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Submission date: 22-May-2025 05:53PM (UTC+0700)
Submission ID: 2682122241
File name: 33596-95141-1-SM_1_.docx (5.19M)
Word count: 3235
Character count: 19234

Enhancing the Forming Performance of Incrementally Formed Stainless Steel Sheet Grade 304 through Customized Heat Treatment Strategies

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Abstract

Growing demand for lightweight and high-strength components in automobile and aerospace industries has promoted the development of novel forming processes such as Incremental Sheet Forming (ISF). Although ISF offers flexibility and low costs for low-volume production, its broader industrial application is influenced by challenges such as surface roughness, springback, and forming limits. This study investigates the effects of customized heat treatment techniques on dieless forming of Stainless-Steel Grade 304 by CNC incremental forming for enhancing formability and minimizing defects. Physical tests were conducted using a CNC machine and a hemispherical tungsten carbide tool with varied metal temperatures ranging from 0 to 700°C. The metal sheets were preheated in a furnace to achieve these temperatures before forming. A detailed investigation, including tensile testing, microstructural examination, surface roughness analysis, and defect analysis, was carried out in order to compare the influence of heat treatment on deformation quality. The results demonstrate that optimization of temperature-time parameters significantly enhances ductility, reduces the springback effect, and improves formability overall. This research contributes to the innovation of effective and flexible metal forming processes by coupling heat treatment with ISF for enhancing the mechanical properties of steel sheets before and after forming. The findings provide valuable knowledge regarding the elimination of significant ISF limitations, the production of higher-quality formed components, and the expansion of potential future ISF applications in the manufacturing sector.

Keywords

Incremental Sheet Forming (ISF), Stainless Steel Grade 304, Heat Treatment, Formability, Surface Quality, Mechanical Properties

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1. Introduction

Incremental Sheet Forming (ISF) is a novel and flexible process to produce complex shapes without using dedicated dies or molds. Different from conventional forming operations, ISF is characterized by a layer-by-layer deformation mechanism, which leads to a high level of flexibility in production. The process offers several advantages, including reduction of tooling costs, enhancement of formability, and the ability to produce customized or small-series components at affordable costs[1, 2]. These advantages make ISF particularly attractive for aerospace, automotive, and biomedical applications, among others, where the demand for lightweight, high-strength, and precisely shaped components continues to grow[3, 4].

While there are numerous benefits of ISF, stainless steel, particularly Grade 304, is extremely difficult to shape. Stainless Steel 304 is widely utilized due to its satisfactory corrosion resistance and desirable mechanical properties. Its high strain-hardening behavior and low ductility, however, make it difficult to shape with the assistance of ISF[5]. Common issues with ISF of Stainless Steel 304 include excessive forming forces, high material thinning, extreme springback, and surface defects, which limit its extensive industrial application[6, 7]. These challenges must be addressed through process improvement by embracing new material processing techniques.

One of the possible ways to enhance formability of metals in ISF is through heat treatment. Heat treatment can increase ductility, reduce forming forces, and alter the microstructure of the material, thus enhancing its formability[8]. Various heat-aided ISF techniques have been researched, such as localized heating by laser beams, electrical resistance heating, and friction heating[9, 10]. These processes have been successfully implemented to improve the ISF of difficult-to-form metals like Titanium and Aluminium. However, the requirement for sophisticated heating systems increases the production complexity level and impedes their industrial use[11].

Although there has been a large amount of research in heat-assisted forming, few studies of pre-forming heat treatment effects on ISF can be found, and even fewer for Stainless Steel 304. Most of the research found in the literature has addressed in-situ heat-assisted forming by carrying out heating during deformation processing rather than optimizing the sheet material before forming[12]. The present study aims at bridging this knowledge deficiency by the methodical investigation of the effect of different pre-forming heat treatment methods on Stainless Steel 304 formability in ISF. Through manipulation of annealing temperature, soaking time, and cooling rate, their effect is evaluated on mechanical properties, forming forces, geometrical accuracy, and surface finish[13].

The findings of this research will promote ISF technology by offering important details concerning the improvement of stainless-steel formability via pre-forming heat treatment. This information will maximize ISF for commercial application to facilitate the production of high-precision stainless steel components with enhanced mechanical performance [14, 15].

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2. Methodology

2.1 Experimental Setup

The 1 mm thick sheet of Stainless Steel 304 was used for the incremental sheet forming process. The sheet was cut to 160 mm × 160 mm size and was clamped rigidly along all four edges during forming. Forming tests were performed on a CNC vertical machining center. The fixture forming zone was 100 mm × 100 mm.

