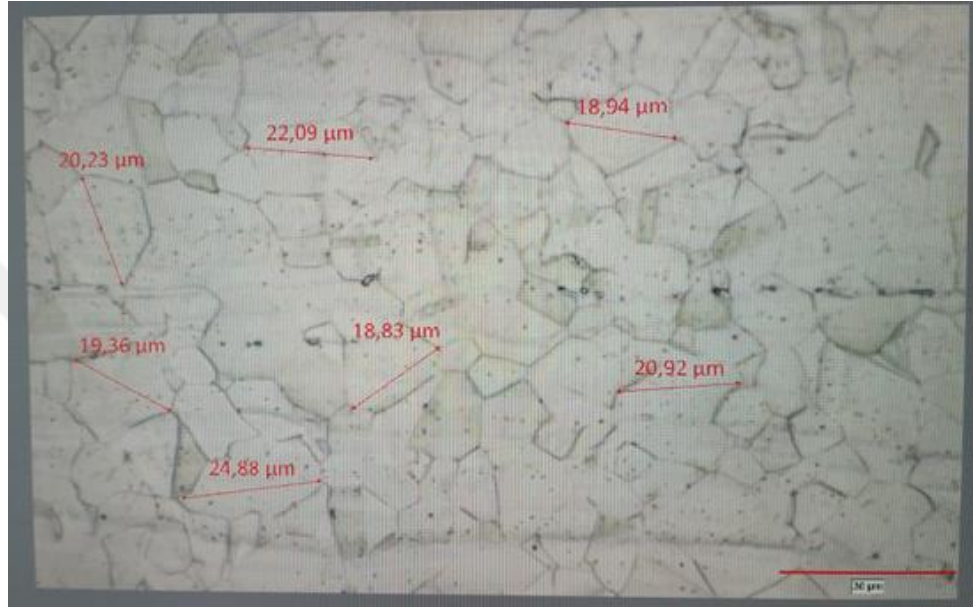


Figure 63 Grain Structure of the C₀ Plate Area 1

For the heat source parameter calibration as stated in Optical Microscopy heading, the trial test coupon (the coupon welded with set parameters) as given in Figure 69 is used. The optical microscope of macro images for the welded zone is given in Figure 70. The preparation operations for macro observation are as follows:

- Specimen preparation as described in section 3.5
- Take the bakelite of the cut specimen
- Grinding with an automatic grinder machine from 240 grit to 4000 grit sandpaper
- Polishing of the specimen with 1-6 μm diamond containing solution
- Rinsing the specimen with water and cleaning water droplets with an airgun

- Etching with Adler etchant
- Rinsing the surface from the etchant with water and cleaning with an airgun

Etching is performed with Adler etchant, this operation is again performed with trial-and-error method to not burn the surface of the specimen. The etchant is implemented with a syringe covering all over the surface of the bakelite specimen.

After the welding was completed, similar preparation operations for microstructure observation were followed. Resulting images after the welding are given below in Figure 64, Figure 65, Figure 66, and Figure 67.

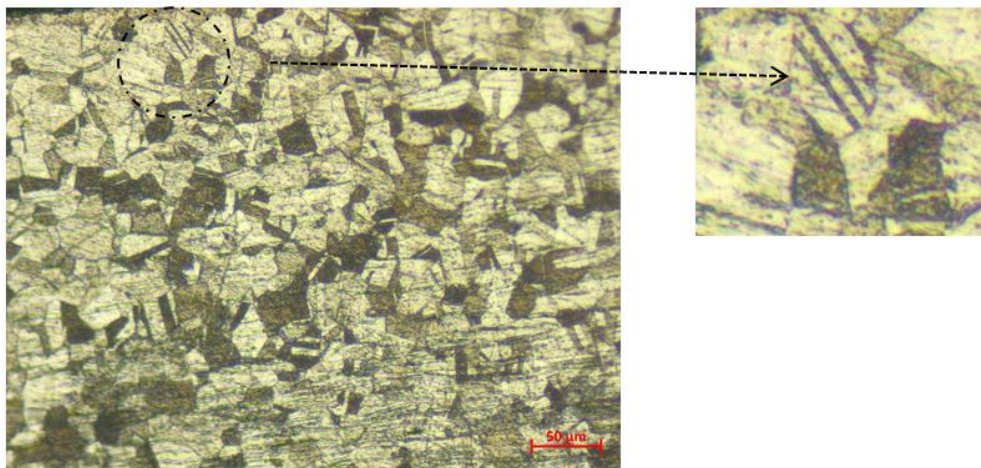


Figure 64 Microstructure of Base Plate after Welding

The average austenite grain size of the base plate is calculated as $341\ \mu\text{m}$. Also, as indicated in Figure 64, due to cold-forming of the plate during the production of sheet stainless steel, twinning in the austenite grains has been observed in the base plate.

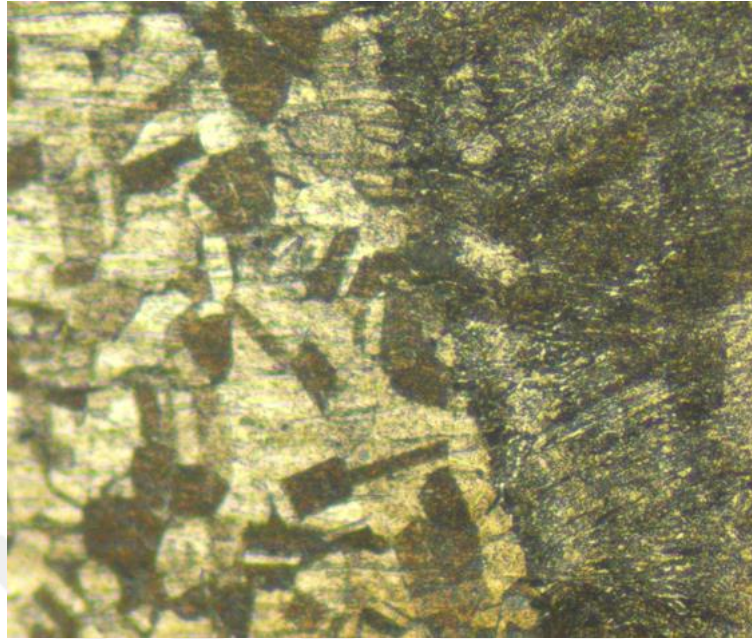


Figure 65 Heat Affected Zone Microstructure

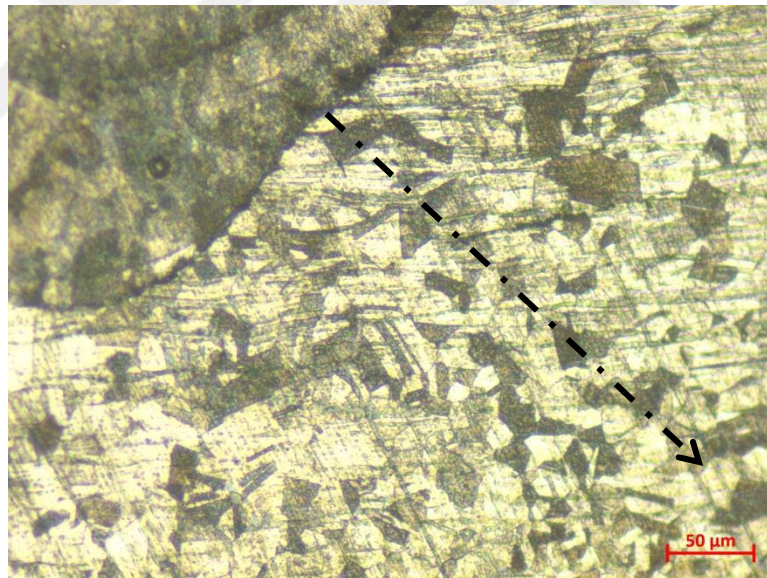


Figure 66 Grain Structure Change Depending on Distance to Weld Pool

The average austenite grain size at the heat-affected zone area is calculated as 559 μm , which shows a 60% increase in the grain size due to the heat applied to the weld pool, as given in Figure 65. This result was expected since at the high

temperatures caused by the laser beam, the grain growth occurs in the heat-affected zone due to increased diffusion to create a more stable microstructure thermodynamically. Also, as given in Figure 66, as the arrow has been followed away from the weld pool, decrease in the grain size has been observed.

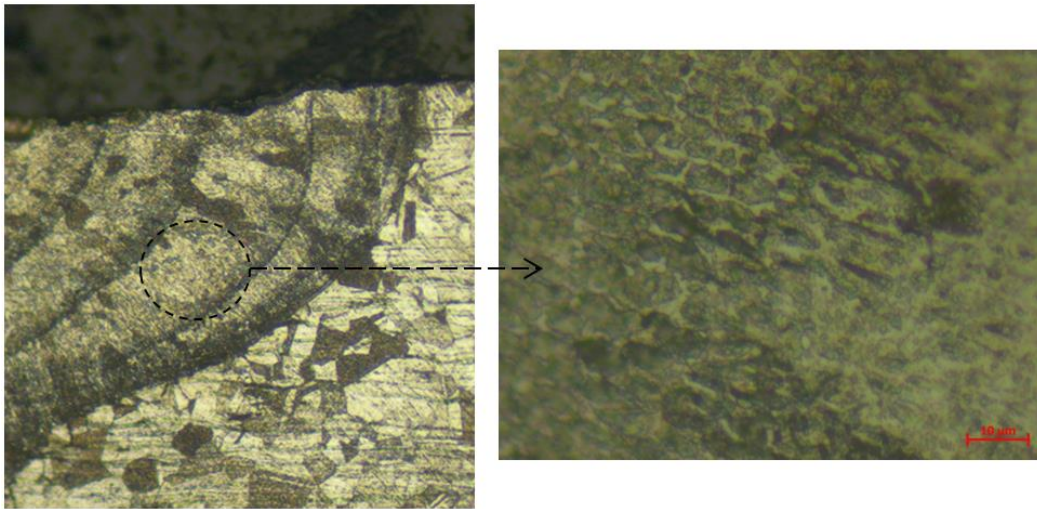


Figure 67 Microstructure at Weld Pool Area

When the weld pool was examined, a dendritic microstructure was observed with a tendency towards the center of the weld pool due to cooling. As seen in the literature [91], this structure is expected at high cooling rates, and the relevant image is shared in Figure 67 above.

While determining the parameters used in the welding operation, experiments were carried out with different parameters as given in Figure 69, and among the tested parameters, porosities, and weld discontinuities were observed and eliminated. Similar to literature review [92,93], at the higher welding speed, higher amounts of porosities were observed due to unstable keyhole phenomena and porosity growth. Therefore, the welding speed was tried not to be kept at very high levels and was gradually decreased. In addition, keeping the welding power at high levels similarly caused an increase in the size of the porosity. The porosity size is observed as maximum (300–500 μm) at 135.3 watts – 4 mm/sec configuration. Moreover, the highest porosity percent (60% of weld line) were observed at 150.3

Watt – 4 mm/sec; that is, almost a continuous porosity line observed at the weld pool. The smallest porosity size (100–200 μm) and least porosity percent ($\sim 5\%$ of weld line) was observed at 135.3 Watt – 3 mm/sec configuration. Detailed parameter trial is given in Figure 68, and the porosity regions are indicated in red boxes.

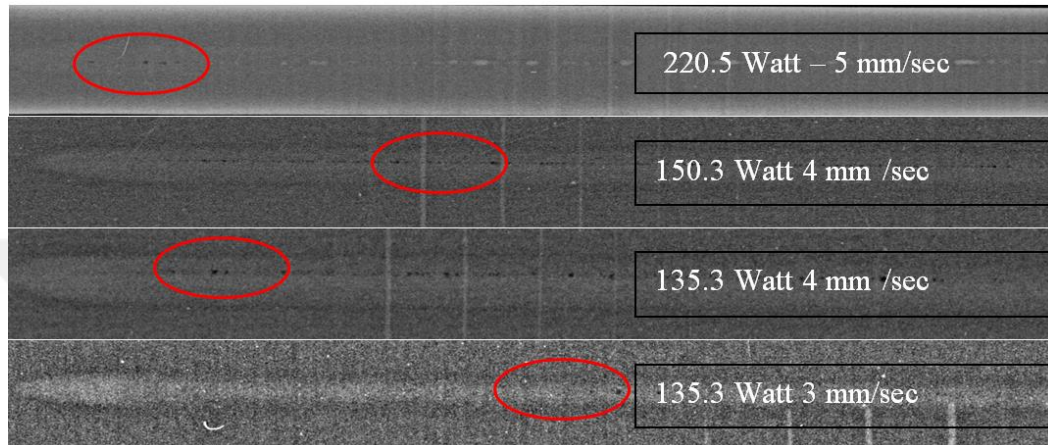


Figure 68 Porosity Relation between Weld Speed and Weld Power

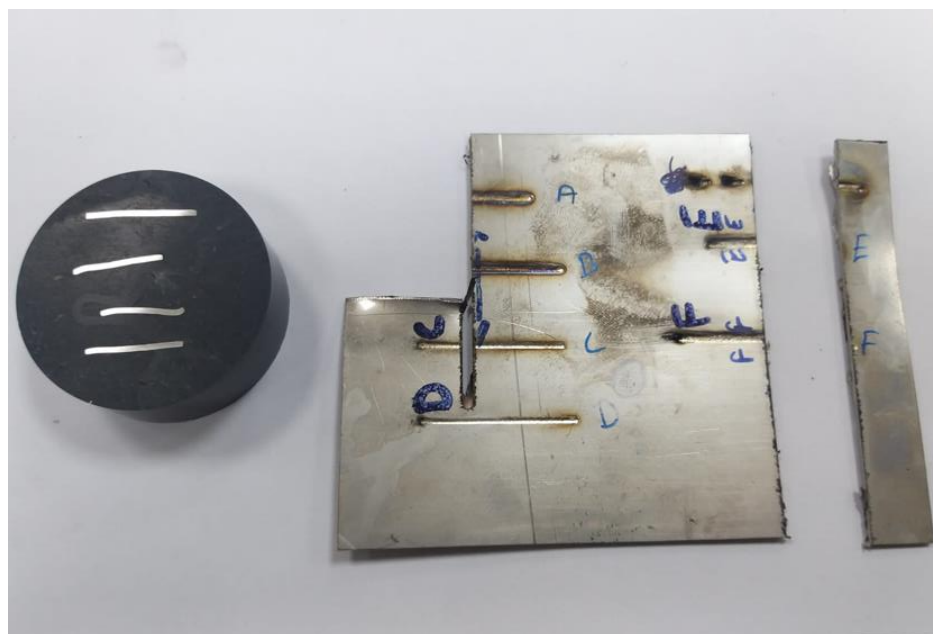


Figure 69 Trial Specimen for Simulation Heat Source Calibration

#	Weld Pool Cap/Depth	Weld Pool Mid-Point/End-Point
C _{112.1-1.75}		
C _{112.1-2.00}		
C _{125.7-1.75}		
C _{125.7-2.00}		

Figure 70 Fusion Zone Macro Images after Welding

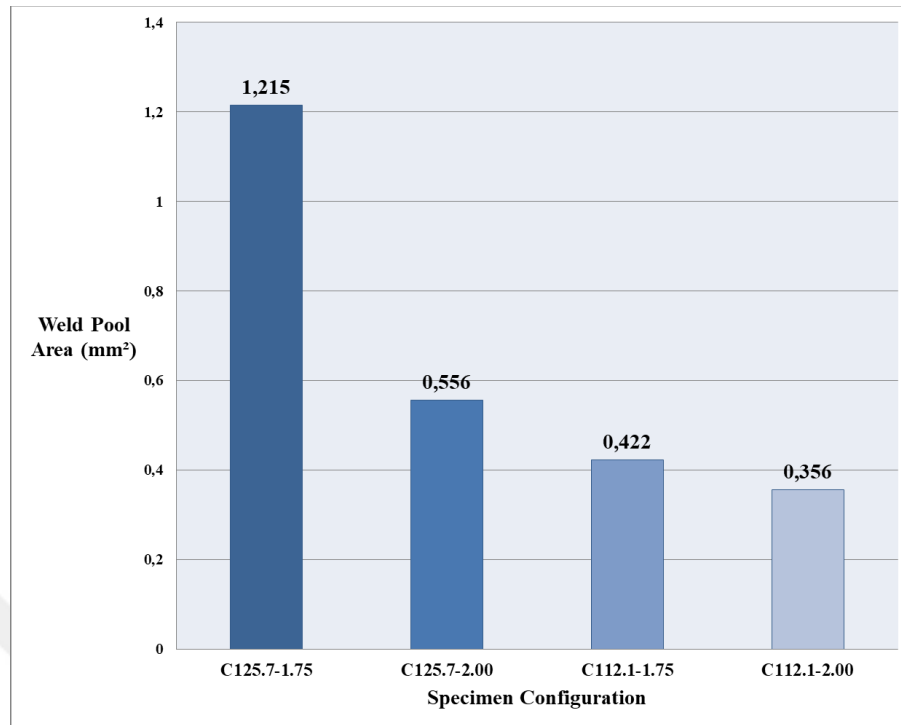


Figure 71 Weld Pool Area Comparison Calculated with ImageJ

Related images for the fusion zone for C_{112.1-1.75}, C_{112.1-2.00}, C_{125.7-1.75}, and C_{125.7-2.00} specimens are given above; the weld pools of the weld samples, whose macros were examined after welding, arrived as expected, as seen in the post-weld eye examination. Here, since the decrease in welding speed causes the J/cm value to increase and the increase in the welding wattage causes the J/cm value to increase, the weld cap and depth of the weld pools are directly affected by these parameters. From the above macro images, it can be understood that the C_{125.7-1.75} specimen has full penetration with a weld cap of 1.606 mm and a 0.557 mm weld root. Moreover, the C_{112.1-2.00} specimen has the narrowest weld cap with 1.223 mm and the lowest weld depth with 0.498 mm. The weld shapes of three specimens can be classified into conduction mode, which are C_{112.1-1.75}, C_{112.1-2.00}, and C_{125.7-2.00}, since their weld bead can be described as a wide and shallow weld nugget. This type of laser welding mode occurs at lower J/cm values. Nevertheless, the laser weld mode of the C_{125.7-1.75} specimen is seen in the keyhole mode; that has an aspect ratio greater than 1.5 (weld depth/weld width). The area difference between the weld specimens

calculated by ImageJ is given in Figure 71; the area difference % and the heat input % comparisons between specimens are given in Figure 72. From the given figures, it can be observed that with an increase in the heat input, the % area of the weld pool increased as expected.

