International Journal of Innovation in
Mechanical Engineering and Advanced Materials
Vol. 7 (No. 3), 2025, pp. 128-138
Journal homepage: publikasi.mercubuana.ac.id/index.php/ijimeam
DOI: 10.22441/ijimeam.v7i3.33596

Enhancing The Formability of SS304 in ISF via Pre-Heating Treatment Strategies

Muhammad Aqib Raza Shah and Agung Shamsuddin Saragih *

Department of Mechanical Engineering, University of Indonesia, Depok 16424, Indonesia
*Corresponding Author: ashamsuddin@eng.ui.ac.id (ASS)

Abstract

The increasing demand for lightweight yet high-strength components in the automotive and aerospace industries has accelerated interest in Incremental Sheet Forming (ISF) as a flexible, dieless, and cost-effective manufacturing process, particularly for low-volume and customized production. Unlike conventional forming processes that rely on expensive dies, ISF offers greater geometric flexibility and rapid prototyping capabilities. However, its broader industrial adoption remains limited due to persistent challenges such as poor surface finish, springback, and restricted formability, especially when forming hard-to-deform materials like Stainless Steel Grade 304 (SS304). This study investigates the influence of customized heat treatment on the formability and deformation quality of SS304 sheets formed via ISF. Sheets were subjected to preheating at controlled temperatures ranging from room temperature to 700°C, followed by dieless forming using a CNC machining center equipped with a hemispherical tungsten carbide tool. Key process parameters, including a step size of 0.3 mm, a feed rate of 180 mm/min, and a tool speed of 500 mm/min, were maintained throughout forming. Comprehensive mechanical and microstructural analyses, including tensile testing, surface roughness evaluation, and optical metallography, were performed. Results revealed significant improvements in formability: ductility increased from 24.28% to 65%, and surface roughness (Ra) decreased from 9.7993 μm to 5.4809 μm after annealing at 700°C and tempering at 500°C. Microstructural analysis confirmed grain refinement and carbide dissolution, contributing to improved plastic flow and reduced surface defects. Integrating controlled heat treatment with ISF significantly enhances forming capabilities, surface quality, and geometric precision of SS304, making it a viable solution for manufacturing complex, high-performance components. These findings provide valuable insights for developing more efficient, defect-minimized, and adaptable forming strategies suitable for advanced manufacturing industries.

Article Info:
Received: 16 May 2025
Revised: 25 June 2025
Accepted: 30 June 2025
Available online: 21 July 2025

Keywords:
Incremental Sheet Forming (ISF); Stainless Steel Grade 304; heat treatment; formability; surface quality; mechanical properties

1. Introduction

Incremental Sheet Forming (ISF) has emerged as a promising dieless manufacturing technique for producing complex sheet metal parts in low-volume or customized production settings. Unlike conventional methods such as stamping or deep drawing, which require rigid and costly dies, ISF utilizes a numerically controlled hemispherical tool to incrementally deform sheet material along a predefined toolpath. This layer-by-layer deformation mechanism allows greater design flexibility, reduced tooling costs, and faster turnaround times [1], [2]. As a result, ISF is increasingly applied in the automotive, aerospace, biomedical, and defense industries, where rapid prototyping, geometric flexibility, and the use of high-performance materials are critical [3]. ISF also enables easier forming of asymmetric and customized geometries that would otherwise be impractical or uneconomical with traditional methods [4].

Despite its flexibility, the ISF process faces significant challenges when forming materials with low room-temperature ductility or high work-hardening rates, such as austenitic stainless steels. Stainless Steel 304 (SS304) is among the most widely used grades in engineering applications due to its corrosion resistance, thermal stability, and mechanical strength [5]. It is extensively used in food processing equipment, automotive exhaust systems, architectural panels, and pressure vessels. However, its high strain-hardening coefficient and relatively low formability under room-

How to cite:

M.A.R. Shah and A.S. Saragih, "Enhancing the formability of SS304 in ISF via pre-heating treatment strategies," *Int. J. Innov. Mech. Eng. Adv. Mater*, vol. 7, no. 3, pp. 128-138, 2025

temperature conditions result in poor ISF performance. Researchers have consistently reported issues such as limited achievable wall angles, localized thinning, surface tearing, high tool forces, and springback when forming SS304 using ISF [6], [7]. These defects not only reduce dimensional accuracy but also compromise component quality and forming reliability in industrial applications.

To address these limitations, several studies have explored thermal assistance strategies to improve the formability of hard-to-deform metals during ISF. Laser-assisted ISF (L-ISF), electric current-assisted forming, friction-assisted ISF, and warm ISF have all demonstrated positive effects in reducing flow stress, improving surface finish, and increasing achievable forming angles [8]. For example, Ambrogio et al. [9] used localized laser heating in ISF to reduce forming forces and delay crack initiation in titanium sheets. Similarly, Xu et al. [10] showed that electrically assisted ISF improved strain distribution and surface integrity in aluminum alloys. However, these in-situ heating methods typically require complex and costly integration of thermal systems, precise synchronization, and safety controls, making them less accessible for broader industrial application [11], [12].