A muffle furnace was used to heat the stainless-steel sheets before forming. The furnace consisted of a small, insulated chamber with an upper limit temperature of approximately 1100°C. A uniform distribution of heat was achieved using a resistance heating element, while heat loss was minimized using high-temperature ceramic fiber insulation. The temperature was controlled using a digital programmable controller with real-time display. A K-type thermocouple was used to accurately measure the temperature inside the chamber. Heat gloves were also required for manual handling, according to the safety recommendations. Once the target sheet temperature was reached and stabilized, the thermocouple was removed, and the forming 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 utilized to minimize friction during room temperature forming. Grease was used before the commencement of the forming process in both cases. The experimental setup is depicted in Figure 1.

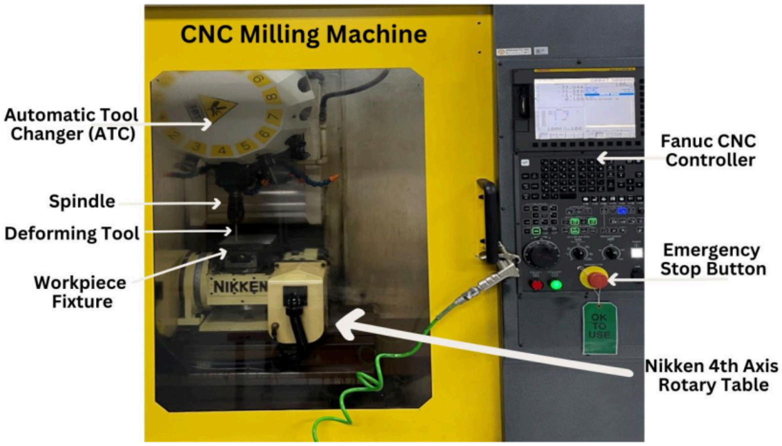

Figure 1: Experimental Setup

2.2 Experimental Design

To investigate the effects of heat treatment on the forming performance of Stainless Steel 304, the sheets were annealed at 700°C. The heating process was carried out in a muffle furnace with a maximum temperature capacity of 1100°C. The sheets were heated gradually from room temperature to 700°C in increments of 100°C (0°C, 100°C, 200°C, and so on) at a heating rate of 30°C/min. At each stage, the sheets were soaked until the target temperature was achieved. Once the desired temperature was reached, the sheets were cooled in air to room temperature. The heat treatment was carried out in a muffle furnace with a maximum temperature capacity of 1100°C.

A conical shape was designed for the forming experiments, featuring an upper diameter of 100 mm and a variable forming angle ranging from 45° to 90° through a circular arc. The forming process utilized a spiral tool path to ensure uniform material deformation and minimize defects. Additionally, as the temperature increased, the forming depth increased by 10 mm, demonstrating the influence of heat treatment on the material's formability. A tungsten carbide tool with a hemispherical head of 11 mm diameter was used. The forming parameters included a step-down size of 0.3 mm and a feed rate of 1000 mm/min. The experimental parameters are summarized in table 1.

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

2.3 Property Measuring Methods

2.3.1 Tensile Testing

Tensile testing was conducted on the Tensilon RTF-2350 Universal Testing Machine (UTM) to determine the mechanical properties of ultimate tensile strength (UTS), yield strength, and elongation. The test was conducted following standard procedure to measure accurately the strength and ductility after heat treatment. Load-displacement data were recorded and evaluated to compare the performance of the material before and after the imposed heat treatment process. The tensile properties of Stainless Steel 304 at various heat treatment temperatures are presented in Table 2.

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

Temperature (°C)	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%GL)
0	749,18	631.16	130.79
200	714,49	610.54	154.31
400	710,62	574.37	296.30
600	697,35	522.82	317.60
700	678,36	522.29	320.60

Figure 2: Tensilon RTF-2350 Universal Testing Machine

2.3.2 Metallographic Analysis

Metallography was performed using a Nikon Eclipse Metallurgical Microscope to examine the microstructural characteristics of the stainless-steel sheets. The samples were prepared using standard grinding, polishing, and etching procedures. Polishing was carried out using sandpaper of progressively finer grits, ranging from 200 up to 2000 grade, and then bleach was used to enhance the surface clarity. Etching was carried out by an electrolytic process using 15% nitric acid (HNO_3) and 85% aqua solution, stirred for 1 hour using a magnetic stirrer, along with the application of 5V during etching to obtain more surface contrast. This practice was found very helpful in revealing grain size, phase distribution, and microstructural evolution on heat treatment. The analysis allowed the assessment of material transformation and its effect on formability. The pictorial representation of metallographic process given in figure 3.