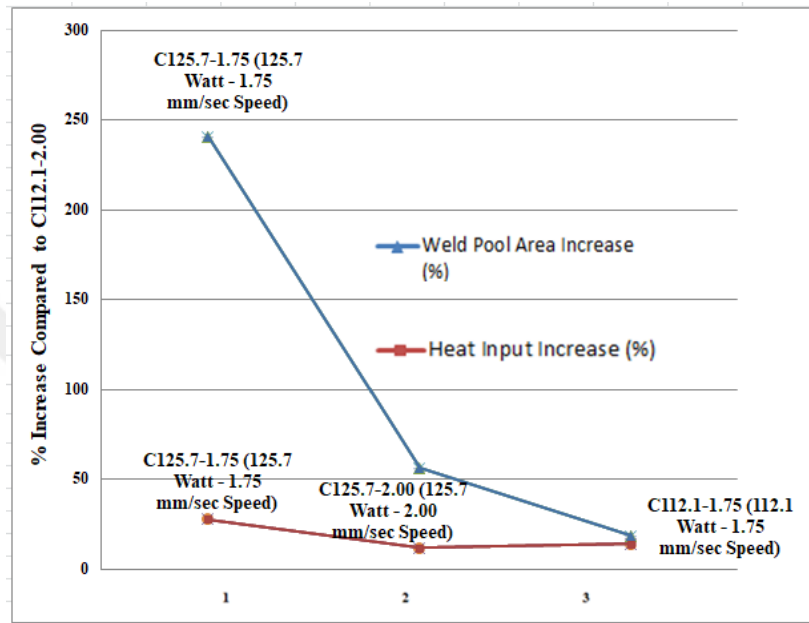


Figure 72 Experimental Weld Pool Area Increase (%) vs Heat Input Increase (%) Compared to C_{112.1-2.00} (112.1 Watt – 2.00 mm/sec Speed)

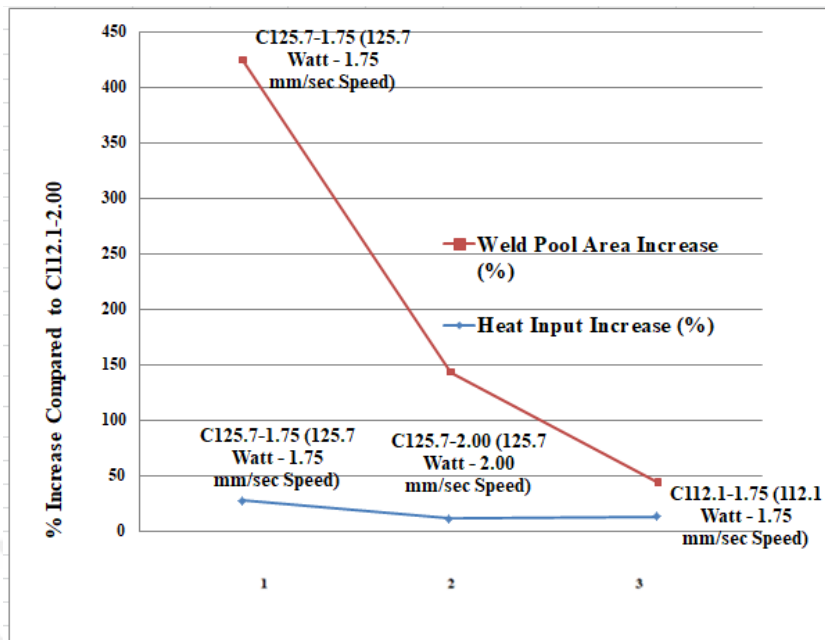


Figure 73 Simulation Weld Pool Area Increase (%) vs Heat Input Increase (%) Compared to C_{112.1-2.00} (112.1 Watt – 2.00 mm/sec Speed)

4.6 Dimensional Measurement before Welding

Before welding, measurements with a height gauge for four specimens are given in the following tables. The format/method used to record the measurements is given under the heading Dimensional Measurement. Since plates were cut from a bigger plate that has dimensions of 1000x2000x0.9 mm and all of them are cut with a laser cutter, no significant difference was observed in the measurement results made before welding.

Table 10 C_{112.1-2.00} Plate before Welding Measurement

Measurement (#)	Parallelism at Edge (mm)	Deflection Angle at Edge (θ°)
1.	-0.08	0.09
2.	-0.05	0.05
3.	-0.03	0.03

Table 10 C_{112.1-2.00} Plate before Welding Measurement (continued)

4.	0	0
5.	+0.01	0.01
6.	+0.01	0.01
7.	0	0
8.	-0.02	0.02
9.	-0.04	0.04
10.	-0.08	0,09

Table 11 C_{112.1-1.75} Plate before Welding Measurement

Measurement (#)	Parallelism at Edge (mm)	Deflection Angle at Edge (θ°)
1.	-0.09	0.10
2.	-0.06	0.06
3.	-0.04	0.04
4.	0	0
5.	+0.01	0.01
6.	+0.02	0.02
7.	+0.02	0.02
8.	+0.02	0.02
9.	0	0
10.	-0.07	0.08

Table 12 C_{125.7-1.75} Plate before Welding Measurement

Measurement (#)	Parallelism at Edge (mm)	Deflection Angle at Edge (θ°)
1.	-0.19	0.21
2.	-0.17	0.19
3.	-0.15	0.17
4.	-0.14	0.16

Table 12 C_{125.7-1.75} Plate before Welding Measurement (continued)

5.	-0.13	0.14
6.	-0.14	0.16
7.	-0.14	0.16
8.	-0.15	0.17
9.	-0.15	0.17
10.	-0.16	0.18

Table 13 C_{125.7-2.00} Plate before Welding Measurement

Measurement (#)	Parallelism at Edge (mm)	Deflection Angle at Edge (θ°)
1.	-0.30	0.34
2.	-0.35	0.40
3.	-0.35	0.40
4.	-0.35	0.40
5.	-0.35	0.40
6.	-0.35	0.40
7.	-0.35	0.40
8.	-0.35	0.40
9.	-0.35	0.40
10.	-0.33	0.37

The measurement parallelism measurement results of C_{112.1-1.75}, C_{112.1-2.00}, C_{125.7-1.75}, C_{125.7-2.00} plates taken with a height gauge are given in Table 10, Table 11, Table 12, and Table 13. The axis of measurement is taken in the z direction as given in the section Dimensional Measurement Figure 40. The meaning of minus sign here indicates that the measured points in the weld zone (mid-point) and edge are below the reference point that is taken as zero in the z direction. Nevertheless, the parallelism at the edge shows variety in different specimens. As it can be seen from Table 12 and Table 13, the parallelism values of C_{125.7-2.00}, C_{125.7-1.75} specimens can

reach up to -0.35 mm. The reason for this large difference in the samples taken before welding is due to the location of the samples in the large 1x2x0.0009 m plate from which they were taken. The samples were removed from a 1x2x0.0009 m plate by laser cutting method, starting from the edges, and parallelism measurements were observed to be higher since the stretching was higher in the plates that remained at the edges. The deflection values are calculated as the arctangent values at the edge of the plate. The related formulation is given below, since the deflection of the plate is started at the weld zone, the x-axis of the tangent value is taken as 50 mm. It should be noted that the deflection angles show consistent results with parallelism.

$$\text{Deflection Angle } (\theta^\circ) = \arctan\left(\frac{\text{Parallelism at Edge}}{50 \text{ mm}}\right) \quad (13)$$

4.7 Dimensional Measurement after Welding

Table 14 C_{112.1-2.00} Plate after Welding Measurement

Measurement (#)	Parallelism at Edge (mm)	Deflection Angle at Edge (θ°)
1.	1.21	1.38
2.	1.47	1.68
3.	1.65	1.89
4.	1.81	2.07
5.	1.96	2.24
6.	2.07	2.37
7.	2.10	2.40
8.	2.14	2.45
9.	2.01	2.30
10.	1.93	2.21

Table 15 C_{112,1-1.75} Plate after Welding Measurement

Measurement (#)	Parallelism at Edge (mm)	Deflection Angle at Edge (θ°)
1.	1.94	2.22
2.	2.20	2.51
3.	2.39	2.73
4.	2.53	2.89
5.	2.69	3.07
6.	2.73	3.12
7.	2.65	3.03
8.	2.49	2.85
9.	2.34	2.67
10.	2.25	2.57

Table 16 C_{125,7-1.75} Plate after Welding Measurement

Measurement (#)	Parallelism at Edge (mm)	Deflection Angle at Edge (θ°)
1.	2.87	3.28
2.	3.32	3.79
3.	3.65	4.17
4.	3.89	4.44
5.	4.12	4.71
6.	4.26	4.86
7.	4.35	4.97
8.	4.23	4.83
9.	4.05	4.63
10.	3.72	4.25

Table 17 C_{125.7-2.00} Plate after Welding Measurement

Measurement (#)	Parallelism at Edge (mm)	Deflection Angle at Edge (θ°)
1.	2.59	2.96
2.	2.89	3.30
3.	3.07	3.51
4.	3.22	3.68
5.	3.32	3.79
6.	3.40	3.89
7.	3.38	3.86
8.	3.28	3.75
9.	3.10	3.54
10.	2.94	3.36

The measurement parallelism measurement results of C_{112.1-1.75}, C_{112.1-2.00}, C_{125.7-1.75}, C_{125.7-2.00} plates taken with a height gauge after welding operation completed are given in the above Table 14, Table 15, Table 16, and Table 17 similar to before the welding operation; the axis of measurement is taken in z direction as given in Figure 40 Coordinate System of Plate Measurement. The meaning of the minus sign here indicates that the measured points in the weld zone (mid-point) and edge are below the reference point that is taken as zero in the z direction, and a positive sign indicates the measured points are above the reference point. Nevertheless, directly comparing the after-welding results will be misleading since the parallelism values of the starting plates are not at the same level. We should consider the difference between before-and-after welding parallelism values. From the measurement results of before-after welding parallelism values; it can be observed that the parallelism value increases with increasing the watt, since the J/cm (Energy per centimeter) increase results in higher fusion zone as given in Figure 70 and Figure 71. The C_{125.7-1.75} specimen has higher fusion zone width and depth than C_{112.1-1.75} specimen has. Which affects the distortion at solidification

since during solidification, the stress tensor at the fusion zone causes the distortion and comparison between these two specimens' results is expected as explained in Figure 5. Comparing the results of the $C_{125.7-2.00}$ specimen and $C_{125.7-1.75}$ shows similar results to the above explanation since the fusion zone of $C_{125.7-1.75}$ is higher in terms of weld cap and weld depth. However, when comparing the $C_{125.7-2.00}$ and $C_{112.1-1.75}$ samples for parallelism values after the welding is completed, it may be misleading to make this comparison by only considering the weld cap and weld depth in the fusion zone. As mentioned above, this comparison should be made by considering the initial parallelism measurements of the parts. $C_{112.1-1.75}$ which has higher J/cm value (640.5) than $C_{125.7-2.00}$ plate (628.5), shows a behavior that not only the energy per length is important about the distortion, instead the effect of weld pool area shows dominance on distortion. It can be explained by the watt value has more effect than the welding speed on distortion since the watt value of $C_{125.7-2.00}$ plate is slightly higher than $C_{112.1-1.75}$ plate. $C_{125.7-2.00}$ and $C_{112.1-2.00}$ plate comparison for parallelism after welding shows expected results since the heat input % is 12% higher for $C_{125.7-2.00}$ plate, which in turn affects weld pool area by 36%. The comparison of $C_{112.1-2.00}$ and $C_{112.1-1.75}$ plates shows similar comparison results as described for $C_{125.7-2.00}$ and $C_{125.7-1.75}$ specimens. The weld pool has higher weld cap and weld depth for $C_{125.7-1.75}$ plate than $C_{125.7-2.00}$ specimen as given in Figure 71. The deflection angle value is derived information from the parallelism value at the edge, thus, the parallelism value comparison for the four specimens is valid for the deflection angle values. The crucial information in the deflection angle calculation is; the J/cm values have 28.2% increase between specimen $C_{125.7-1.75}$ and $C_{112.1-2.00}$ specimen (The highest J/cm specimen and the lowest J/cm specimen); that is 560.5 to 718.2 J/cm, the deflection angle values for the $C_{125.7-1.75}$ and $C_{112.1-2.00}$ specimens shows proportional behavior with energy per centimeter increment, below Figure 74 shows the conclusion of the explanation given above. In short, $C_{125.7-1.75}$ specimen showed the greatest deformation, which also has the highest volume in the weld pool. $C_{112.1-2.00}$ specimen showed the lowest deformation, which also has the smallest volume in the weld pool.

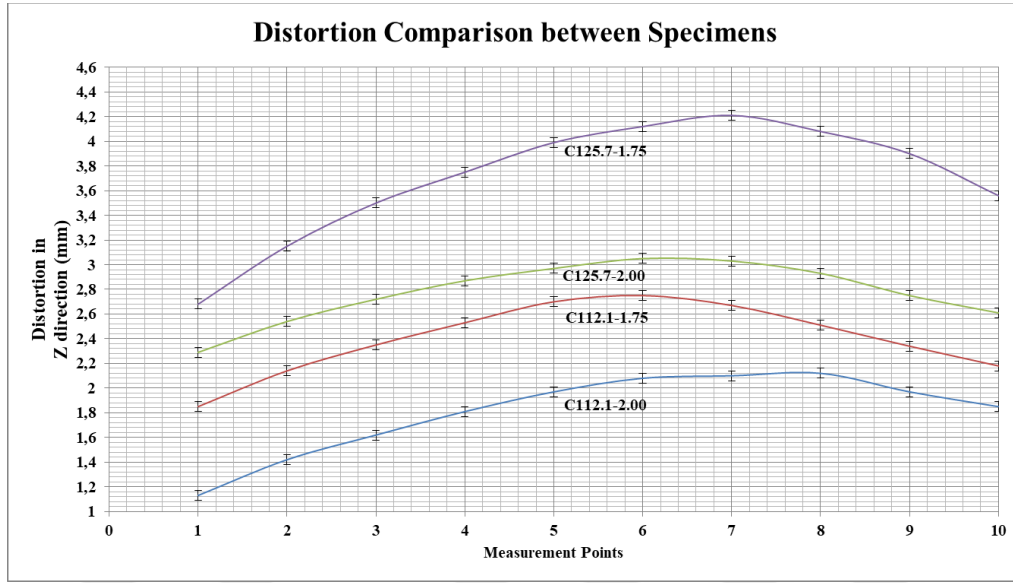


Figure 74 Distortion Comparison in Z Direction between Weld Plates

4.8 Validation of Simulation with Experimental Work

The weld pool area calibration with a trial test coupon is performed for four different test coupons that are C_{112.1-1.75}, C_{112.1-2.00}, C_{125.7-1.75}, and C_{125.7-2.00} for the C_{125.7-1.75}TSC test coupon (residual stress coupon, two side clamped); thus, no excess weld pool area calibration operation is performed. Related images of comparison for experimental data and calibrated weld pools are given in Figure 78. Related dimensional comparison in terms of percentages is given in Table 18.

Table 18 Dimensional Comparison Between Experimental and Simulation Weld Bead in Percentage

#	Area Difference Calculated by ImageJ (%)	Number of Thermal Analysis for Calibration
C112.1-1.75	34.36	35
C112.1-2.00	40.44	28
C125.7-1.75	13.25	31
C125.7-2.00	11.51	38

From Table 18, it can be understood that the optimization of the heat source parameters is performed with trial and error. Several attempts have been performed to minimize the difference between experimental dimensions of the weld bead and simulation. As shown in Figure 75 and Figure 76, 3 points were selected from the center of the weld pool, heat-affected zone, and base metal, and the cooling curves of these three points have been given below.

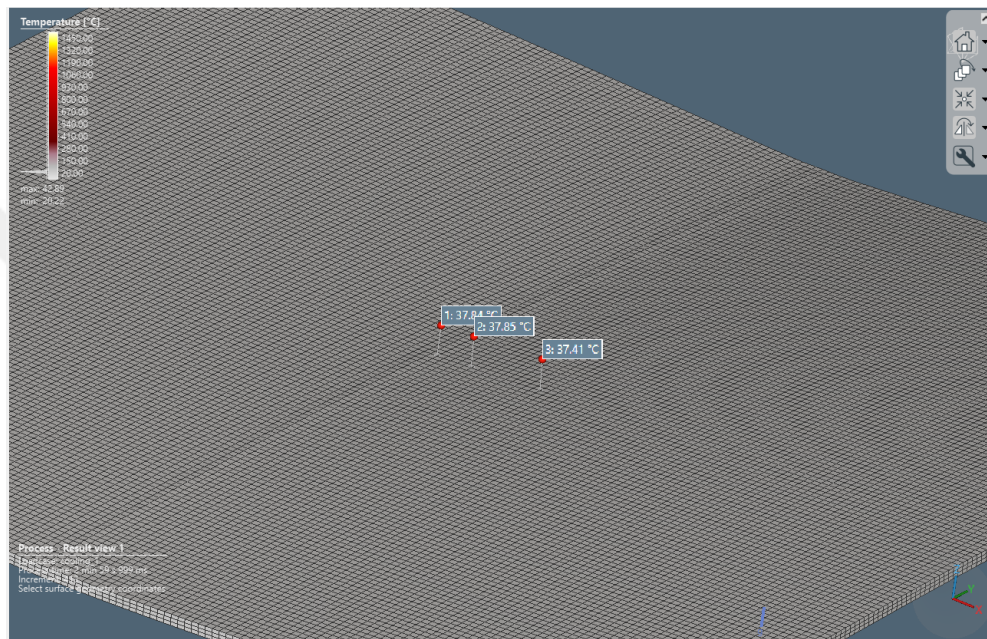


Figure 75 Points Taken for Temperature History

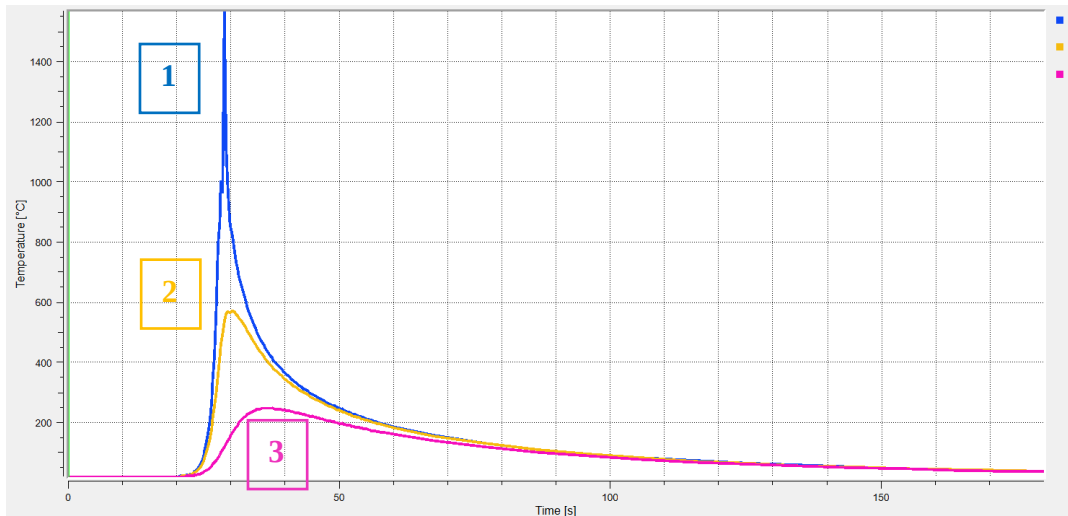


Figure 76 Temperature History of Given Points in Figure 75

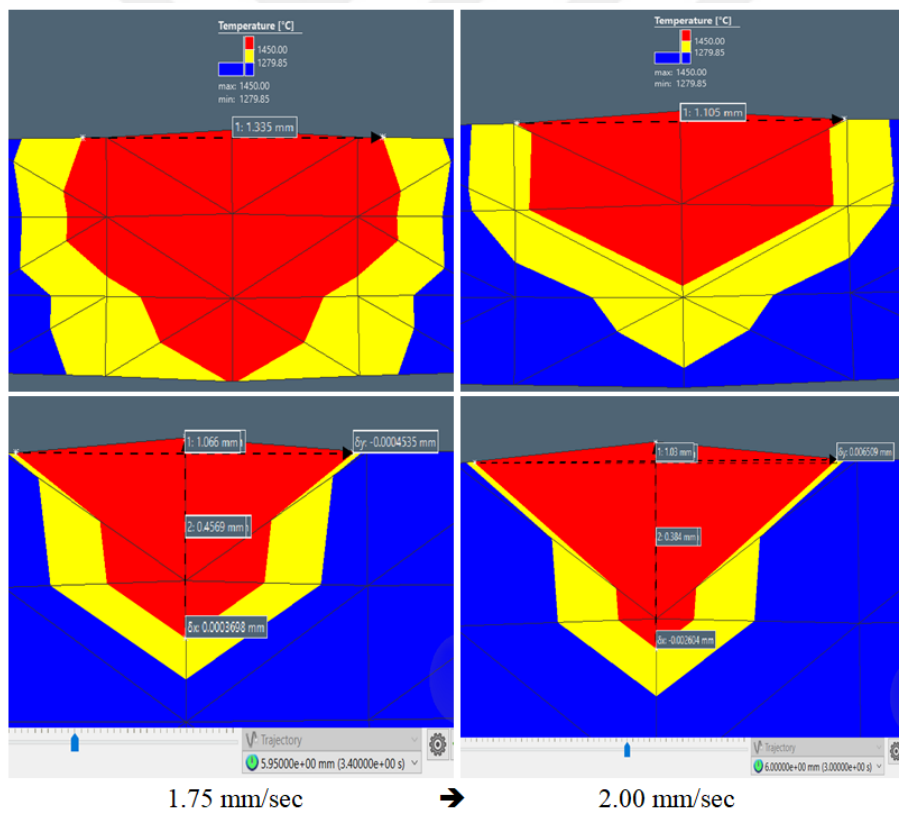


Figure 77 Effect of Weld Speed on Weld Pool Geometry

For 1.75 mm/sec welding given in the above Figure 77, at this slower speed, the weld pool has been seen larger and wider due to the higher heat input per unit