By contrast, heat treatment prior to forming—particularly annealing—represents a relatively simpler and more scalable approach to enhancing material formability. Pre-heating modifies the sheet's microstructure before deformation, promoting grain growth, eliminating dislocations, dissolving carbides, and relieving internal stresses. Mechanical properties such as yield strength, ductility, and toughness are critical to forming performance, and these microstructural changes directly influence them [13], [14]. For instance, Fratini et al. [15] demonstrated that warm pre-treatment of titanium sheets before ISF increased formability by enlarging wall angle limits and reducing fracture risks. Similar results were reported by Faraji et al. [16], who applied annealing to magnesium alloys before forming, leading to improved elongation and smoother surfaces.

Although these approaches have proven effective for non-ferrous alloys, the existing body of knowledge on heat-treatment-assisted ISF of Stainless Steel 304 remains limited. Most current research on SS304 ISF has focused either on in-process heating techniques or toolpath optimization [17], [18], while relatively few studies have examined the effect of controlled pre-forming heat treatments on forming behavior, microstructure, and final part quality. Kumar et al. [19] highlighted the importance of heating rates and soaking times in influencing material performance but did not provide detailed analysis of their impact on SS304 microstructure and surface topography.

This research aims to address this gap through a systematic study of the effects of custom-designed pre-forming heat treatments on the Incremental Sheet Forming of Stainless Steel 304. The experiments investigate how annealing parameters (temperature, soaking time, cooling rate, and cooling method) affect critical formability metrics such as forming depth, surface roughness, springback, and failure modes. Additionally, mechanical performance, including tensile properties, and microstructural evolution were analyzed using metallography. Establishing correlations between pre-treatment conditions and ISF outcomes is expected to yield insights that can support the development of effective, cost-efficient methods for forming stainless steel components in high-precision, low-volume production environments.

2. Methods

2.1. Experimental design

The experimental procedure was designed to investigate the effect of pre-forming heat treatment on the formability of Stainless Steel 304 sheets using the ISF process. As shown in Figure 2, the workflow began with material preparation, followed by annealing at various temperatures (ranging from room temperature to 700°C) in a muffle furnace at a controlled heating rate of 30°C/min. After

Table 1. Experimental parameters

No.	Temperature (°C)	Lubricant	Tool Diameter (mm)	Step size (mm)	Tool Speed (mm/mint)
1	0	Grease	11	0.3	200
2	200	Grease	11	0.3	200
3	400	Grease	11	0.3	200
4	600	Grease	11	0.3	200
5	700	Grease	11	0.3	200
6	700	Grease	11	0.3	200

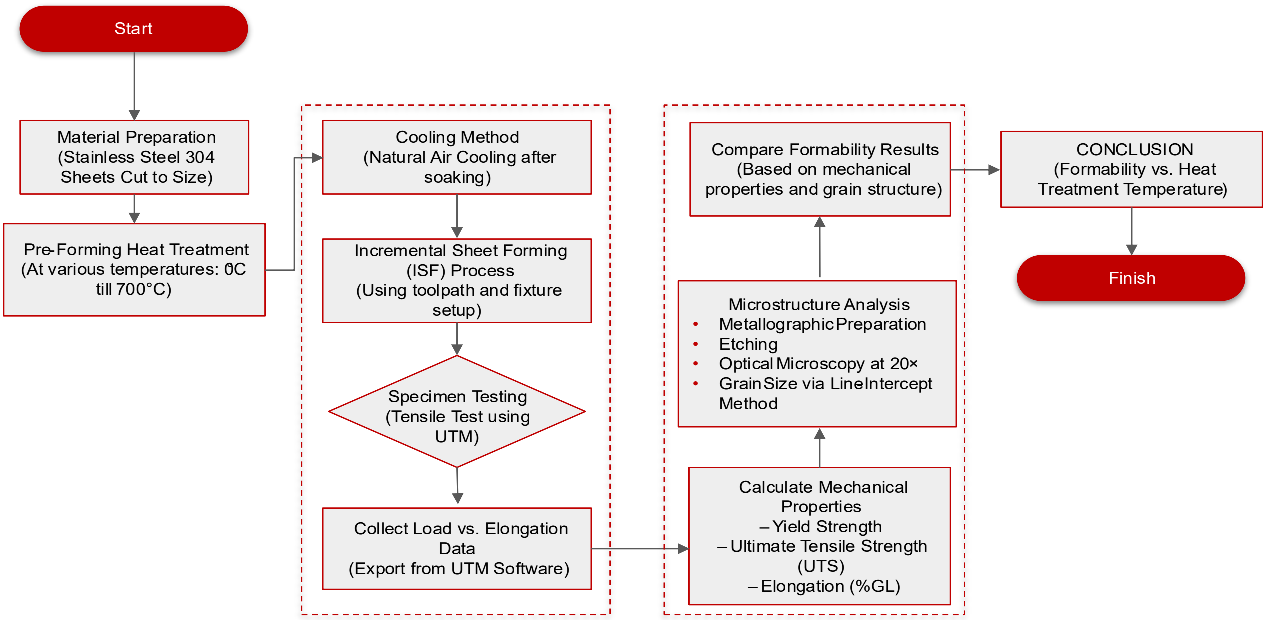

Figure 2. Process flow of experimental procedure

soaking, the sheets were air-cooled and subsequently formed using ISF on a CNC vertical machining center. The toolpath followed a spiral profile to deform the sheet into a conical shape, with forming angles ranging from 45° to 90°. A tungsten carbide tool with an 11 mm hemispherical tip was used under fixed forming parameters: a step size of 0.3 mm, tool speed of 200 mm/min, and feed rate of 1000 mm/min, with grease applied as a lubricant. Details of the forming parameters are summarized in Table 1.