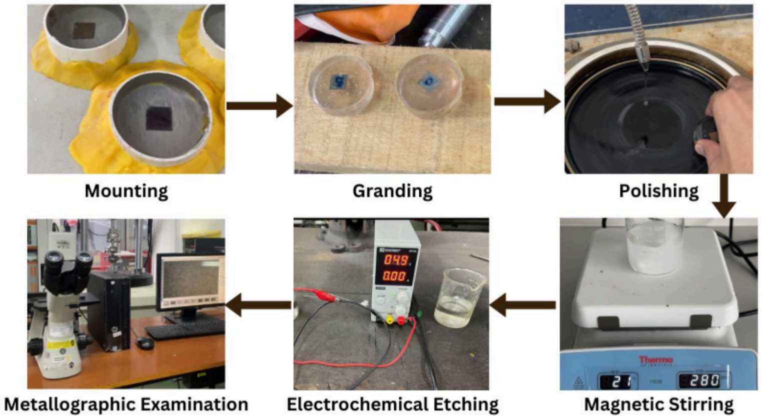

Figure 3: Metallographic steps for microstructure analysis

2.3.3 Surface Roughness Measurement

SURFCOM 2900 surface roughness tester was utilized in measuring the surface texture and quality of the stainless-steel sheets. Initial surface roughness measurement was undertaken following the deformation process to be able to conclude the influence of incremental forming on the material's surface finish. Precise measurement of surface profiles and surface roughness parameters were taken using this equipment, which play a significant role in understanding material behavior under incremental forming processes. To further study the effect of heat treatment, the deformed sample was tempered at 500°C, and surface roughness was measured again. It was discovered that the surface smoothness was improved dramatically, with customized heat treatment being proved effective at minimizing surface irregularities and enhancing formability. Surface roughness measurements were taken to assess surface quality improvement after heat treatment[16].

Figure 4: SURFCOM 2900 for surface roughness measurement

3. Results and Discussion

3.1 Properties of Heat-Treated Stainless Steel 304 Sheets

Mechanical properties of SS304 sheets were investigated before and after heat treatment. At low temperatures (0–100°C), the material showed original mechanical properties, and there was negligible thermal expansion along with no apparent microstructural change. At temperatures increasing to 200–400°C, slight softening occurred since grain boundary movement had initiated, even though overall strength was not altered.

In the range 400–600°C, partial recrystallization occurred, leading to grain refinement and improved ductility with a slight loss in yield strength. At 700°C, there was excessive grain growth with a significant reduction in tensile and yield strength and improvement in formability. Oxidation effects were more pronounced at the upper temperature range, compromising surface quality[17].

These findings highlight the temperature-dependent behavior of Stainless Steel 304, with low temperature maintaining strength, moderate temperature enhancing ductility, and high temperature leading to grain growth, with a decrease in strength but improvement in formability. The Microstructural Evolution shown in Figure 5.