length. The material has more time to absorb heat, resulting in a more extensive molten area. Also, the slower speed allows for deeper penetration as the heat has more time to transfer through the material, resulting in a more profound weld. In terms of the shape of the weld pool, the weld bead has been concluded to be wider and flatter because of the larger weld pool and slower solidification rate. For 2.00 mm/sec weldings given on the right side of the image at this faster speed, the weld pool has been seen as smaller and narrower. The reduced heat input per unit length means the material has less time to melt, leading to a more confined weld pool. Furthermore, the faster speed resulted in shallower penetration due to the lower heat input and shorter interaction time with the material. When the weld pool shape is compared, the weld bead has been observed as narrower and more pronounced due to the smaller weld pool and faster solidification.

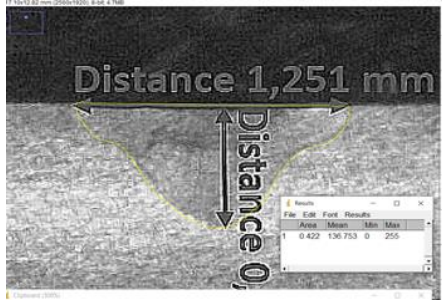
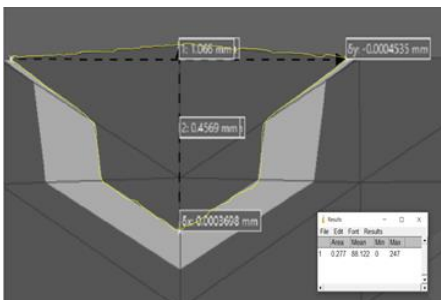
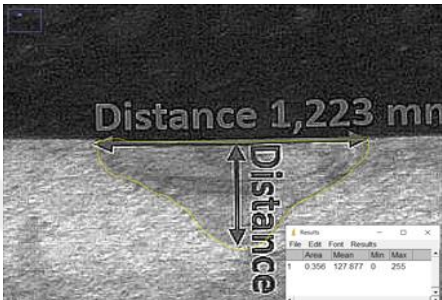
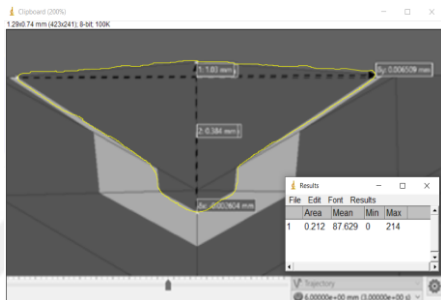
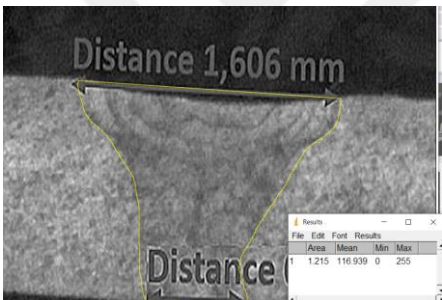
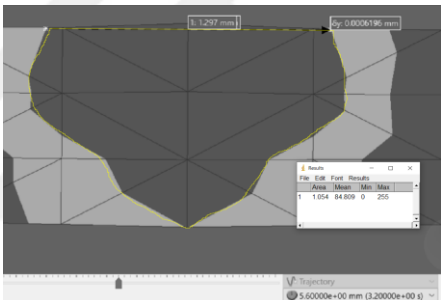
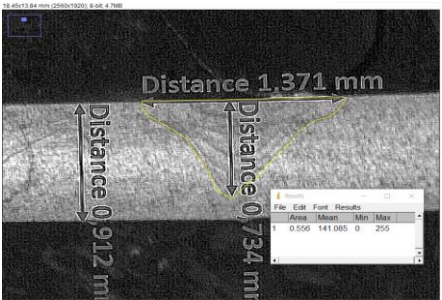
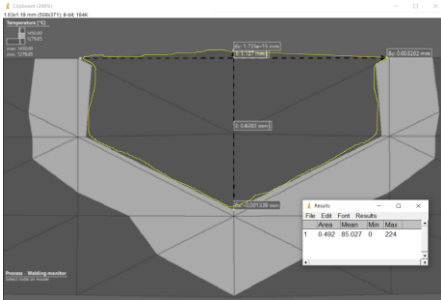
#	Experimental Weld Area	Simulation Weld Pool Area
$C_{112.1-1.75}$		
$C_{112.1-2.00}$		
$C_{125.7-1.75}$		
$C_{125.7-2.00}$		

Figure 78 Experimental – Simulation Weld Bead Dimension Comparison

4.8.1 Residual Stress Comparison of Simulation and Test Results

Similar to distortion measurements, since the probe diameter used in residual stress measurements is 1 mm and the mesh used in the model is 0.6 mm, the difference

between the maximum and minimum values of the values collected from the simulation will be taken as the measurement uncertainty, as shown in Figure 87. For the given figure, the measurement uncertainty for node 1 is taken as 322.87 MPa (Node 5) – 274.92 MPa (Node 2). The situations affecting the measurement uncertainty in the results of the C125.7-1.75TSC and C125.7-1.75 plates measured with XRD within the scope of the experiment are stated below. XRD measurements were calculated based on the EN 15305 “Non-destructive Testing—Test Method for Residual Stress Analysis by X-ray Diffraction” standard. The measurement error in X-ray diffraction residual stress measurement can be attributed to 3 main headings that are given below:

1) Specimen Related Parameters

- Surface waviness due to welding operation: since no additional surface grinding/machining operation is performed for the fusion zone after welding, there is a high surface waviness in and around the area where the weld pool is located. Also, as it is stated in Fitzpatrick’s work, grinding, machining, or wire brushing may introduce an extra surface residual stress; thus, these operations should be avoided [94].
- If the material has a multi-phase structure (Austenitic-Ferritic) as in this experiment, the measurement results will cover the entire sample and can be explained according to the volume fractions of the phases.
- Weld plate’s grain texture: the crystal structure and texture of the sample cause irregular scattering of X-rays and increase measurement uncertainty in plates with high texture.

2) Measurement Procedure

- The goniometer, particularly its alignment, is the most significant source of error in XRD residual stress measurements. Modern

goniometers with optical gratings offer high reproducibility. However, alignment issues can introduce significant errors, especially in 3- or 4-axis goniometers. In this work, the 2-axis goniometer Xstress G2R equipment is used.

- The shape of the X-ray peak (peak profile) depends on the nature and configuration of defects in the material, which cannot be generalized. Incorrect peak position determination can lead to significant errors in stress measurement. In this work, the Full Width Half Maximum Method has been used.

3) X-Ray Source

- If the incident X-rays cause the sample to emit fluorescent X-rays, it can lead to a high background and poor peak-to-background ratio. For example, using copper K- α radiation on an iron sample can cause iron to emit its fluorescent X-rays. Therefore, selecting a longer wavelength X-ray source that does not cause fluorescence will solve the problem. Therefore, Mn X-Ray source is selected, which is also recommended for Austenitic stainless steels.
- Different crystallographic planes respond differently to elastic (residual stress) and inelastic strain. Measurements on different planes are generally not comparable. Therefore, as recommended for austenitic stainless steels, the (311) plane is selected [95].

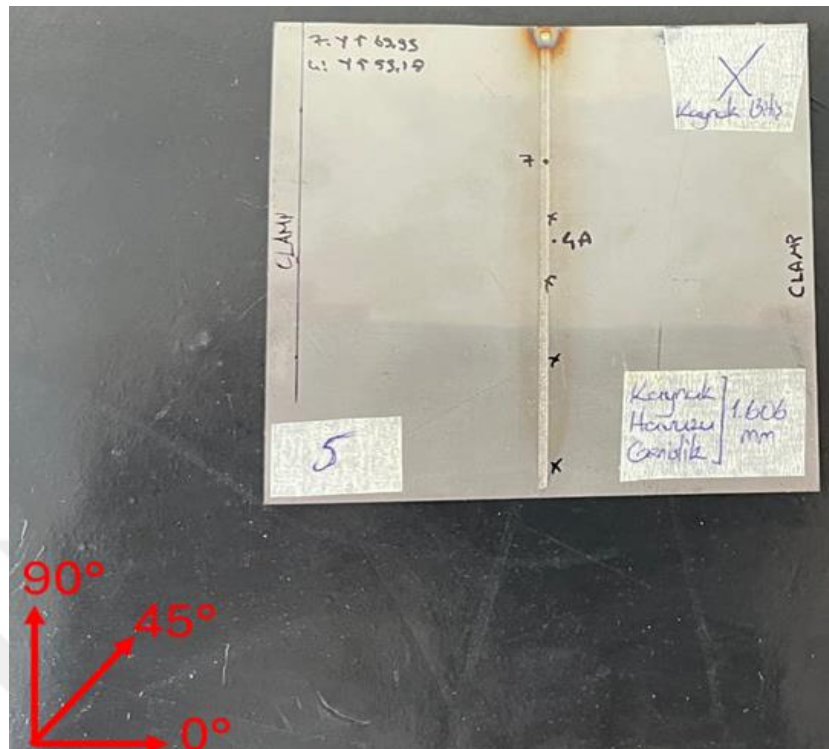


Figure 79 C_{125.7-1.75TSC} Specimen XRD Measurement Points at Weld Face

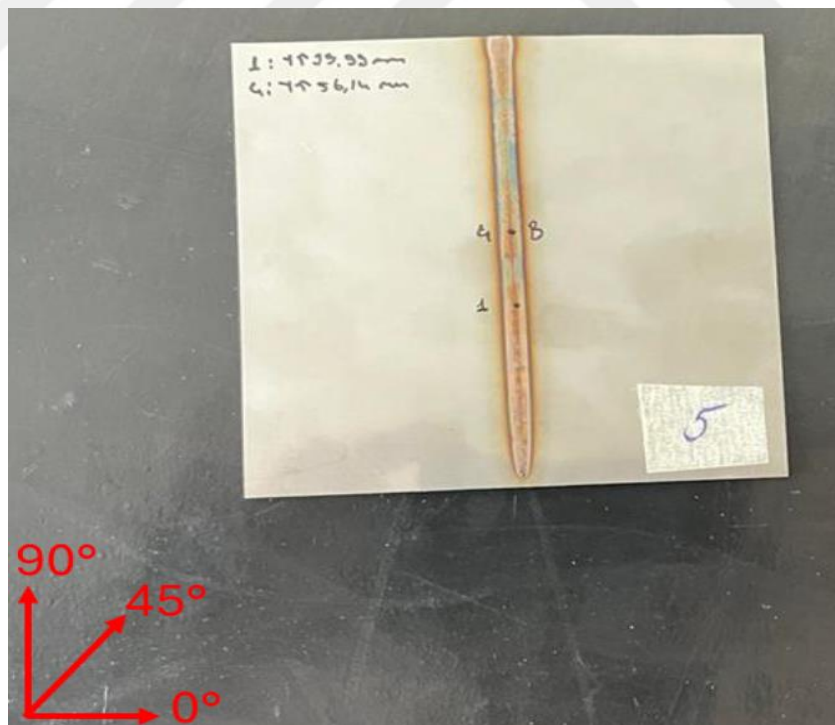


Figure 80 C_{125.7-1.75TSC} Specimen XRD Measurement Points at Back of Weld Face

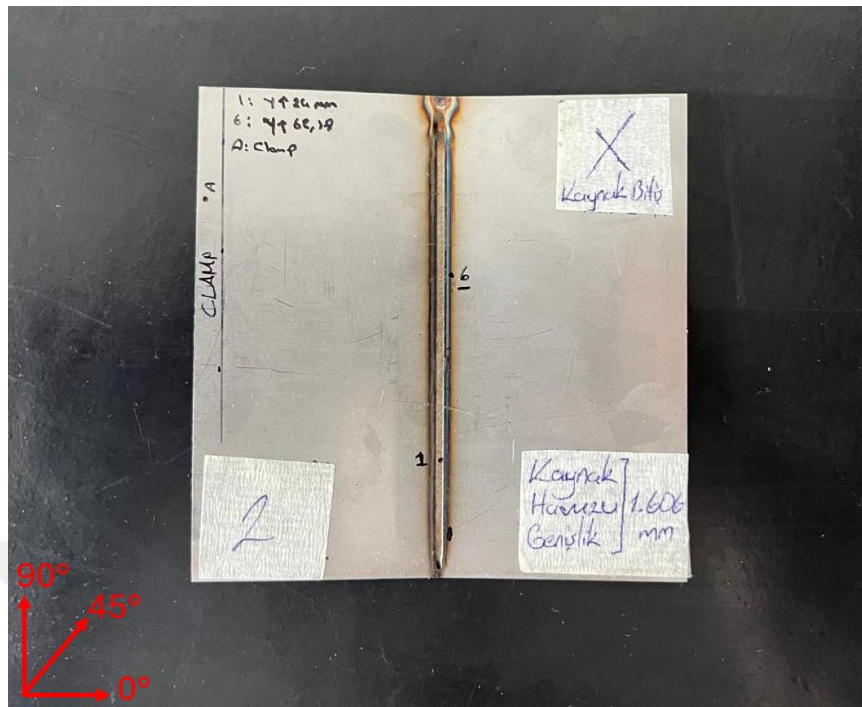


Figure 81 C_{125.7-1.75} Specimen XRD Measurement Points at Weld Face

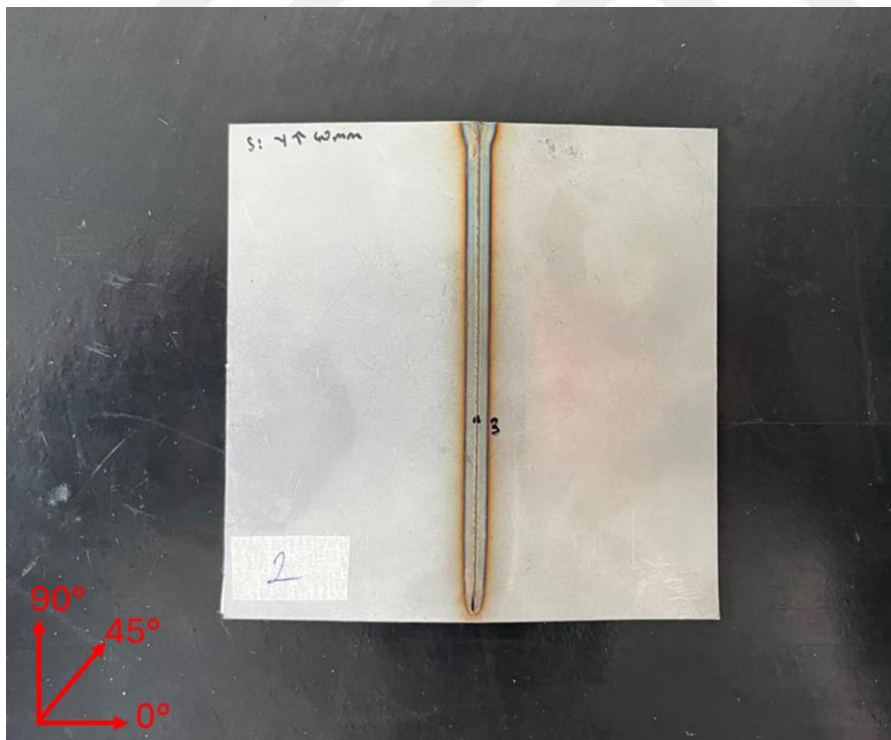


Figure 82 C_{125.7-1.75} Specimen XRD Measurement Points at Back of Weld Face

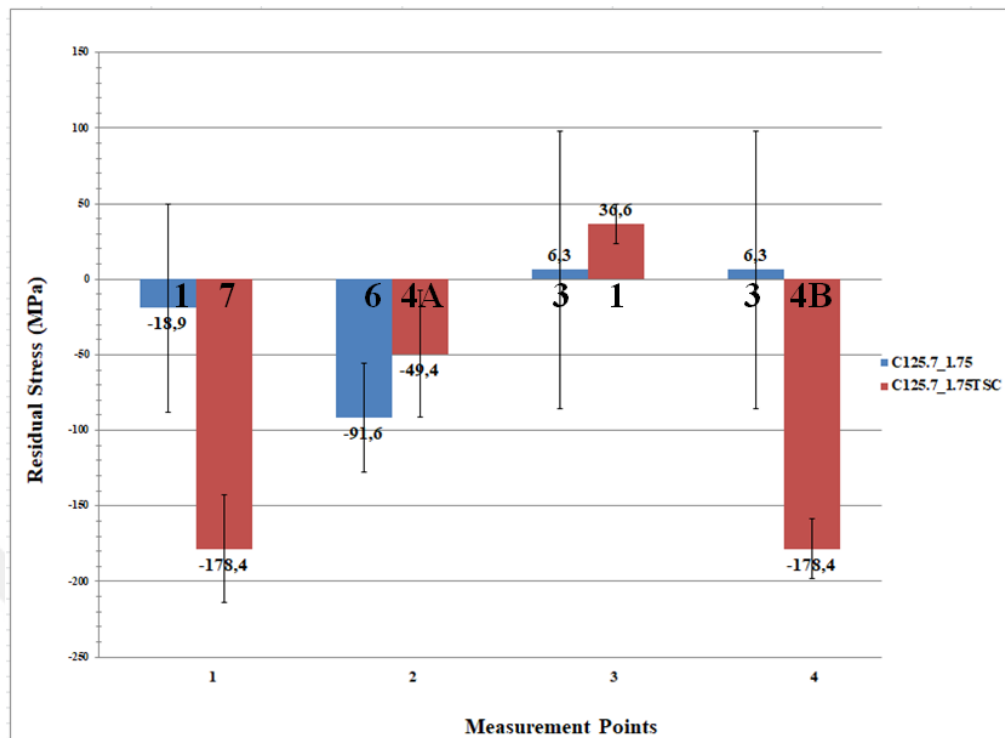


Figure 83 XRD Transverse Residual Stress Measurement Comparison of C_{125.7-1.75TSC} and C_{125.7-1.75}