Post-forming, tensile tests were conducted using a Tensilon RTF-2350 universal testing machine (UTM) in accordance with ASTM E8/E8M standards to determine mechanical properties such as yield strength, ultimate tensile strength (UTS), and elongation. Surface roughness was measured both before and after tempering at 500°C using a SURFCOM 2900 surface tester. Microstructural analysis was performed through metallographic preparation, electrolytic etching with 15% oxalic acid, and optical microscopy at 20× magnification. Grain size was evaluated using the linear intercept method. These combined characterization methods enabled a comprehensive evaluation of formability as a function of heat treatment temperature. The experimental procedure workflow is illustrated in Figure 1.

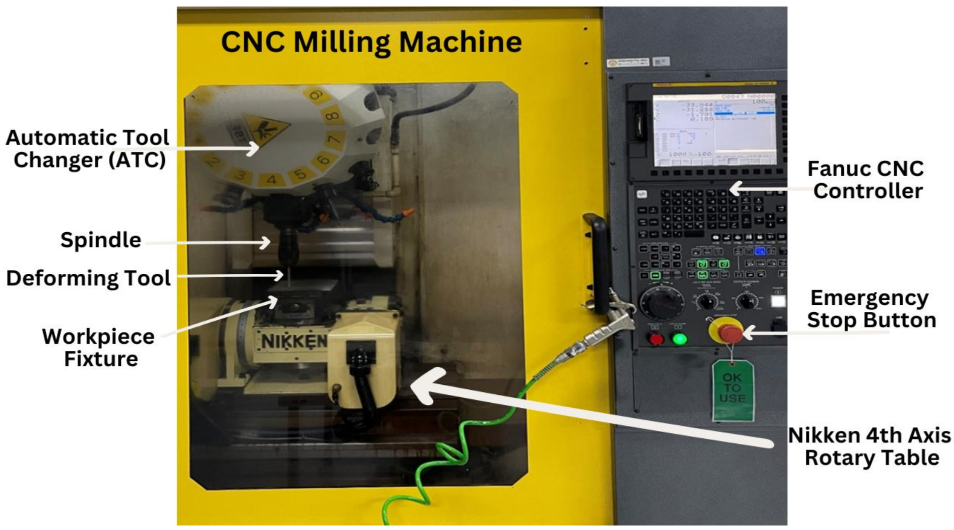

Figure 1. Experimental setup

Figure 3. Tensilon RTF-2350 Universal Testing Machine

2.2. Experimental setup

A 1 mm thick sheet of Stainless Steel 304 was used for the incremental sheet forming (ISF) process. The chemical composition of the material was as follows (in wt.%): C ≤ 0.08, Cr 18–20, Ni 8–10.5, Mn ≤ 2.0, Si ≤ 1.0, P ≤ 0.045, S ≤ 0.03, with Fe as the balance. The sheet was cut into 160 mm × 160 mm samples and rigidly clamped along all four edges during forming. Forming tests were conducted on a CNC vertical machining center using a fixture with a forming zone of 100 mm × 100 mm.

A muffle furnace was used to heat the stainless-steel sheets prior to forming. The furnace consisted of a small, insulated chamber with a maximum temperature of approximately 1100°C. Uniform heat distribution was achieved using a resistance heating element, while heat loss was minimized using high-temperature ceramic fiber insulation. The temperature was controlled by a digital programmable controller with real-time display. A K-type thermocouple was used for accurate temperature measurement inside the chamber. Heat-resistant gloves were required for manual handling, in accordance with safety protocols. Once the target sheet temperature was reached and stabilized, the thermocouple was removed, and the forming process was initiated.

Due to the elevated temperatures, grease was applied evenly on the sheet surface to serve as a lubricant during forming. Grease lubrication was also used during room temperature forming to

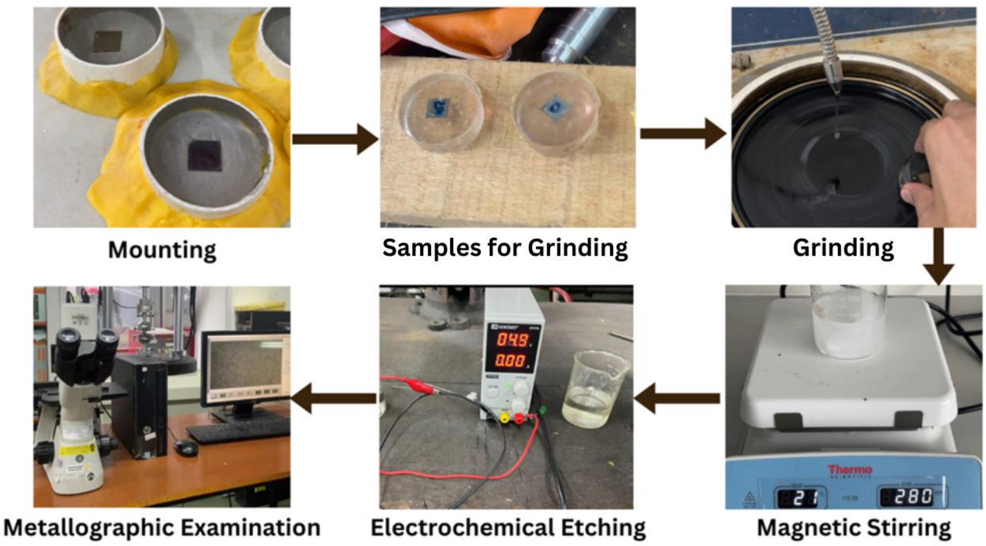

Figure 4. Metallographic steps for microstructure analysis

minimize friction. In both cases, lubrication was applied prior to the commencement of the forming process. The experimental setup is illustrated in Figure 2.