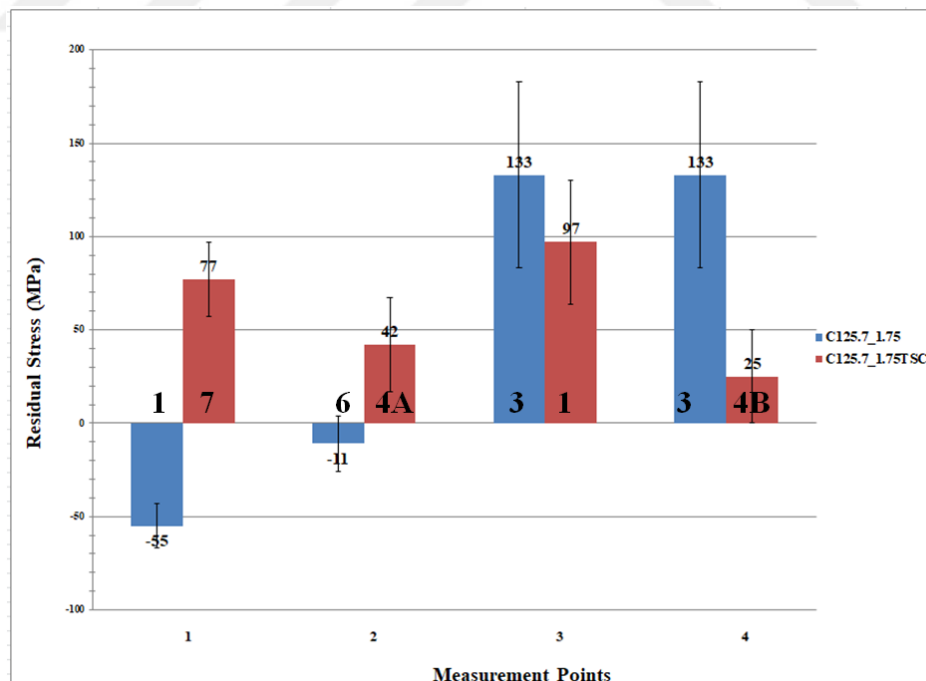


Figure 84 Simulation Transverse Residual Stress Measurement Comparison of C_{125.7-1.75TSC} and C_{125.7-1.7}

While comparing the results observed in the given Figure 83, measurement points point 1 and point 7, point 6 and point 4A, point 3 and point 1, and point 3 and point 4B were compared. This comparison was made by considering the location of the measurement point on the plate. The measurement results at the middle point in the weld pool were compared with each other, and the measurement results in the HAZ region were compared with each other, and the measurement results at the middle point of the weld pool in the back region of the plate were compared with each other. The comparison of measurement results was carried out by considering the normal stress values on the X axis and the measurement uncertainties of these values. For this reason, no comparison was made between equivalent stress values or mean normal stress values. The measurement results obtained with XRD were evaluated based on the EN 15305 standard. As stated above, the manganese radiation source recommended for stainless steel materials in the standard was used. Similarly, measurements were taken from the (3,1,1) plane recommended in the standard. The main reason for choosing manganese as the radiation source is that Mn K α radiation can penetrate deeper into the material. The reason for taking measurements from the (3,1,1) plane is that XRD measurements have higher diffraction angles, and small residual stresses can be detected at higher diffraction angles. Information about the XRD feature and material properties used and test details is included in the table below. As expected, the measurement results were observed at higher values for the C_{125.7-1.75TSC} sample fixed from both sides. Residual stress formation occurs due to microscopic and macroscopic mismatch or inherent strain or inherent deformation. Residual stress is observed when the material is rigidly fixed and occurs on a macroscopic/microscopic scale when the material is exposed to a load but cannot be deformed. When the measurement results were compared one by one, it was observed that there was a compressive residual stress in point 1 and point 7 in Figure 83. The locations of these measurements taken on the plate are above the weld pools; point 1 is located closer to the beginning of the weld. Point 7 is located closer to the end of the weld, but both points are located on the weld pool as marked; therefore, these two points are

located on the weld pool as the X-axis principal stress value (transverse stress) was compared with each other while evaluating. From the measurement results, the residual stress value at point 7 is higher than that at point 1, but the measurement uncertainty at point 1 is observed to be much higher than the measurement uncertainty at point 7. The reason for the increase in measurement uncertainty is that the surface waviness at point 1 is at a higher level compared to point 7. The measurement results turned out to be compressive residual stress; from the literature review, it has been seen that the transverse residual stress shows an M-shaped behavior as given in Figure 85 and Figure 86. Which can be described as a small area in the weld pool showing compressive residual stress on one side of a clamped plate, so the measurement value at the weld pool with XRD is expected to be compressive in a small area and tensile at a larger area. Which is caused by rapid solidification and shrinkage due to the liquid, solid phase transformation in the weld pool, tensile residual stresses are formed in the weld pool, and compressive residual stresses are formed at the Heat Affected Zone to balance the stress in the fusion zone. Nevertheless, the situation explained above can be concluded as follows: for point 1 compared to point 7, the measurement uncertainty is given as ± 69 MPa, which means this measurement can vary within a +50 MPa, -90 MPa range. If the measurement result of point number 1 is a point taken from the weld pool as expected, it is expected to be a compressive residual stress in a small region, which seems like the XRD results are taken from that area. However, point 7 was evaluated as compressive residual stress in XRD, which may be defined as a misleading result. Point 6 and point 4A on the $C_{125.7-1.75TSC}$ and $C_{125.7-1.75}$ plates were compared with each other since both points were within the Heat Affected Zone, and the measurement result of both points was compressive residual stress as expected. Moreover, from the expected situation in the literature, the transverse stress value in the $C_{125.7-1.75}$ plate was higher than the $C_{125.7-1.75TSC}$ plate. Nevertheless, it should be taken into consideration that the measurement point was not taken from a single node, but the result was collected by scanning an area with a 1 mm diameter probe of the used equipment. It can be explained that

for the C_{125.7-1.75} plate, the measurement result taken from an area closer to the HAZ region dominates; however, for the plate fixed from two sides, as given in Figure 85, this measurement seems to be taken in a transition region between the weld pool and the HAZ.

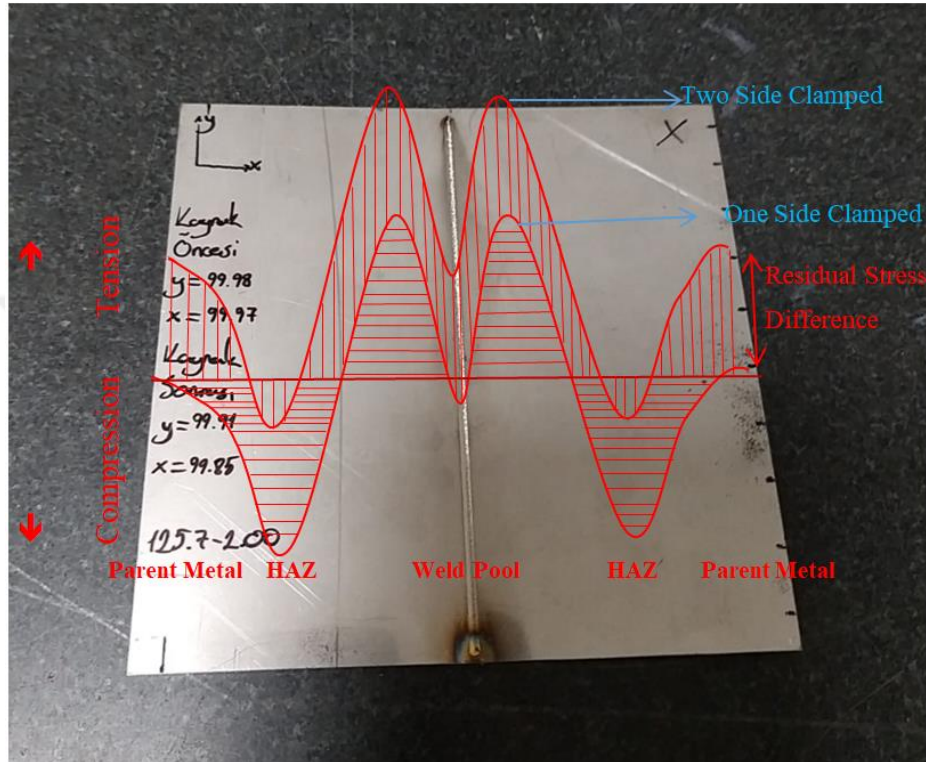


Figure 85 Schematic Transverse Residual Stress (σ_x) Distribution on the Weld Plates

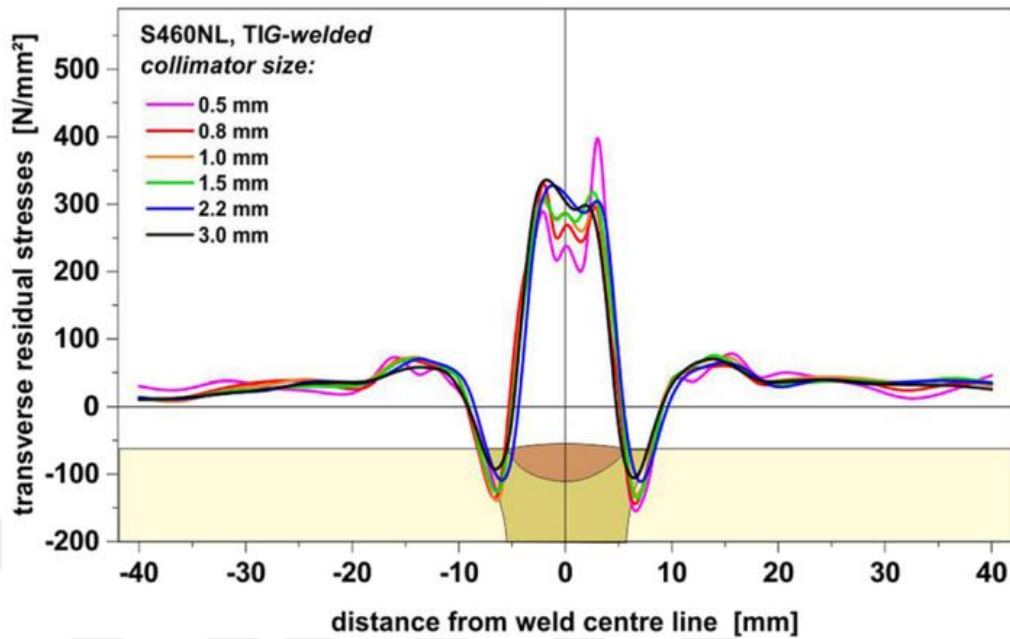


Figure 86 M Shaped Transverse Residual Stress Curve at Weld Pool [96]

When comparing number 3 in the $C_{125.7-1.75}$ plate and number 1 in the $C_{125.7-1.75TSC}$ plate, both points are located at the back of the weld face, right in the center of the weld pool. It is worth mentioning here that the surface waviness in the weld pool is high, as this parameter is complete fusion, and it is observed in Figure 70 that the weld root has appeared from the back of the plate. The evaluation needs to be made in this context; tensile force is observed at the center of the weld root point, as observed from simulation and literature. The expectation here is that the tensile residual stress of the coupon fixed on both sides is observed to be higher, and this was seen in the measurement results. When comparing number 3 in the $C_{125.7-1.75}$ plate and number 4B in the $C_{125.7-1.75TSC}$ plate, again both points are located at the back of the weld face, but point 4B is located closer to the end point along the weld trajectory compared to point 1. That is, it is slightly further along the y-axis from point 3 on the $C_{125.7-1.75}$ plate. As a result of the measurement observed here, the 4B measurement gave a high compressive residual stress value. However, in the observed simulation results, such a result was not observed for both plates in the residual stress values taken from different times, except for the time interval when

the welding torch passed through this region. Therefore, this measurement result is considered to be incorrect. Which may be caused by the surface waviness, the XRD measurement point to be taken.

Table 19 Residual Stress Measurement with XRD

XRD Equipment Properties			Materials Properties		
Radiation Source	:	Manganese	Elastic Modulus (GPa)	:	193
Radiation Source Wavelength (Å)	:	2.103	Poisson's Ratio	:	0.298
Probe Diameter	:	1 mm	Solution Anneal Temperature (°C)	:	1050

The comparison of the simulation results according to Figure 84 with literature results for point 1 and point 7, as it can be seen, point 1 showed a compressive residual stress and point 7 showed a tensile residual stress in the transverse residual stress, which shows consistency with the literature. For point 6 and point 4A that lie in the HAZ region, the 6 showed a compressive residual stress, which means that this region lies in the HAZ region from the given Figure 85; however, point 4A showed a tensile residual stress behavior, which means this region is at the transition region to the weld pool–HAZ area. For point 3, point 1 at weld root surfaces, both of them showed a tensile residual stress behavior, which means these regions are taken from the weld pool area; however, one side clamped C_{125.7-1.75} plate showed higher tensile residual stress than point 1, which can be described as this region is closer to the weld pool center and point 1 is closer to the HAZ. For point 3 and point 4B, the comparison at the weld root point 4B again showed a tensile residual stress, but lower than point 3, which can be described similarly to the above explanation.

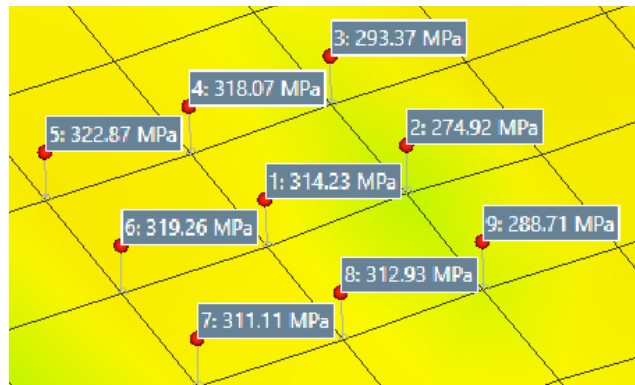


Figure 87 Residual Stress Comparison Method Example for Node 1

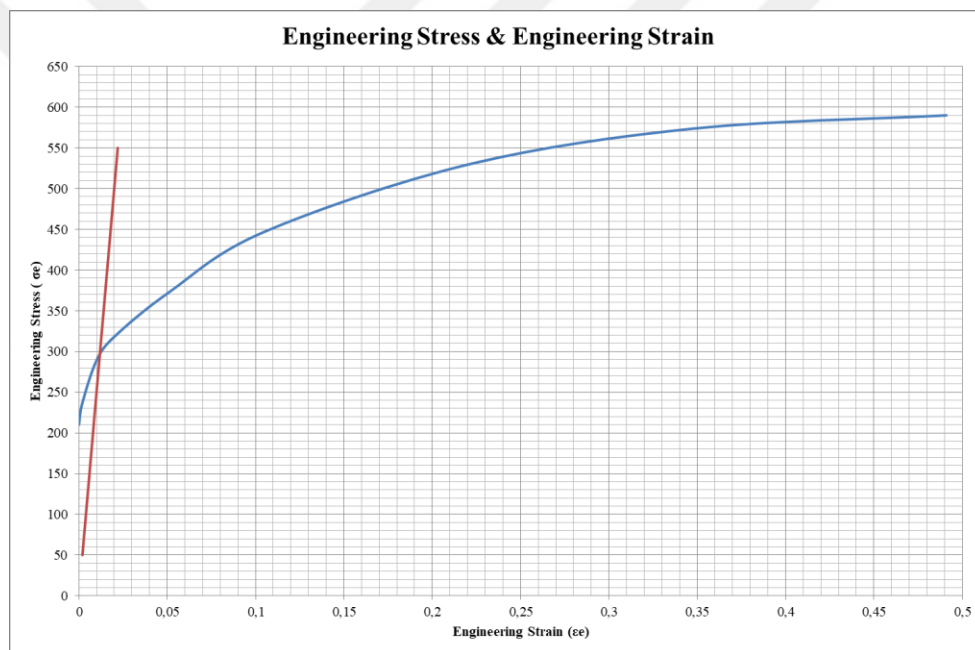


Figure 88 Engineering Strain vs Engineering Stress of 316L Material Used for Simulations

As given in Figure 88, the yield strength of the used material for simulation is 300 MPa (Calculated with the 0.2% Offset Method) and its tensile strength is 600 MPa. To compare the residual test results of simulation and real experiments, the difference between the material defined in Simufact Welding (316L_sw) and real experiment material should be considered; otherwise, the comparison results would be misleading.

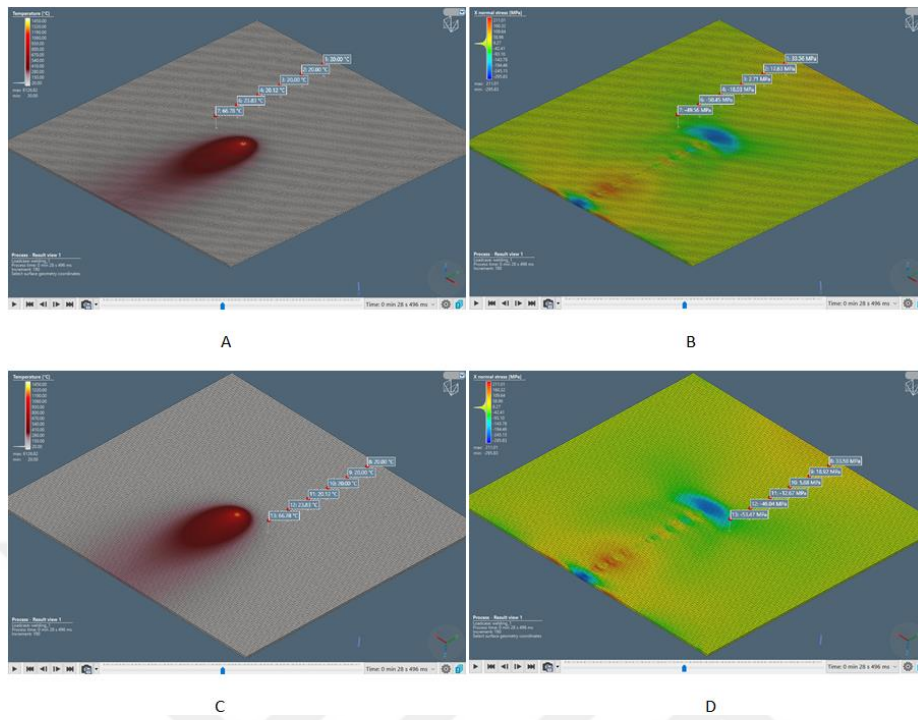


Figure 89 C_{125.7-1.75}TSC Temperature&X Normal Stress Distribution at Weld Face (A-B) Back of Weld Face (C-D) when Laser Beam at Half-Point of Plate

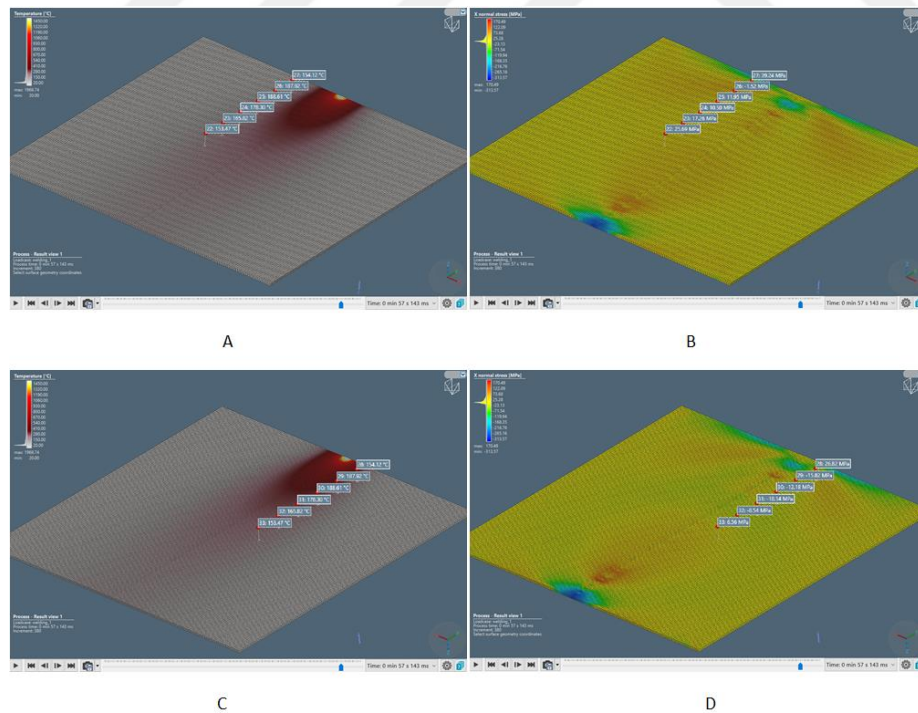


Figure 90 C_{125.7-1.75}TSC Temperature&X Normal Stress Distribution at Weld Face (A-B) Back of Weld Face (C-D) when Laser Beam at End-Point of Plate

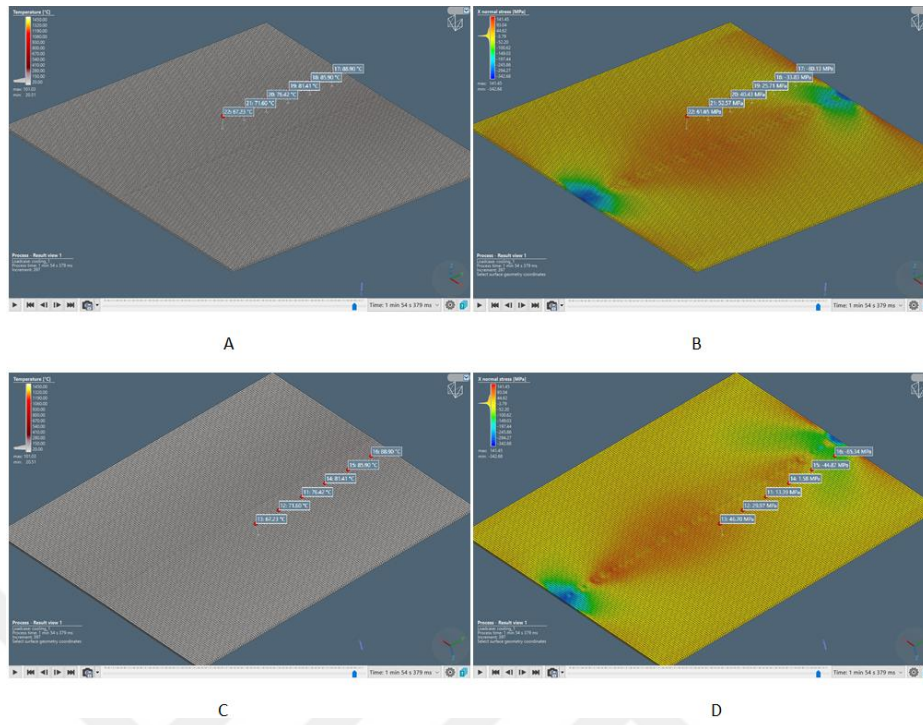


Figure 91 $C_{125.7-1.75TSC}$ Temperature&X Normal Stress Distribution at Weld Face (A-B) Back of Weld Face (C-D) after Cooling 60 seconds

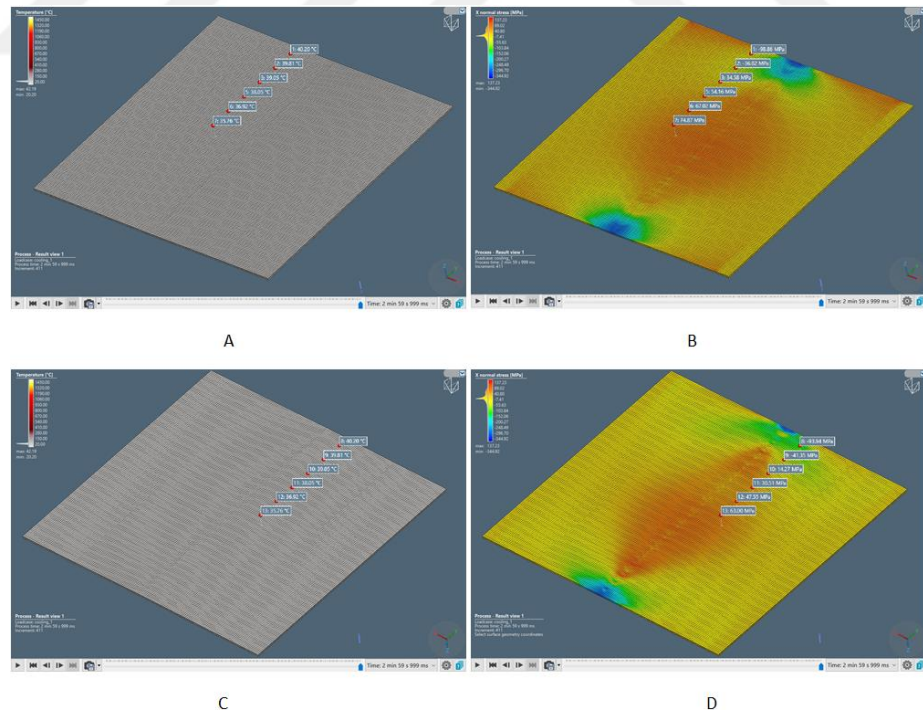


Figure 92 $C_{125.7-1.75TSC}$ Temperature&X Normal Stress Distribution at Weld Face (A-B) Back of Weld Face (C-D) when Cooling Completed

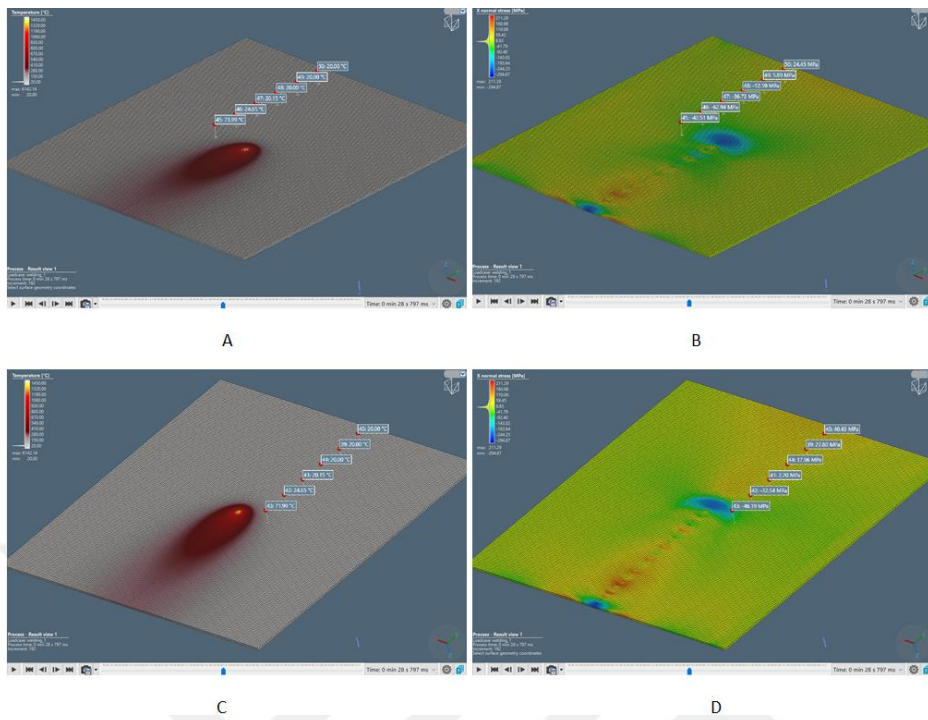


Figure 93 C_{125.7-1.75} Temperature&X Normal Stress Distribution at Weld Face (A-B) Back of Weld Face (C-D) when Laser Beam at Half-Point of Plate

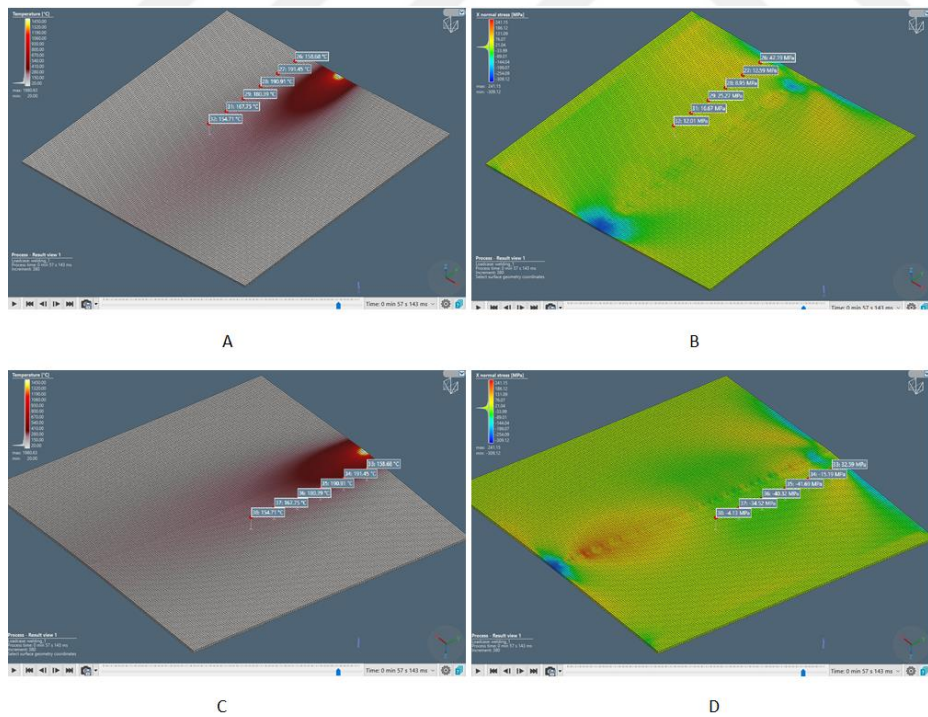


Figure 94 C_{125.7-1.75} Temperature&X Normal Stress Distribution at Weld Face (A-B) Back of Weld Face (C-D) when Laser Beam at End-Point of Plate

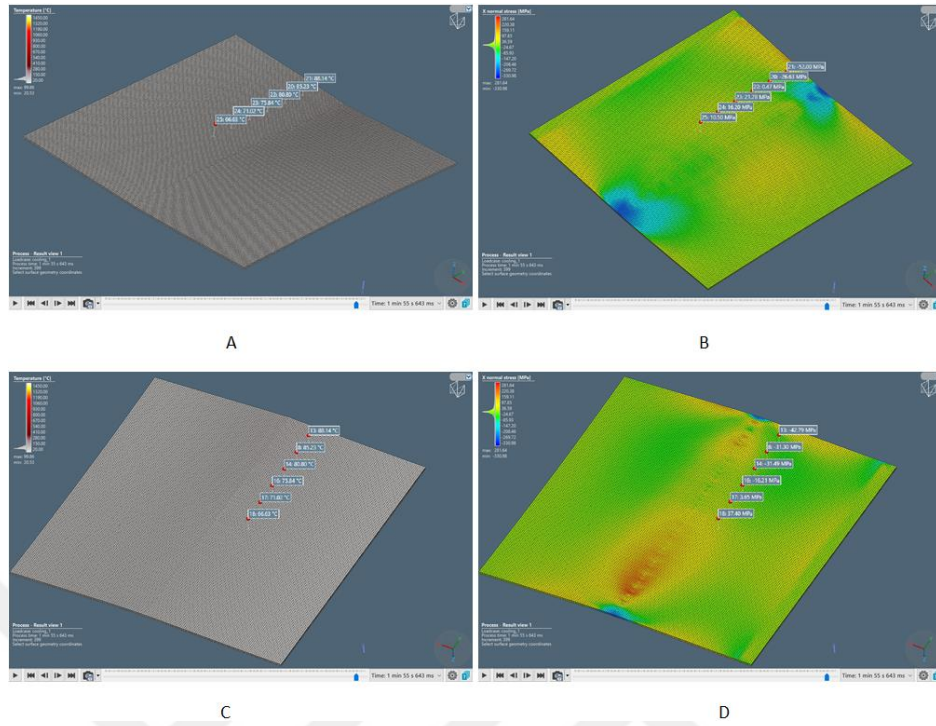


Figure 95 $C_{125.7-1.75}$ Temperature&X Normal Stress Distribution at Weld Face (A-B) Back of Weld Face (C-D) after Cooling 60 seconds

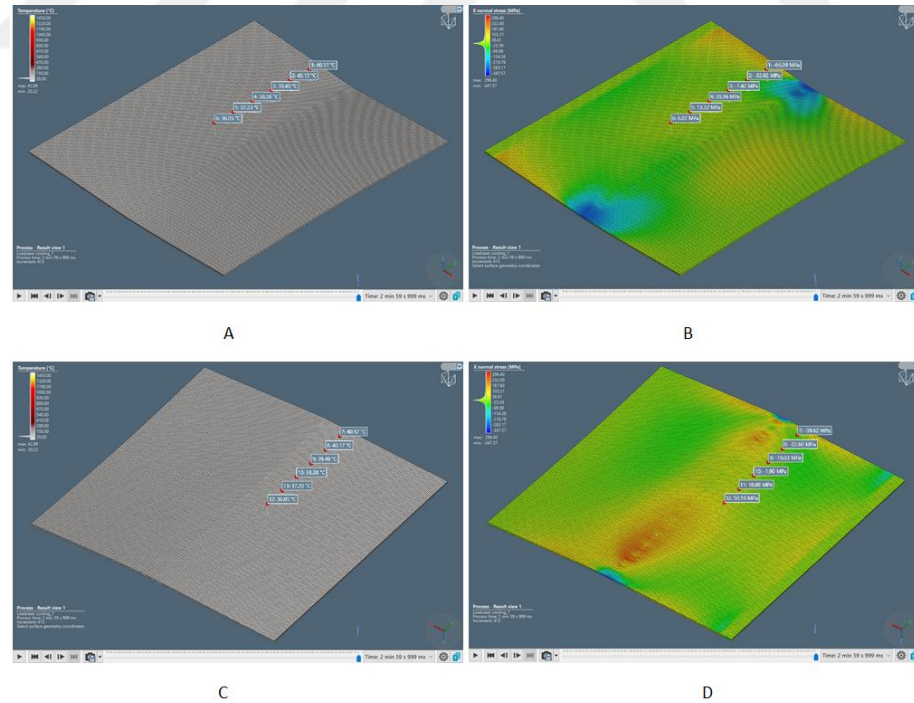


Figure 96 $C_{125.7-1.75}$ Temperature&X Normal Stress Distribution at Weld Face (A-B) Back of Weld Face (C-D) when Cooling Completed

Table 20 X Normal Stress Comparison between C_{125.7-1.75} & C_{125.7-1.75TSC} for 6 Nodes at 4 different Weld Time

Highest X Normal Stress Comparison of C_{125.7-1.75} & C_{125.7-1.75TSC}	Tensile Stress C_{125.7-1.75} (MPa)	Tensile Stress C_{125.7-1.75TSC} (MPa)	Compressive Stress C_{125.7-1.75} (MPa)	Compressive Stress C_{125.7-1.75TSC} (MPa)
Back of Weld Face at Laser Beam at Half-Point	40	33	-46	-53
Weld Face at Laser Beam at Half-Point	24	33	-42	-50
Back of Weld Face at Laser Beam at End-Point	33	27	-42	-18
Weld Face at Laser Beam at End-Point	47	40	9	-1,5
Back of Weld Face after Cooling 60 Seconds	37	47	-43	-85
Weld Face after Cooling 60 Seconds	22	62	-52	-80
Back of Weld Face after Cooling Completed	51	63	-39	-93
Weld Face after Cooling Completed	20	75	-66	-99