2.3. Properties measuring methods

2.3.1. Tensile testing

Mechanical property testing revealed significant changes in tensile strength, ductility, and hardness following the heat treatment process. Tensile testing showed a reduction in ultimate tensile strength (UTS) for heat-treated samples compared to the as-received condition, accompanied by a considerable increase in elongation, indicating improved ductility. Among the tested conditions, sheets heat-treated at 700 °C exhibited the most balanced mechanical performance, offering sufficient strength to meet service requirements while enhancing formability. Tensile tests were conducted using a Tensilon RTF-2350 universal testing machine (UTM) in accordance with ASTM E8/E8M standards, employing flat specimens with dimensions of 70 mm × 15 mm to determine UTS, yield strength, and elongation.

2.3.2. Metallographic analysis

Metallographic analysis was performed using a Nikon Eclipse metallurgical microscope to examine the microstructural characteristics of the stainless-steel sheets. Sample preparation followed the standard procedure outlined in ASTM E3, which included grinding, polishing, and etching. Polishing was carried out using silicon carbide abrasive papers with progressively finer grits ranging from 200 to 2000, followed by thorough cleaning to enhance surface clarity. Electrolytic etching was then performed using a 15% solution of oxalic acid dihydrate ($C_2H_2O_4{\cdot}2H_2O$, Merck, Emsure®, CAS No. 6153-56-6) in distilled water, continuously stirred for 1 hour using a magnetic stirrer. A 5V potential was applied during the etching process to achieve optimal surface contrast. This method was effective in revealing grain boundaries, phase distribution, and microstructural changes resulting from heat treatment. The observations were used to assess material transformations and their correlation with improved formability. A visual representation of the metallographic procedure is shown in Figure 4.

2.3.3. Surface roughness measurement

A SURFCOM 2900 surface roughness tester was used to measure the surface texture and quality of the stainless-steel sheets. Surface roughness measurements were performed in accordance with ISO 4287, using the average roughness parameter (Ra) to assess surface finish. Initial roughness measurements were taken before the incremental forming process to establish a baseline for evaluating its effect on the surface condition of the material. This analysis provided insight into the impact of the forming process on surface integrity and formability. To further study the effect of heat treatment, the deformed samples were tempered at 500°C, and surface roughness was measured again using the same procedure. These measurements contributed significantly to understanding the correlation between thermal treatment and surface quality in incremental sheet forming.

Figure 5. Surfcom 2900 for surface roughness measurement

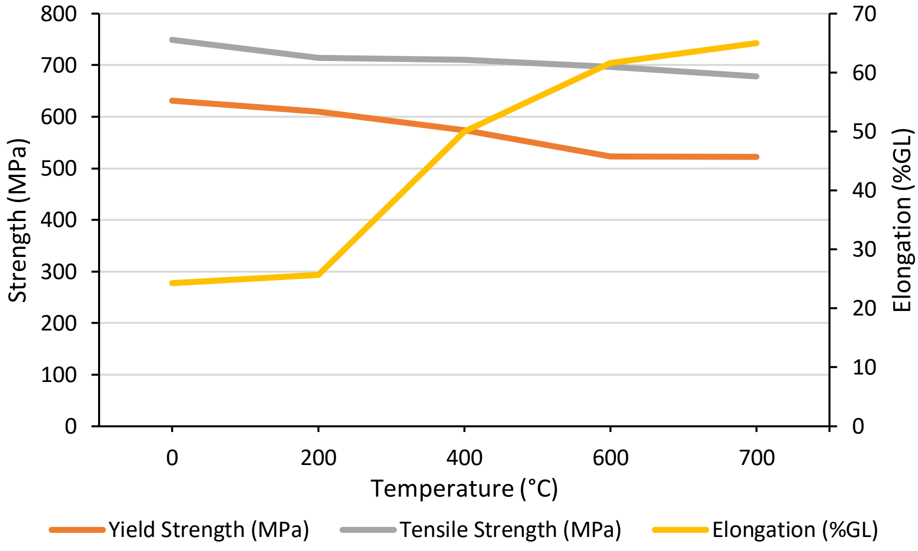

Figure 6. Effect of temperature on mechanical properties of Stainless Steel 304

3. Results and Discussion

3.1. Properties measuring methods

Tensile testing was performed using a Tensilon RTF-2350 universal testing machine (UTM) to measure the ultimate tensile strength (UTS), yield strength, and elongation of the material. Standard procedures were followed during testing to ensure accurate measurement of mechanical properties after heat treatment. Load-displacement data were recorded for comparative analysis of the material's behavior before and after heat treatment. The tensile properties of Stainless Steel 304 at various heat treatment temperatures are summarized in Table 2.

Table 2 shows that both the yield strength and tensile strength of SS304 decreased as the heat treatment temperature increased. When cooled to room temperature (after heating), the yield strength dropped to 631.16 MPa, and at a heat treatment temperature of 700°C, the tensile strength and yield strength were reduced to 522.29 MPa and 678.36 MPa, respectively. This reduction in strength is attributed to the annealing effect, which promotes recovery through dislocation rearrangement and the relief of internal stresses, resulting in material softening. Conversely, elongation improved significantly, increasing to 65.00% at 700°C compared to 24.28% in the as-received condition. This increase in ductility indicates that heat treatment enhanced the material's formability, making it easier to deform via plastic flow during the forming process. These findings confirm that pre-heating is an effective method for improving formability, albeit at the expense of reduced strength, making SS304 more suitable for dieless forming processes such as incremental sheet forming.

3.2. Microstructural evolution

Microscopic analysis was conducted using a Nikon Eclipse metallurgical microscope to investigate the material changes induced by heat treatment. The as-received Stainless Steel 304 exhibited a uniform, fine austenitic grain structure with high dislocation density. Progressive grain growth was

Table 2. Tensile properties of Stainless Steel 304 at different heat treatment temperatures

Temperature (°C)	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%GL)
0	631.16	749,18	24.28
200	610.54	714,49	25.71
400	574.37	710,62	50.00
600	522.82	697,35	61.66
700	522.29	678,36	65.00

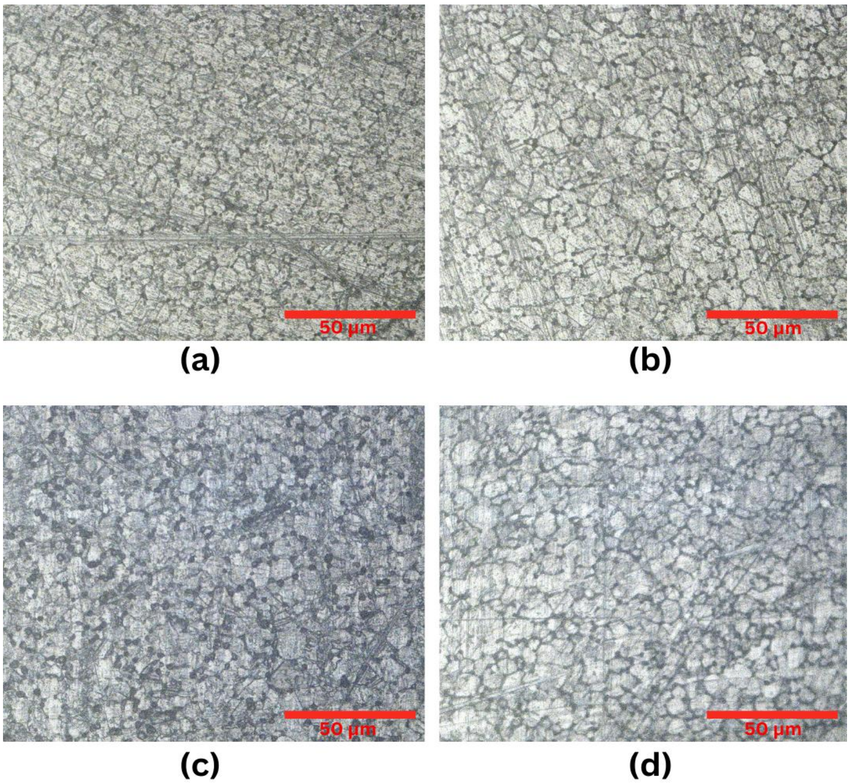

Figure 7. Microstructure morphology of heat-treated sheets (a) 0°C (b) 400°C heat treatment, (c) 600°C heat treatment, (d) 700°C heat treatment. All results at 20x magnification

observed with increasing temperature and soaking time. At 700°C, the grains became more equiaxed and homogeneous, accompanied by a noticeable reduction in dislocation density and internal stresses. This microstructural transformation enhanced the material's ability to undergo plastic deformation, as reflected in the increased ductility observed in tensile tests. Evidence of carbide dissolution at grain boundaries was also noted, contributing to reduced strain localization during forming. Mild sensitization effects were observed at intermediate temperatures but were mitigated by full annealing, which dissolved chromium carbides and restored the material's corrosion resistance. These microstructural changes and their effects at different stages of heat treatment are illustrated in Figure 7.

Moreover, the line intercept method was applied for quantitative grain size analysis, as shown in Table 3. The as-received sample exhibited a fine and stable austenitic structure, with an average grain size of 21.48 µm at 0°C. After heat treatment, grain size progressively decreased, reaching a minimum of 17.90 µm at 600°C, indicating a well-defined and uniform grain structure due to maximum recrystallization. However, grain coarsening began at 700°C, where the average grain size increased slightly to 19.73 µm due to prolonged exposure to heat. These grain size variations closely align with the microstructural evolution observed under the microscope and have a direct impact on the material's mechanical performance in forming processes, particularly regarding ductility, strength, and formability.

3.3. Forming force, springback, and geometric accuracy in ISF

Springback and geometric accuracy were evaluated by comparing the actual formed shapes to the target geometries after the Incremental Sheet Forming (ISF) process. Untreated Stainless Steel

Table 3. Tensile properties of Stainless Steel 304 at different heat treatment temperatures.