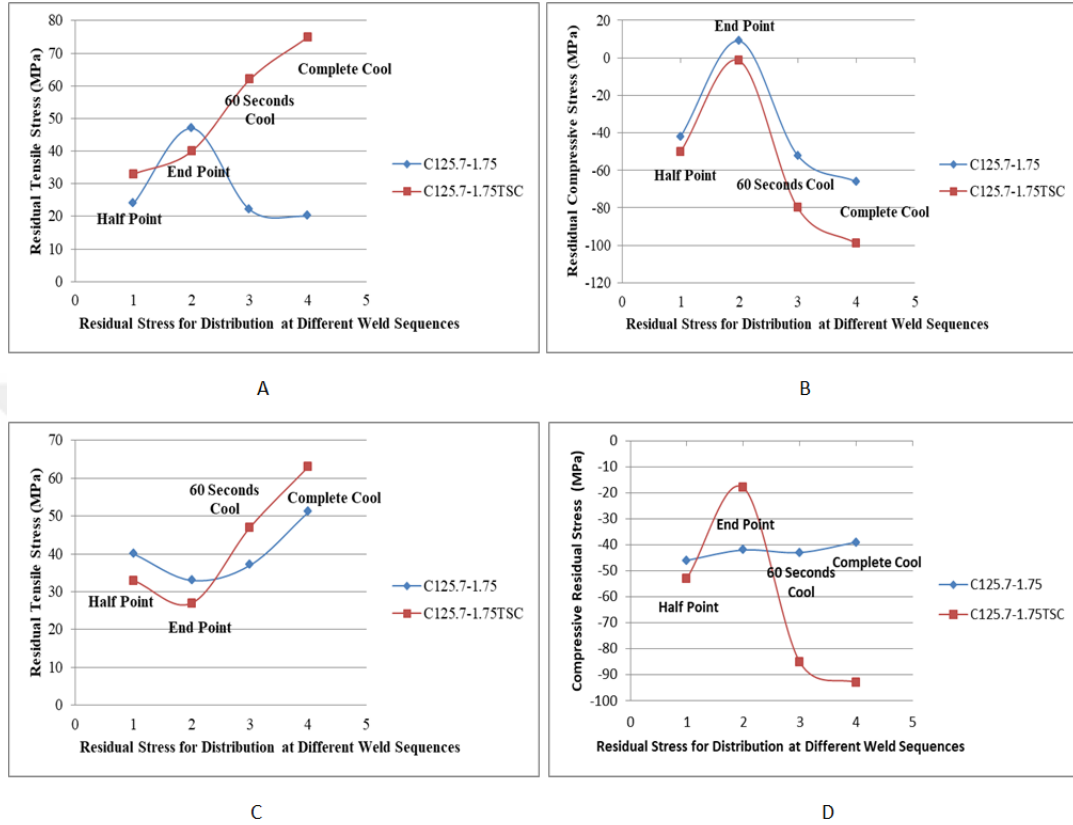


Figure 97 Tensile&Compressive Stress Comparison between C_{125.7-1.75} & C_{125.7-1.75TSC} for 6 Nodes at 4 different Weld Time for Weld Face (A-B) and Back of Weld Face (C-D)

When the simulation results of C_{125.7-1.75TSC} and C_{125.7-1.75} plates are evaluated within the scope of the σ_x residual stress value, as can be seen in the figures above, there are measurement results taken when the welding torch is in the middle of the plate, at the end of the plate, after the welding process is completed and cooled for 60 seconds, and after the cooling is completely completed. These figures were created with the data in Table 20. As can be seen, the comparison results cover the front and back sides of the weld plates. Since the measurements of the experimental results include XRD results obtained from both the front and back sides, a similar method was followed in the simulation results. As expected from

the simulation results, higher values for both tensile residual stress and compressive residual stress were observed on the back and front sides of the plate fixed from both sides. The points measured from both plates are the same as the nodes. Differences in the results were observed when the welding torch was in the middle of the plate, and when it was in the middle of the plate, since the plate has not yet reached a thermally stabilized state and the heat released from the welding process has not penetrated the remaining parts of the plate.

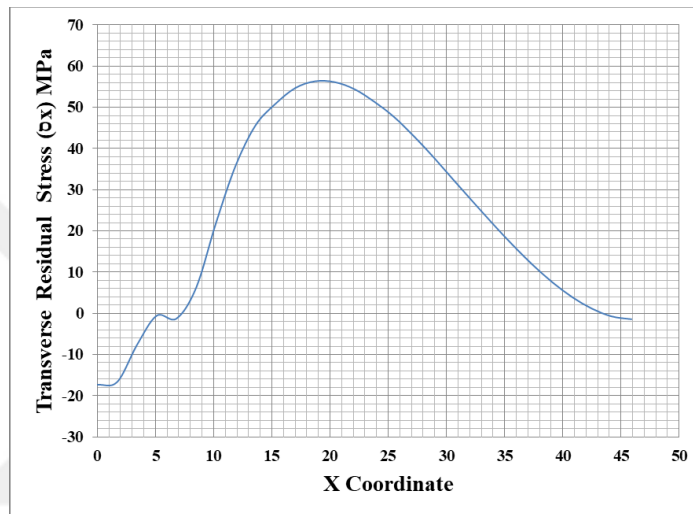


Figure 98 Transverse Residual Stress Distribution of $C_{125.7-1.75}$ at Half-Point in Y axis as a Line Perpendicular to Weld Direction

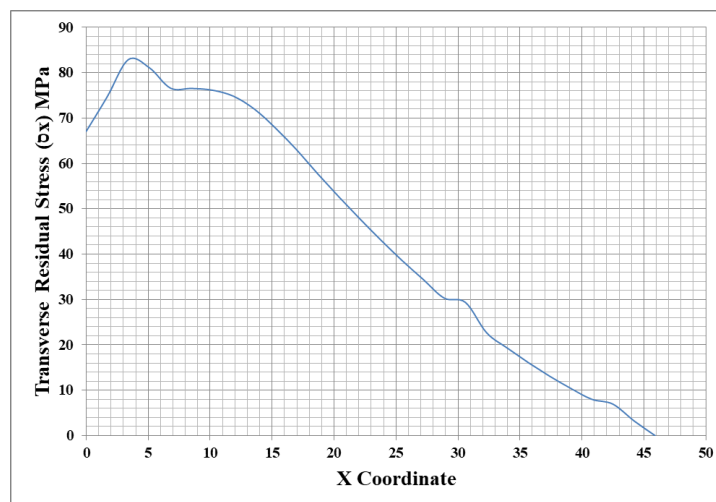


Figure 99 Transverse Residual Stress Distribution of $C_{125.7-1.75TSC}$ at Half-Point in Y axis as a Line Perpendicular to Weld Direction

The comparison seen in Figure 98 and Figure 99 shows the values of the transverse residual stress values perpendicular to the weld pool for the C_{125.7-1.75}TSC and C_{125.7-1.75} plates taken after the plate has cooled completely. In comparison with the literature, the results show that the residual stress value of the 125.7 plate starts as compressive and increases through the HAZ region, then towards the edge of the plate it decreases to 0 MPa. These results show consistency with the literature review, as it is given in Figure 86, it should be noted that only half of the surface of the weld plate's transverse residual stress values are given in Figure 97, as shown in Figure 100 given below. When comparing the transverse residual stress for the two-side clamped C_{125.7-1.75}TSC plate with literature, it showed a greater amount of residual stress as expected. Also, as shown in Figure 97, the starting residual stress in the weld pool showed tensile residual stress behavior, which is similar to the literature review results given in Figure 11, Figure 85, and Figure 86.

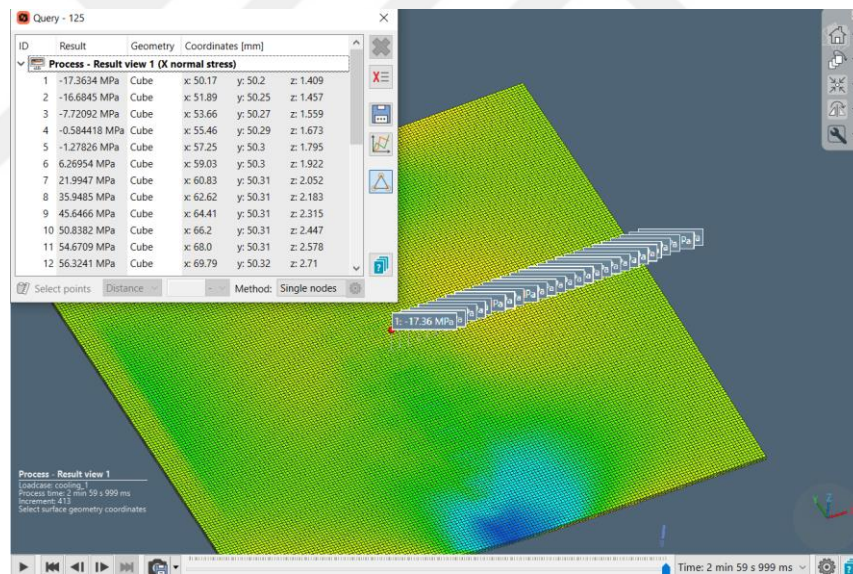


Figure 100 Transverse Residual Stress Measurement Points as a Line in Simufact Welding

Sl.	Clamping force (N/mm)	Case
1	Free clamping	Case 1
2	100	Case 2
3	1000	Case 3
4	10,000	Case 4

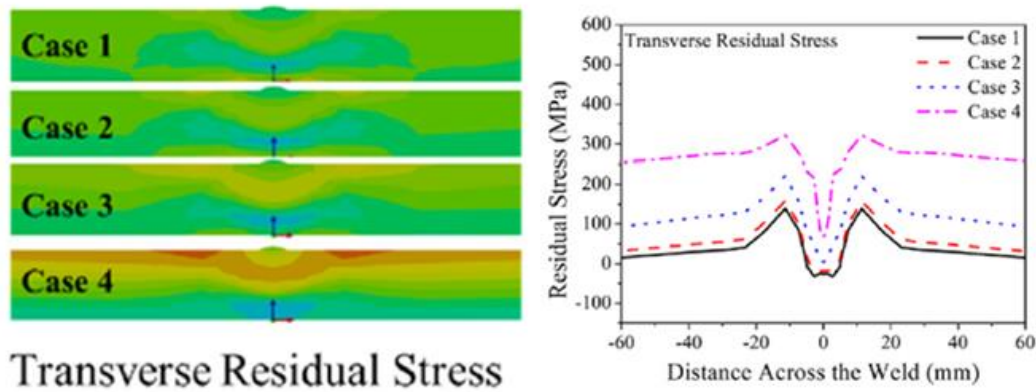


Figure 101 Transverse Residual Stress in Literature for Different Clamp Forces [97]

The results in the literature and the simulation results in the study within the scope of the thesis were compared for both the plate fixed from one side and the plate fixed from both sides. The point that should be taken into consideration is that the values on both sides of the weld pool in the simulation show symmetric results (as given in Figure 100). In the simulation study within the scope of the thesis, only the residual stress value of a 50 mm part of the test plate was plotted on the graph. For both in literature and simulation, the transverse residual stress is taken perpendicular to the weld pool. Comparison of simulation results with literature:

- 1- Transverse residual stress shape shows parallel results between the simulation and the literature for both the plate fixed from two sides and the plate fixed from one side. When Figure 100 is examined, it is observed that there is a lower residual stress in the initial part of the weld pool, the residual stress value increases in the transition to the HAZ region, and the residual stress value decreases as it moves away from the weld pool towards the edge.

- 2- Additionally, as observed from the simulation results, the residual stress value profile in the plate fixed from two sides shows a higher distribution than the plate fixed from one side. Consistent with this result, it is seen in the literature that the residual stress value of the plate in the free form and the clamp force increase, causing an increase in the residual stress value throughout the plate.

4.8.2 Distortion Comparison with Simulation and Measurement Results

The following point is important when comparing simulation and experimental results in terms of distortion; when evaluating the comparison in experimental results, if the pre-welding measurement results were positive in parallelism value, they were subtracted from the post-welding parallelism measurement results, and if they were negative in parallelism value, they were added. The reason for this situation is that the plate starting from the simulation is in perfect form and the parallelism value is initially zero, but in the plates used in the experimental study, there is a form deviation before welding and therefore a parallelism value. As explained above, if these values are negative, they are added to the measurements taken after welding, if they are positive, they are subtracted, and it is aimed to find the distortion value resulting from the welding operation. As described in the heading of Dimensional Measurement, the fact that the probe tip of the dial indicator watch consists of a 2 mm diameter sphere causes uncertainty in comparing the experimental results and simulation results. While obtaining distortion values in the simulation results, since a measurement result is taken from the node and the mesh size used in the simulation is defined as 0.6 mm by mesh convergence analysis, there is a measurement uncertainty coming from the simulation in the distortion value comparison. To reduce this measurement uncertainty to an insignificant level, the average measurement value of the set of points around the node was taken for the mesh with a size of 0.6 mm, as defined in the figure below for node 74 surrounded with nodes 75, 76, 77, 78, 79, 80, 81, and

82 should be taken into consideration. Therefore, the maximum distortion in Z axis – the minimum distortion in Z axis value will be the measurement uncertainty of this simulation result, for given Figure 103; for instance, 3.51 (Node 79) – 3.39 (Node 72) = 0.12 is taken as $u_{\text{simulation}}$ for node 74.

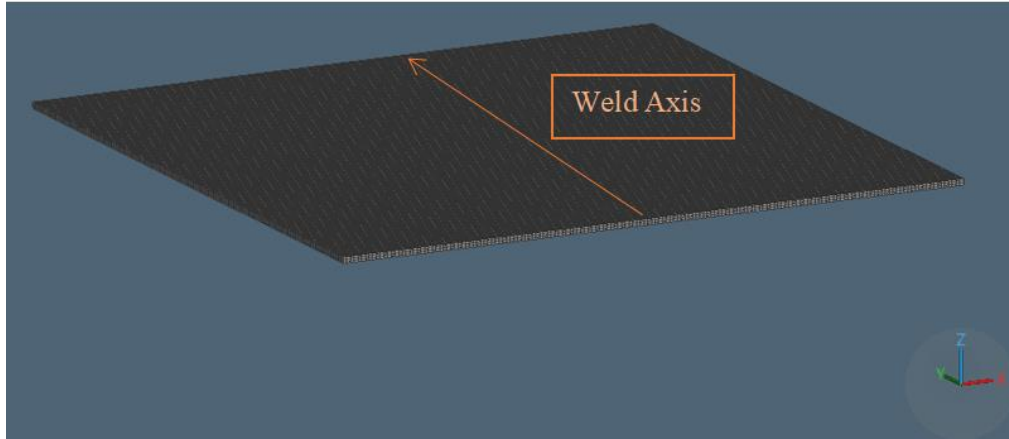


Figure 102 Reference Axis Frame for Distortion Images

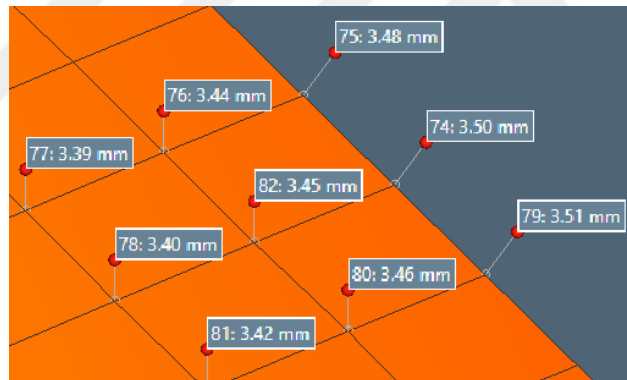


Figure 103 Distortion Comparison Method Example for Node 74

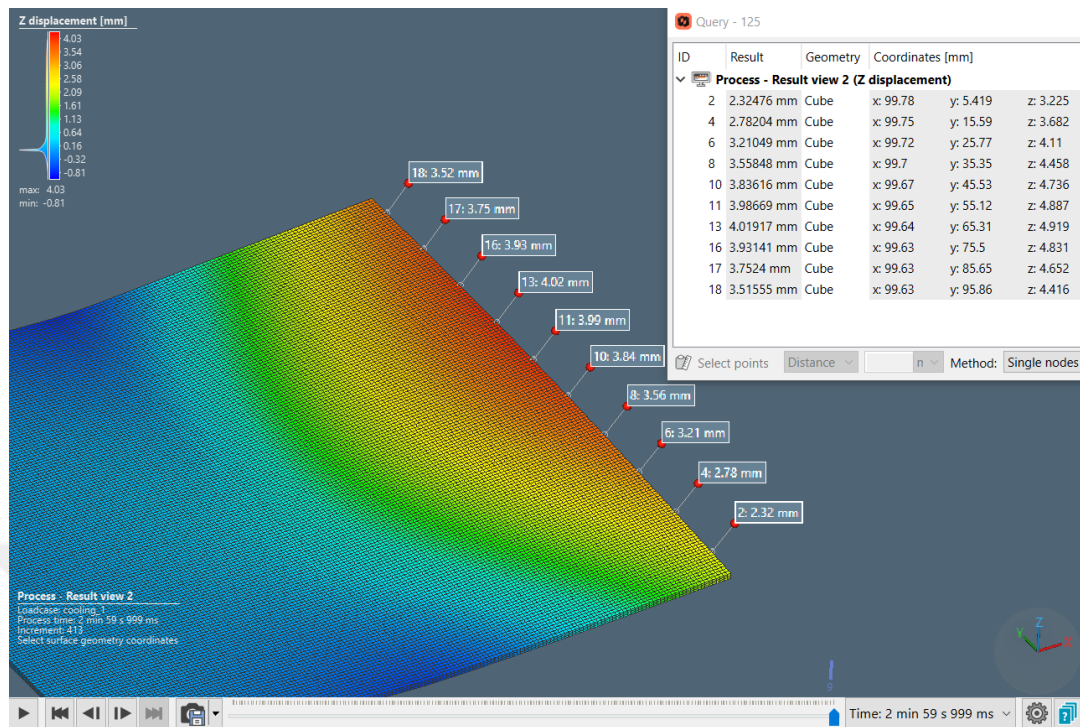


Figure 104 C_{125.7-1.75} Distortion at Edge Zone after Welding/Cooling Completed