Temperature (°C)	Avg. Grain Size (µm)
0	21.48
400	20.12
600	17.90
700	19.73

Table 4. Impact of temperature on strain distribution and formability

Temperature (°C)	Grid Length (mm)	Depth (mm)	Major Strain (ε_major)	Minor Strain (ε_minor)	Cracking Status (Cracked/Uncracked)	Formability Index
0	10	30	0.16	0.06	Uncracked	0.62
200	10	40	0.20	0.02	Uncracked	0.90
400	10	50	0.25	0.03	Uncracked	0.88
600	10	60	0.36	0.08	Cracked	0.77
700	10	70	0.37	0.09	Cracked	0.75
700	10	60	0.53	0.14	Uncracked	0.73

304 sheets exhibited significant springback due to residual stresses, resulting in dimensional inaccuracies as the material partially returned to its original shape [20]. In contrast, heat-treated sheets—especially those annealed at 700°C—exhibited reduced springback. Heat treatment softened the material, enhanced plastic deformation, and minimized residual stresses. At this temperature, recrystallization and grain growth improved ductility while reducing elastic recovery. Consequently, the final parts exhibited improved geometric precision, and the heat-treated sheets became more suitable for precision applications.

3.4. Formability of the formed parts

Sheet formability was assessed in terms of maximum achievable forming angle and forming depth, which reflect the material's ability to undergo plastic deformation without failure. Heat-treated sheets showed significantly improved forming limits due to enhanced ductility and reduced residual stresses. A maximum forming angle of 54° was achieved for samples annealed at 700°C, compared to only 30°C for untreated sheets, confirming the positive effect of annealing on the material's stretchability and overall formability.

When the metal was annealed at 600°C and deformed to a depth of 60 mm, cracking occurred. Increasing the annealing temperature to 700°C and deforming the sample to 70 mm also resulted in cracking. However, when the annealing temperature was maintained at 700°C but the deformation depth was reduced to 60 mm, the sample did not crack, as shown in Figure 8. This indicates that while formability improves at elevated annealing temperatures, excessive deformation depth still leads to failure. Thus, there is a balance between deformation depth and annealing temperature that governs crack prevention. The samples illustrating these deformation modes are shown in Figure 6. These results suggest that controlled heat treatment can enhance the adaptability of stainless-steel sheets in incremental sheet forming (ISF) applications. The formability analysis of SS304 at various temperatures is presented in Table 4.

The Formability Index (FI) was also determined based on forming angle and depth, providing a normalized indication of material stretchability. The FI was calculated using the major and minor strains in the deformed areas according to the following equation:

$$\textit{Formability Index} = (\varepsilon_{major} - \varepsilon_{minor}) / \varepsilon_{major} \quad (1)$$

Here, ε_{major} and ε_{minor} represent the principal strains measured from the grid deformation pattern on the sheet surface. The Formability Index quantifies the material's stretchability in biaxial

Table 5. Surface roughness measurement of SS304 deformed samples

Trial No.	Heat Treatment	Surface Roughness (Ra, μm)	Surface Roughness after Tempering	Max Thickness (mm)	Min Thickness (mm)	Average Thickness (mm)
1	0	9.7993	8.2374	0.89	0.73	0.81
2	200	8.0866	7.7394	0.90	0.67	0.78
3	400	7.7394	7.3419	0.79	0.65	0.72
4	600	7.0397	6.4527	0.68	0.64	0.66
5	700	6.7725	6.2548	0.60	0.54	0.57
6	700	6.6190	5.4809	0.66	0.58	0.62

directions and is widely used in sheet metal forming studies. Higher FI values indicate greater formability. Table 3 presents the results of the formability analysis at different temperatures.

These findings confirm that controlled heat treatment enhances the adaptability of stainless-steel sheets in Incremental Sheet Forming (ISF) by improving formability and reducing the risk of cracking.

3.5. Surface topography

Surface roughness was evaluated to assess the influence of heat treatment on the surface quality of the incrementally formed Stainless Steel 304 sheets. The results showed that annealed sheets exhibited significantly smoother surfaces. This improvement is attributed to reduced material hardness and enhanced ductility, which facilitated smoother material flow during forming. Metallographic analysis confirmed grain refinement at elevated temperatures, supporting the observation that finer microstructures contributed to minimizing surface imperfections. Grease lubrication further reduced surface defects by lowering friction between the tool and sheet, thereby preventing tool marks and surface tearing. The best surface finish was achieved in sheets annealed at 700°C and formed under grease lubrication. Additionally, tempering at 500°C after forming further improved surface smoothness by relieving residual stresses and stabilizing the microstructure. Surface roughness (Ra) decreased from 9.7993 µm in untreated samples to 5.4809 µm after annealing at 700°C followed by tempering at 500°C. The complete surface roughness results are presented in Table 5

3.6. Comparative assessment of SS304, aluminium, and titanium for ISF

The findings of this study are consistent with previous research conducted on other metals, such as aluminium and titanium, in incremental sheet forming (ISF). Earlier studies have shown that both preheating and in-process thermal assistance in heat-assisted ISF enhance ductility, reduce forming forces, increase achievable wall angles, and improve geometric precision [21]. A similar positive effect was observed in the current study on SS304, demonstrating that controlled heat treatment has beneficial effects on formability and surface quality. While aluminium is highly formable, lightweight, and easy to process—with rapid prototyping possible and minimal tool wear [22]—it lacks the strength and corrosion resistance of stainless steel. Titanium, on the other hand, offers excellent strength-to-weight ratio and corrosion resistance, making it suitable for aerospace and biomedical applications [23]; however, its high material cost, along with the need for high-temperature forming and oxidation control, limits its broader industrial use. Stainless Steel 304 offers a practical compromise between formability, mechanical strength, corrosion resistance, and cost. Although SS304 is more difficult to cast than aluminium, it is generally easier and more economical to process than titanium. Under suitable heat-assisted ISF or post-forming conditions, SS304 can be formed into complex geometries while maintaining structural integrity and surface quality. These comparisons suggest that the choice between SS304, aluminium, and titanium in ISF is not only a matter of geometric design and part performance requirements, but also involves considerations of technical feasibility and economic viability.

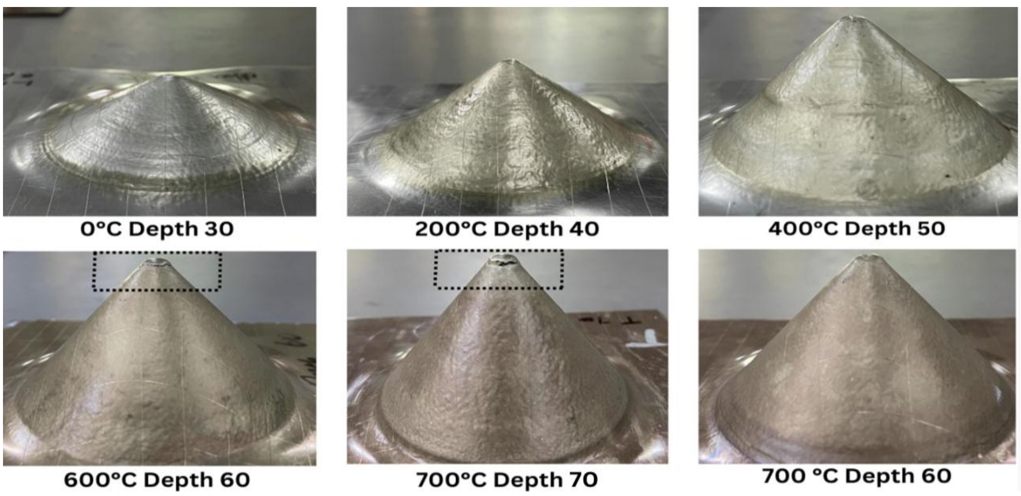

Figure 8. Conical incremental deformed shapes at different temperatures

4. Conclusions

This study systematically examined the influence of optimized heat treatment on the formability of incrementally formed Stainless Steel 304 sheets. Exposure to high temperatures during annealing, followed by tempering at 500°C, enhanced the ductility of the material and significantly improved both surface finish and geometric precision. The experimental data indicated that heat treatment at 700°C successfully increased elongation by 40.62%, reduced surface roughness from 9.80 µm to 5.48 µm Ra, and enabled a maximum forming angle of 54°, compared to only 30° for untreated sheets. Partial recrystallization was observed at lower annealing temperatures, whereas excessively high annealing temperatures led to excessive grain growth, resulting in material softening and reduced strength. The softening of forming forces in heat-treated sheets promoted better plastic flow, reduced work-hardening, and improved process efficiency. Geometric accuracy analysis further confirmed that heat-treated samples exhibited fewer shape deviations, validating the effectiveness of thermal optimization in controlling final part dimensions. These results demonstrate the potential of thermal-assisted ISF as an effective approach to increasing the formability of SS304, particularly for complex components requiring enhanced ductility and surface quality. Future research could focus on integrating real-time monitoring, advanced toolpaths, and AI-based optimization to expand the applicability of heat-assisted ISF in broader industrial practices.

Acknowledgements

The authors sincerely acknowledge Mr. Feri Ferdiansyah, Laboratory Attendant at Department of Mechanical Engineering, University of Indonesia, for his valuable assistance in conducting the experiments.

References

[1] D. Afonso, R. Alves de Sousa, R. Torcato, and L. Pires, *ISF Rapid Tooling Applications*, in *Incremental Forming as a Rapid Tooling Process*, SpringerBriefs in Applied Sciences and Technology. Cham, Switzerland: Springer, 2019. doi: 10.1007/978-3-030-15360-1_5.

[2] A. Kumar, "Critical state-of-the-art literature review of surface roughness in incremental sheet forming: a comparative analysis," *Appl. Surf. Sci. Adv.*, vol. 23, p. 100625, 2024. doi: 10.1016/j.apsadv.2024.100625.

[3] V. Kiridena, R. Verma, T. Gutowski, and J. Roth, "Rapid freeform sheet metal forming: technology development and system verification," Final Technical Report, Ford Motor Company, Detroit, MI, USA, 2018. doi: 10.2172/1433826.

[4] J. Shin, "Investigation of Incremental Sheet Forming (ISF) using Advanced Numerical and Analytical Approaches," M.S. thesis, Horace H. Rackham Sch. Grad. Stud., Univ. of Michigan, Ann Arbor, MI, USA, 2021. doi: 10.7302/2657.