Figure 105 C_{125.7-1.75} Simulation vs Experimental Distortion Comparison

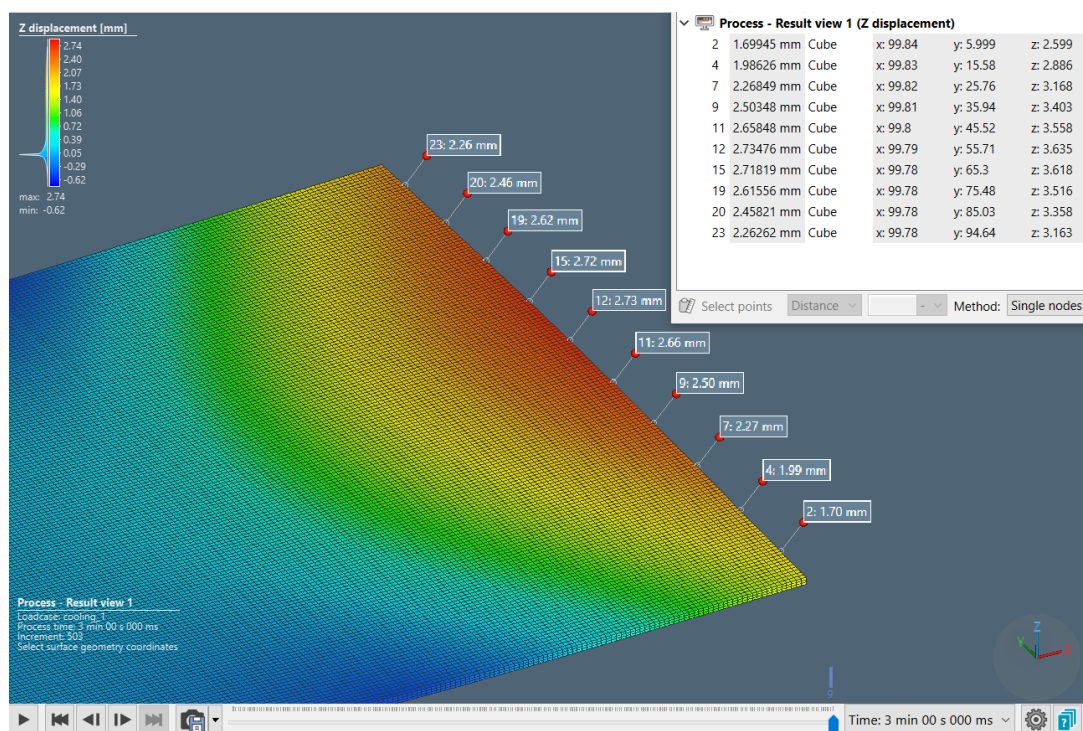


Figure 106 C_{125.7-2.00} Distortion at Edge Zone after Welding/Cooling Completed

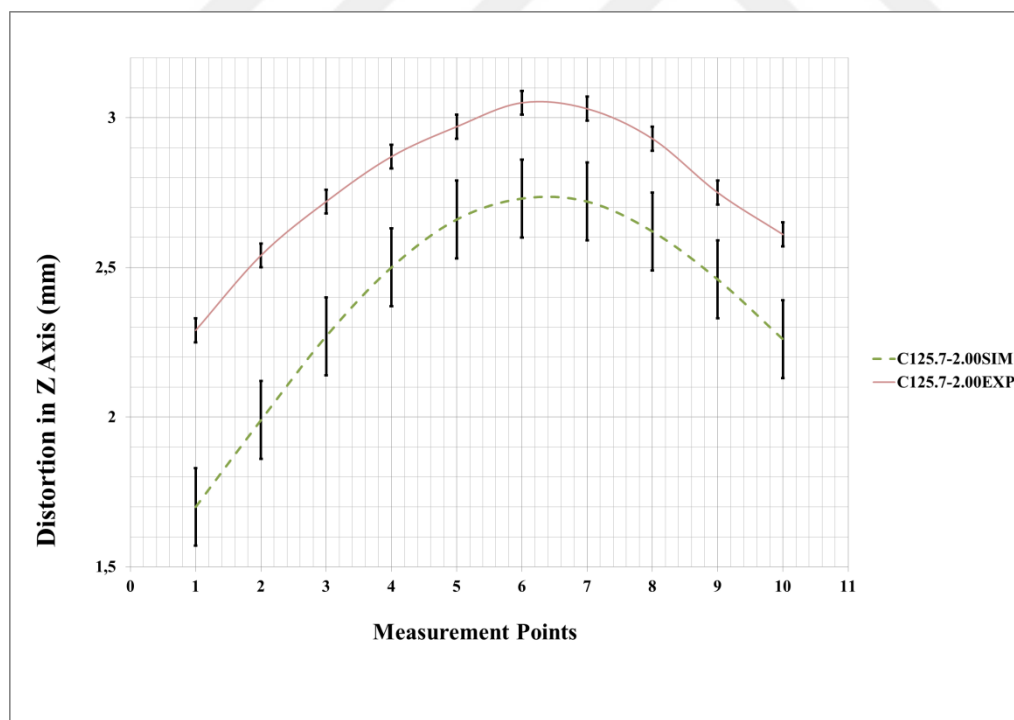


Figure 107 C_{125.7-2.00} Simulation vs Experimental Distortion Comparison

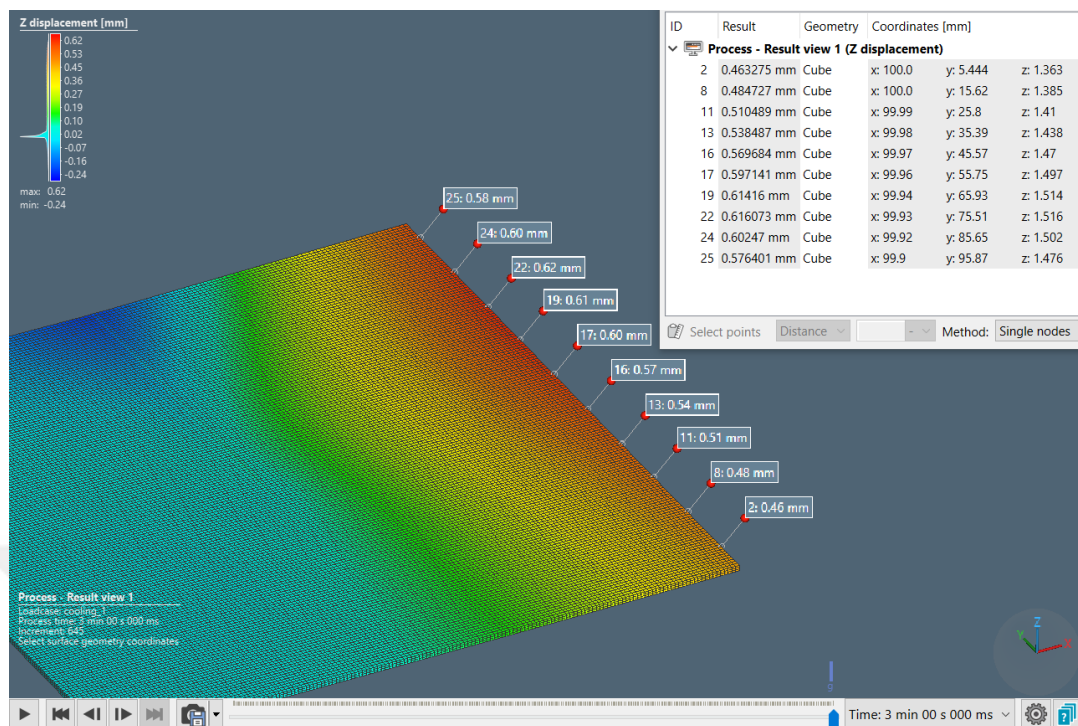


Figure 108 C_{112.1-1.75} Distortion at Edge Zone after Welding/Cooling Completed

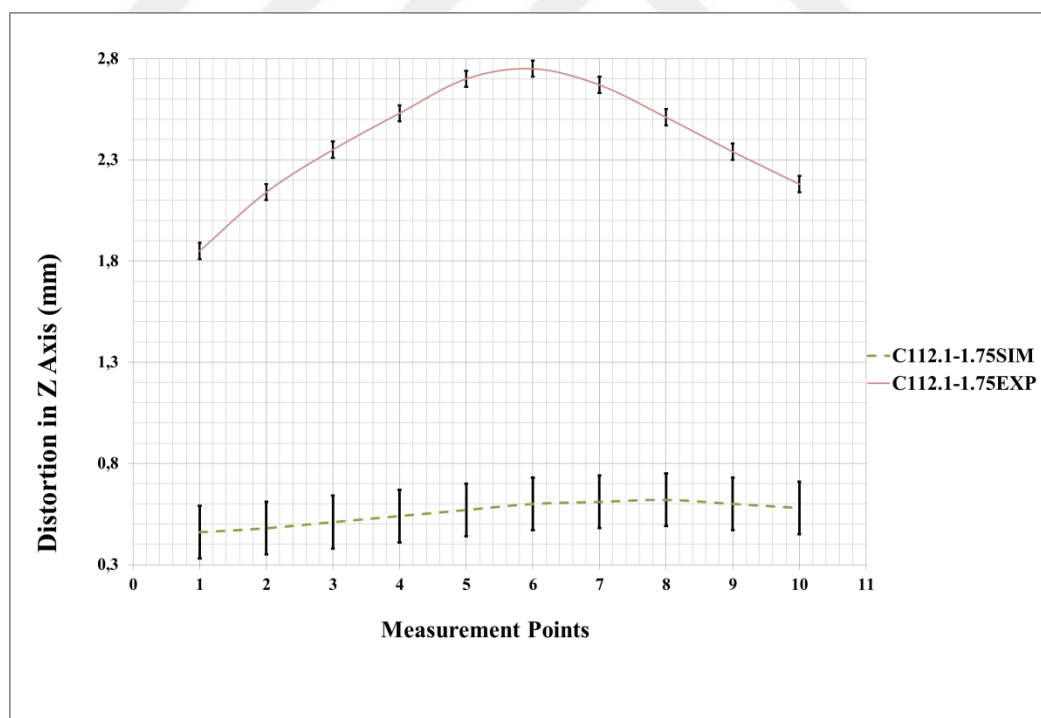


Figure 109 C_{112.1-1.75} Simulation vs Experimental Distortion Comparison

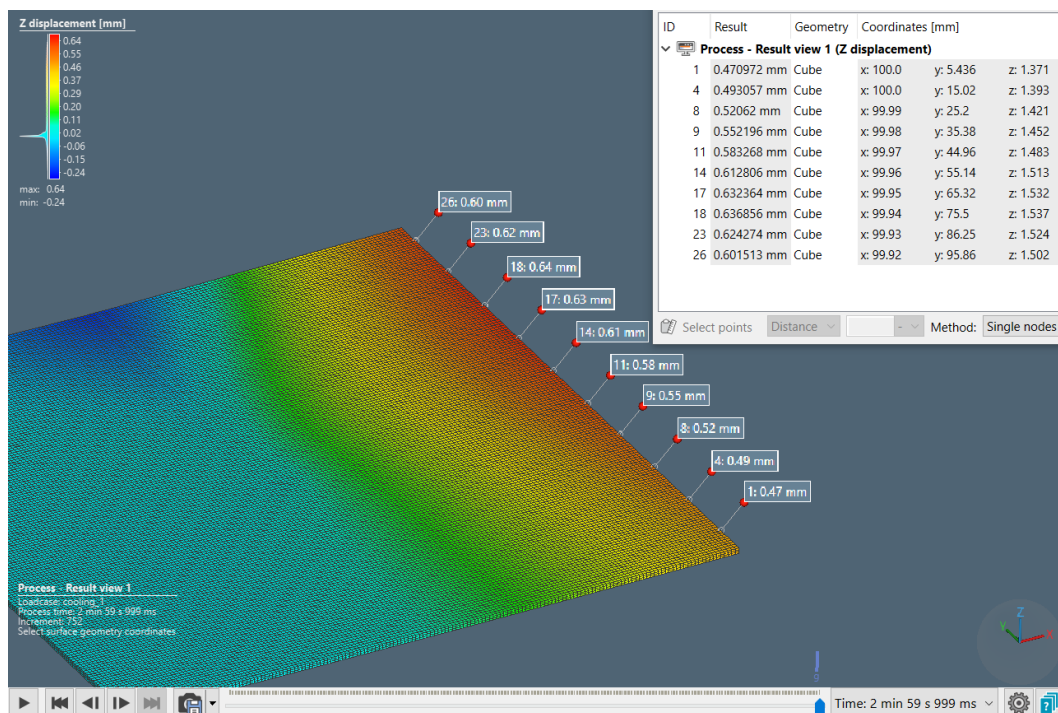


Figure 110 C_{112.1-2.00} 0.6 mm Mesh Distortion at Edge Zone after Welding/Cooling Completed

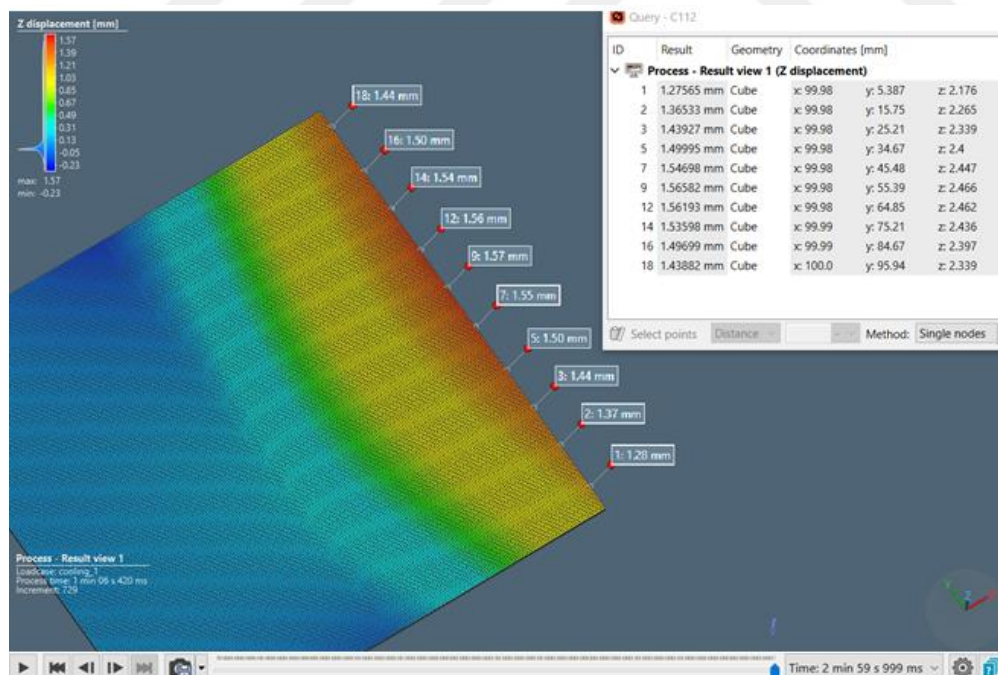


Figure 111 C_{112.1-2.00} 0.45 mm Mesh Distortion at Edge Zone after Welding/Cooling Completed

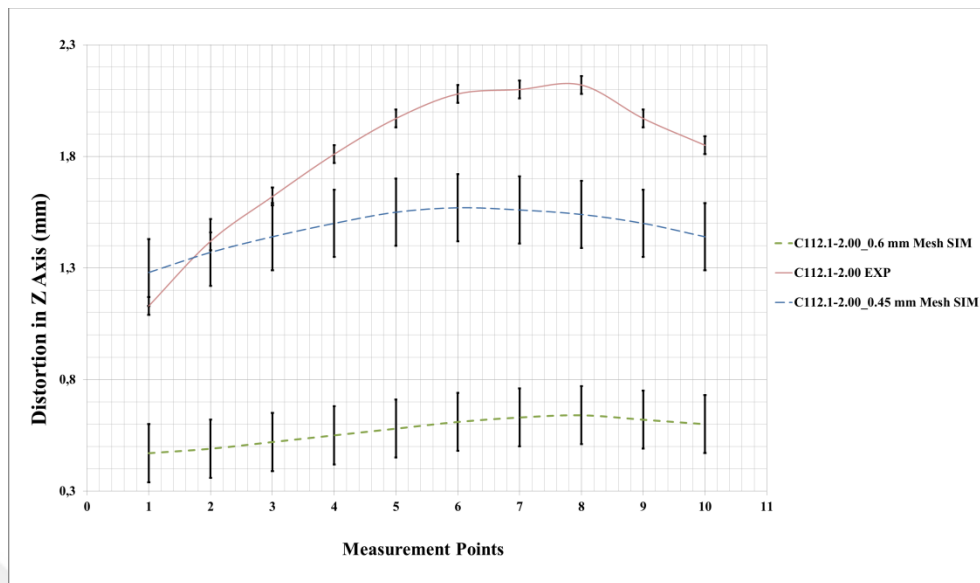


Figure 112 C_{112.1-2.00} Simulation vs Experimental Distortion Comparison

The comparison between simulation and experimental results for C_{112.1-1.75}, C_{112.1-2.00}, C_{125.7-1.75}, C_{125.7-2.00} should be evaluated by considering the following issues:

- 1) Weld pool area differences; the weld pool area in the experiment and the weld pool area in the simulation, the greater the weld pool area, the greater the distortion.
- 2) The difference between the yield strength of the raw material used in the experiment and the yield strength of the material used in the simulation; as given in the above headings Mechanical Tests of Base Metal, residual stress comparison of simulation and test results yields a 3% difference, which can be explained as; the higher yield strength in simulation will result in less deformation for same thermal force.
- 3) Heat transfer state in the experiment (non-steady state) and transfer state used in the simulation (steady state).

- 4) Although in a small amount, the Mitutoyo fixture used in the experiment is made of stainless steel and conduction heat transfer occurs, and in the simulation, this should be neglected because the contact surface is 5 mm as stated in the assumptions section.
- 5) Argon gas is used as a protective gas to prevent oxidation on the weld surface, whereas in simulation no protective gas is used.
- 6) Laser weld efficiency in simulation is taken as 100%, and only heat source calibration and weld pool area comparison are performed with experimental specimens, nevertheless, the absorption in laser welding experiments is not 100%. In keyhole formation of laser welding, the efficiency of absorption increases due to multiple reflections. However, for low heat input welding conditions such as $C_{112.1-1.75}$, $C_{112.1-2.00}$, and $C_{125.7-2.00}$ configurations, no keyhole formation is observed.

The differences can be summarized under the following headings. The situations defined in items 2, 3, 4, 5, and 6 above are valid for the entire configuration, and a detailed explanation has been provided for each configuration specifically for item 1. From the given results above in Figure 105 and Figure 107, simulation results and experimental results in the $C_{125.7-1.75}$ and $C_{125.7-2.00}$ plates' distortion measurements converge. However, for the $C_{112.1-1.75}$ and $C_{112.1-2.00}$ plates, the simulation results were obtained at much lower values than the experimental results. The main reason for this situation is the percentage difference in the resource pool is much higher for these two configurations. As shared in Figure 113 and Figure 114 below for $C_{112.1-2.00}$ specimen example, in the scenario where the resource pool is calibrated larger in the simulation, the simulation distortion results reach much higher levels compared to the experimental results. When the weld pool area in simulation is greater than 87% of the experimental weld pool area, the distortion difference is increased. To resolve this situation, the weld pool observed in the experiment and the weld pool observed in the simulation were approximated in terms of area using the trial and error method in thermal analyses in Simufact

Welding, as given in Table 18. In this trial-and-error method, the disc radius and surface heat source depth parameters in the heat source given in Figure 52 were tried to be adjusted. It is seen that the experimental and simulation distortion results converge when the weld pool area difference is at 11.51% and 13.25%. As defined above, the fact that the resource pool is different for 2 different parameters and the size of the resource pool in the simulation is smaller than the pool in the real experiment distorts to be less, while a larger resource pool distorts to be at much higher levels in the simulation. Additionally, to observe the effect of the operation performed under the title of mesh convergence on distortion, the mesh size was reduced to 0.45 mm, and the experiment was repeated with the same parameters. In parallel with what was observed in the mesh convergence analysis, the reduction of the mesh size caused a significant amount of increase in computation time (60%), but the trade-off in computation time was achieved by obtaining a result closer to reality in the distortion value. These distortion results are given in Figure 111 and Figure 112 (blue dashed line).