[5] I. Hong and C. H. Koo, "Antibacterial properties, corrosion resistance and mechanical properties of Cu-modified SUS 304 stainless steel," *Mater. Sci. Eng. A*, vol. 393, no. 1-2, pp. 213–222, 2005. doi: 10.1016/j.msea.2004.10.032.

[6] A. Dewangan, A. Patel, and A. Bhadania, "Stainless steel for dairy and food industry: a review," *J. Mater. Sci. Eng.*, vol. 4, no. 5, pp. 1–4, 2015. doi: 10.15740/HAS/RJAHDS/6.1/66-71.

[7] R. Prasad, M. Oraon, and V. Sharma, "Exploring advancements in incremental sheet metal forming," *Eng. Res. Express*, vol. 7, no. 012401, 2025. doi: 10.1088/2631-8695/adac2d.

[8] Z. Jiang, "Process Understanding of Hybrid Multi-Step Incremental Sheet Forming," Ph.D. dissertation, Northwestern Univ., Evanston, IL, USA, 2022.

[9] G. Ambrogio, S. Bruschi, F. Gagliardi, A. Ghiotti, and L. Filice, "Surface and microstructure considerations in high speed single point incremental forming of Ti6Al4V sheets," *Key Eng. Mater.*, vol. 611, pp. 1071–1078, 2014. doi: 10.4028/www.scientific.net/KEM.611-612.1071.

[10] D. Xu *et al.*, "Enhancement of process capabilities in electrically-assisted double sided incremental forming," *Mater. Des.*, vol. 92, pp. 268–280, 2016. doi: 10.1016/j.matdes.2015.12.009.

[11] R. G. Spruit, J. T. Van Omme, M. K. Ghatkesar, and H. H. P. Garza, "A review on development and optimization of microheaters for high-temperature in situ studies," *J. Microelectromech. Syst.*, vol. 26, no. 6, pp. 1165–1182, 2017. doi: 10.1109/JMEMS.2017.2757402.

[12] J. L. Triplett Kingston, P. R. Dahlen, and P. C. Johnson, "State-of-the-practice review of in situ thermal technologies," *Groundw. Monit. Remediat.*, vol. 30, no. 4, pp. 64–72, 2010. doi: 10.1111/j.1745-6592.2010.01305.x.

[13] X. Xu, X. Li, X. Gou, Y. Li, Q. Ye, and Y. Tian, "Synergistic enhancement of strength, ductility, and toughness in a low carbon micro-alloy steel with an ultrafine-grained heterogeneous lamellar structure," *Mater. Sci. Eng. A*, vol. 878, p. 145205, 2023. doi: 10.1016/j.msea.2023.145205.

[14] M. Oliaei and R. Jamaati, "Improvement of the strength-ductility-toughness balance in interstitial-free steel by gradient microstructure," *Mater. Sci. Eng. A*, vol. 845, p. 143237, 2022. doi: 10.1016/j.msea.2022.143237.

[15] L. Fratini, F. Micari, G. Buffa, and V. Ruisi, "A new fixture for FSW processes of titanium alloys," *CIRP Ann.*, vol. 59, no. 1, pp. 271–274, 2010. doi: 10.1016/j.cirp.2010.03.003.

[16] G. Faraji, P. Yavari, S. Aghdamifar, and M. M. Mashhadi, "Mechanical and microstructural properties of ultra-fine grained AZ91 magnesium alloy tubes processed via multi pass Tubular Channel Angular Pressing (TCAP)," *J. Mater. Sci. Technol.*, vol. 30, no. 2, pp. 134–138, 2014. doi: 10.1016/j.jmst.2013.08.010.

[17] M. D. Adams, "Investigation of Temperature and Deformation Path Effects on Induced Martensite Transformation of SS304L During Double-Sided Incremental Forming," M.S. thesis, Univ. of New Hampshire, Durham, NH, USA, 2023.

[18] E. H. A. Uheida, "Development and optimisation of incremental sheet forming of titanium grade 2: process mapping," M.S. thesis, Stellenbosch Univ., Stellenbosch, South Africa, 2017.

[19] A. Kumar, S. Kumar, K. S. Rautela, A. Kumari, S. Shekhar, and M. Thangavel, "Exploring temperature dynamics in Madhya Pradesh: a spatial-temporal analysis," *Environ. Monit. Assess.*, vol. 195, no. 11, p. 1313, 2023. doi: 10.1007/s10661-023-11884-5.
[20] M. Mithu, M. A. Karim, F. A. Taj, and A. Rahman, "Predicting springback in V-bending: Effects of load, load holding time, and heat treatment on common sheet-metal forming operations," *Mater. Today Commun.*, vol. 43, p. 111668, 2025. doi: 10.1016/j.mtcomm.2025.111668.
[21] A. Kumar *et al.*, "A comprehensive review on heat-assisted incremental sheet forming," *Int. J. Interact. Des. Manuf.*, vol. 18, no. 6, pp. 3583–3601, 2024. doi: 10.1007/s12008-023-01670-5.
[22] S. Durairaj, "Effect of micro texture on the performance of cutting tools for aluminium," Ph.D. dissertation, Nanyang Technol. Univ., Singapore, 2020.
[23] R. Skiba, *Advanced Materials Engineering Fundamentals*, After Midnight Publishing, 2025.