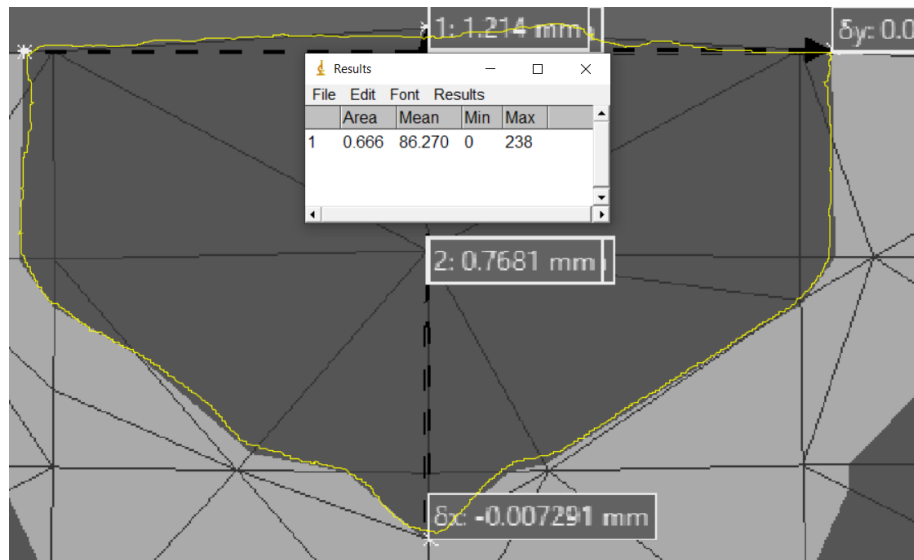


Figure 113 Weld Pool Area of High Heat Input Specimen for C_{112.1-2.00}

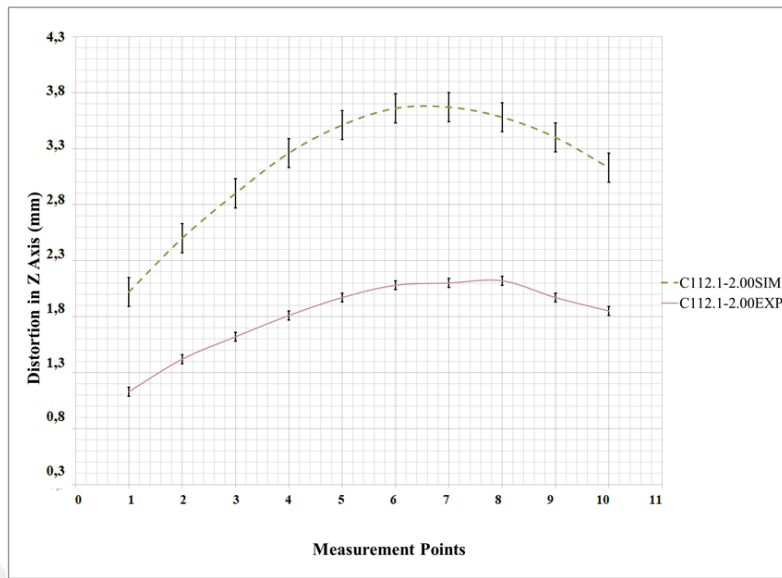


Figure 114 Distortion Comparison of Simulation and Experimental for Higher Weld Pool Area in Simulation

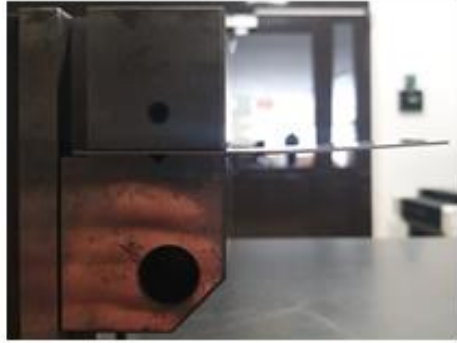
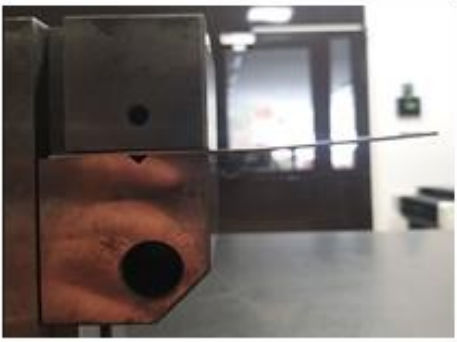
#	Y Axis	X Axis
C _{112.1-1.75}		
C _{112.1-2.00}		
C _{125.7-1.75}		
C _{125.7-2.00}		

Figure 115 Distortion of Plates after Welding

CHAPTER 5

CONCLUSION

This study investigated the effects of laser power and welding speed on the distortion and residual stress state in the laser-welded 316L austenitic stainless steel plates for one-side and two-side clamping conditions using the Simufact Welding software. The simulation results were validated in the welded plates with the dimensions of 100 mm x 100 mm x 0.9 mm via dimensional measurements for distortion and X-ray diffraction measurements for residual stress. Moreover, metallographic investigations, hardness and tensile tests, and nondestructive tests were performed on the specimens prepared from the base metal and weldments. The key findings are summarized below:

1. At 1.75 mm/sec, the slower speed increases heat input, resulting in larger, deeper weld pools and a flatter bead. At 2.00 mm/sec, the faster speed yields a smaller, shallower weld pool with a more pronounced crown. A weld speed higher than 3 mm/sec produced porosities due to unstable keyhole phenomena. A welding power higher than 135 watts caused porosities with a 300-500 μm size, which is not accepted for the aviation standard AWS D17.1.
2. The weld zone consists of a columnar dendritic structure. The average grain size is approximately 559 microns in the heat-affected zone while around 341 microns in the base metal. Nondestructive evaluations showed no defect in the weldments.
3. The simulations and XRD measurements gave mostly similar results. In the laser-welded plates, two-side clamping resulted in about 35% higher transverse residual stress (30 MPa) than one-side clamping.
4. Simulation results aligned well with distortion measurements. Distortion differences in the Z-axis correlated with weld pool area variations, and the

highest displacement (2.7 – 4.2 mm) occurred in the plates welded with the highest heat input (718 J/cm).

5. The comparison of residual stress measurements revealed that the results at 5 out of 8 points overlapped between the simulations and experimental results. Also, when comparing the distortion values from simulations and experiments using the Mean Absolute Percentage Error (MAPE) method, it was observed that for configurations with weld pool area differences of 11.5% (C125.7-2.00) and 13.2% (C125.7-1.75), the distortion values showed 95.7% and 83.0% similarity, respectively.



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APPENDICES

APPENDICES

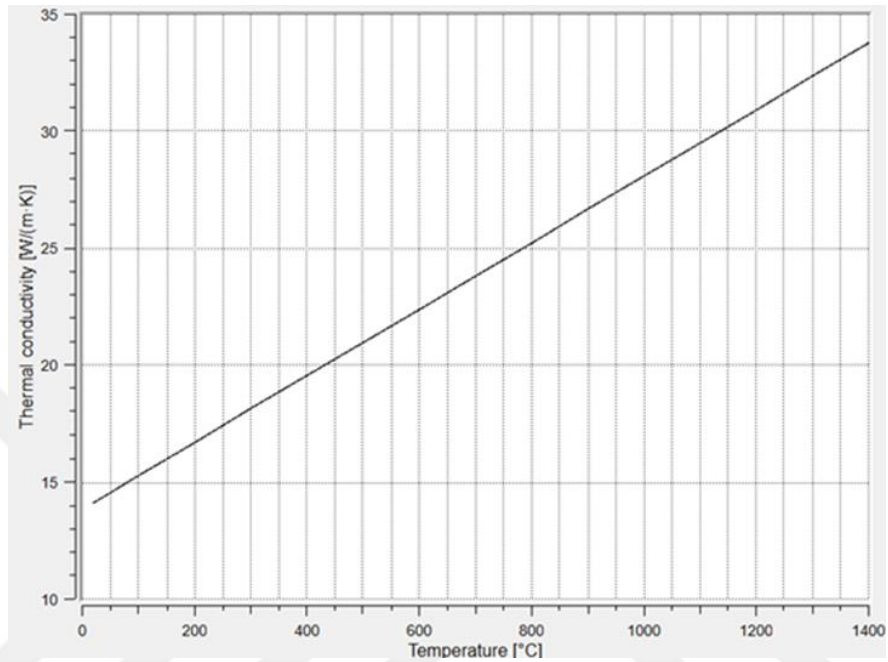


Figure 116 Thermal Conductivity vs Temperature for 316L_sw in Simufact Welding Material Database

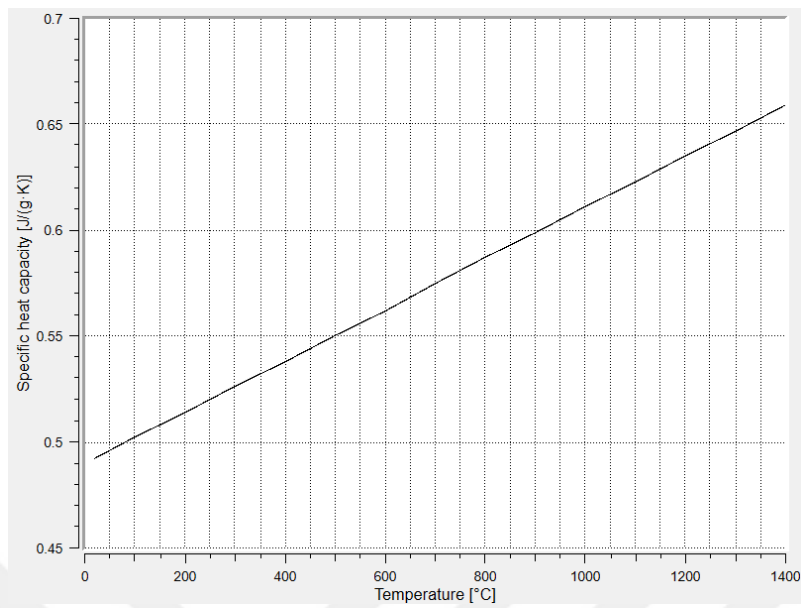


Figure 117 Specific Heat Capacity vs Temperature for 316L_sw in Simufact Welding Material Database

Density:	Constant	7966.0	kg/m ³
Dissipation factor:	Constant	0.9	-
Latent heat			
Solidus temperature:	☒	1279.85	°C
Melting temperature:	☒	1450.0	°C
Evaporation temperature:	☐	No optional value set	
Latent heat for melting:	☒	256400.0	J/kg
Latent heat for evaporation:	☐	No optional value set	

Figure 118 Density, Solidus, Liquids, and Latent Heat for 316L_sw in Simufact Welding Material Database

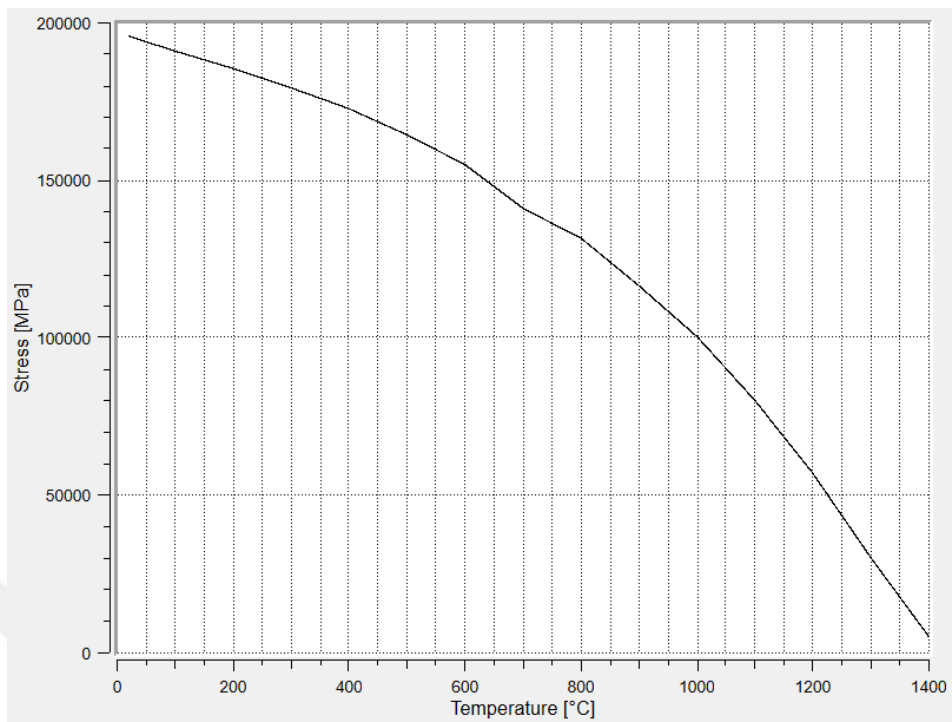


Figure 119 Young's Modulus vs Temperature for 316L_sw in Simufact Welding Material Database

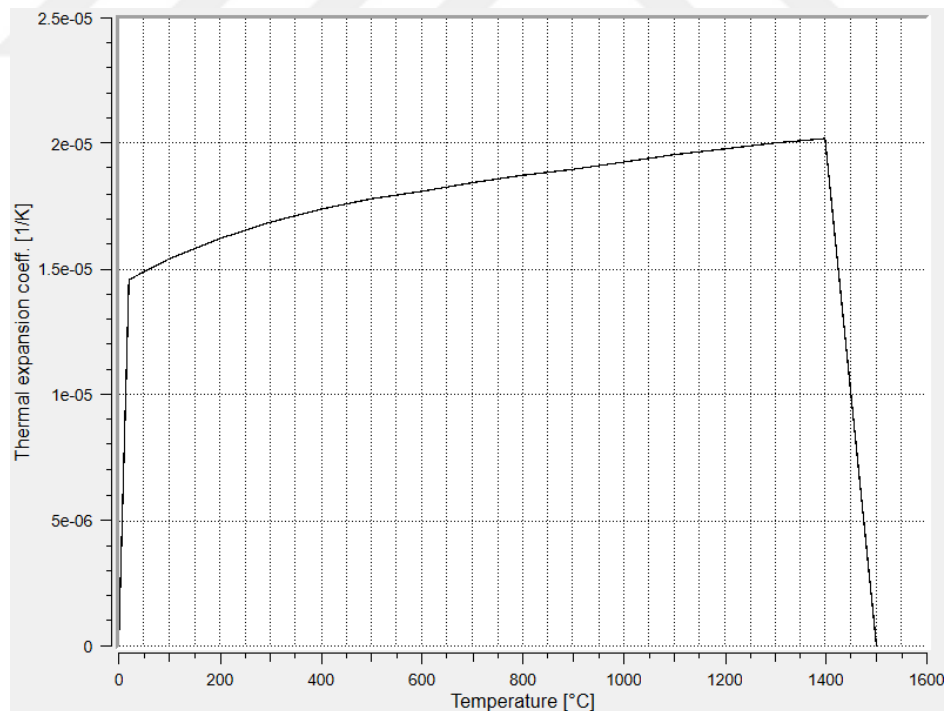


Figure 120 Thermal Expansion Coefficient vs Temperature for 316L_sw in Simufact Welding Material Database

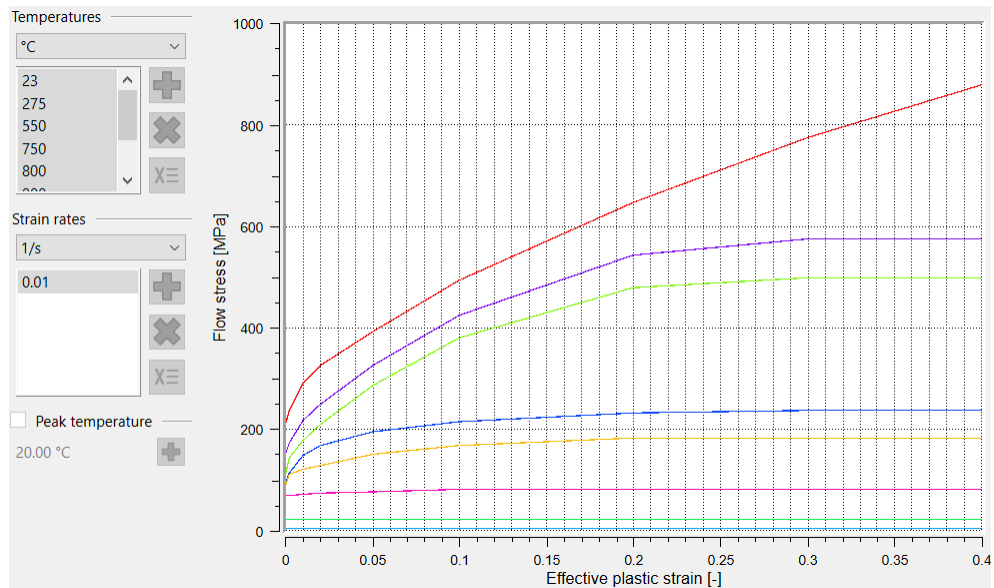


Figure 121 Flow Curves vs Effective Plastic Strain for Different Temperatures for 316L_sw in Simufact Welding Material Database

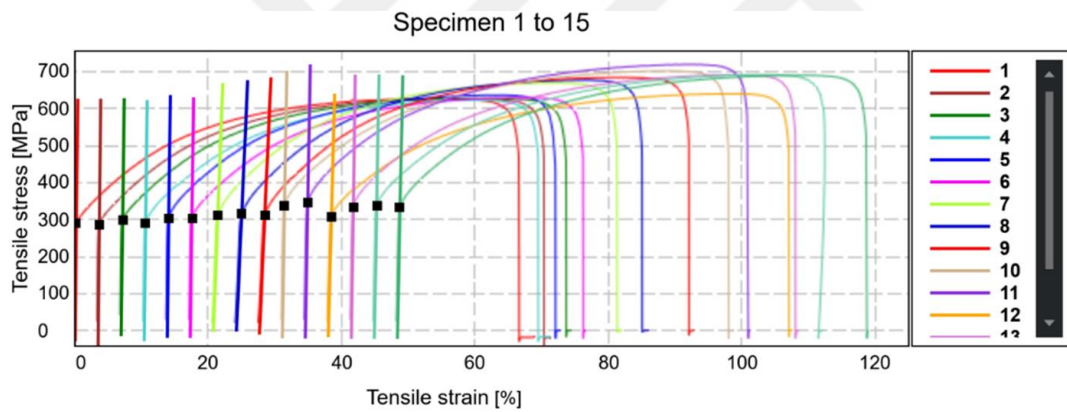


Figure 122 Tensile Test Results for Base Metal (1-3) and Welded Zone (4-15) (Tensile test results are shown as shifted to the right due to being plotted on the same graph, each shifted starting point corresponds to zero strain point)