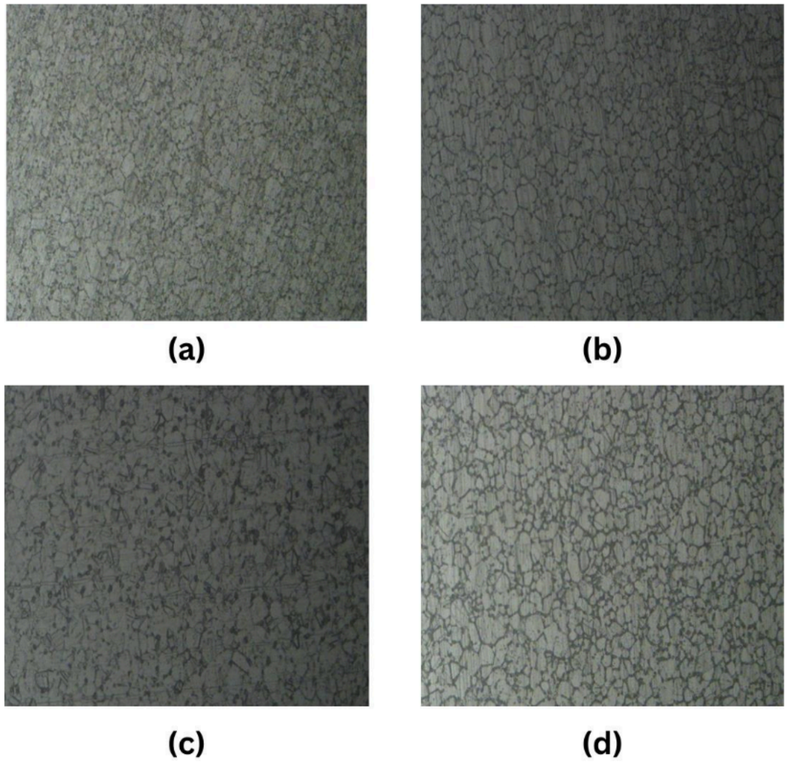

Figure 5: Microstructure morphology of heat-treated sheets (a) 0 °C (b) 400 °C heat treatment, (c) 600 °C heat treatment, (d) 700 °C heat treatment. All results at 20x Magnification

3.2 Forming Force, Springback, and Geometric Accuracy in ISF

Springback and geometric accuracy were determined in relation to actual and target shapes after the Incremental Sheet Forming (ISF) process. Untreated stainless steel 304 sheets exhibited significant springback with residual stresses, which caused dimensional inaccuracy since the material partially returned to its original shape[18]. Heat-treated sheets, particularly 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. As such, the finally produced parts had their geometric precision improved, while the heat-treated sheets became suitable for precision use.

3.4 Formability of the Formed Parts

Sheet formability was evaluated in terms of maximum forming angle and depth, which corresponded to the ability of the material to undergo plastic deformation without failure. Heat-treated sheets exhibited significantly improved forming limits due to enhanced ductility and negligible residual stresses. A maximum forming angle of 54° was achieved for the 700°C annealed samples, whereas it was 30° for untreated sheets, indicating the positive effect of annealing on the stretchability of the material.

When the metal was annealed at 600°C and deformed to a depth of 60 mm, it cracked. Increasing the annealing temperature to 700°C and deforming the sample to 70 mm also resulted in cracking. But when the annealing temperature was maintained at 700°C but the depth of deformation was reduced to 60 mm, the sample did not crack. This implies that formability increases at elevated annealing temperatures, but excessive deformation depth still leads to failure. There is a balance between deformation depth and temperature that is responsible for the avoidance of cracks. The samples illustrating these modes of deformation are shown in Figure 6. These improvements suggest that controlled heat treatment can enhance the adaptability of stainless-steel sheets in incremental sheet forming (ISF) applications. Formability Analysis of SS 304 at Various Temperatures given the Table 4.

Table 3: 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

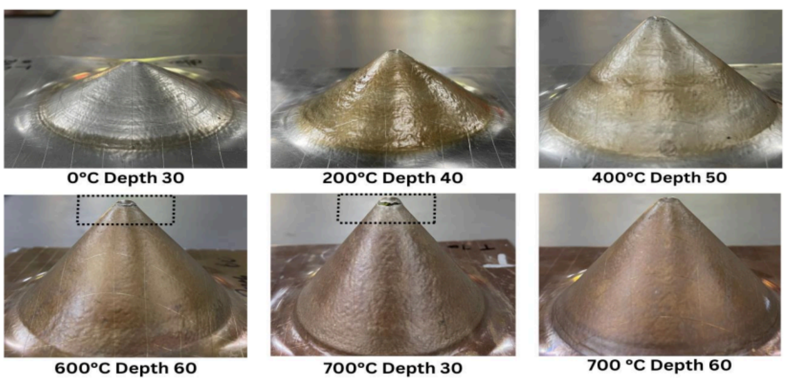

Figure 6: Conical Incremental Deformed Shapes at different Temperatures

3.5 Surface Topography

Surface roughness was measured to determine the influence of heat treatment on the surface finish of the formed sheets. The outcome revealed that annealed sheets exhibited smoother surfaces due to grain refinement, which reduced surface imperfections. Grease lubrication during forming also lowered surface flaws by reducing friction and avoiding excessive wear of material. Best surface quality was realized on 700°C annealed sheets under grease lubrication due to optimized heat treatment that improved the material surface quality. Further, samples after deformation also went through a 500°C tempering treatment that continued to ensure surface smoothness through stress relieving and better microstructure refinement, yielding higher surface roughness and overall finish. Surface Roughness measurements shown in the Table 4.

Table 4: 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

4. Conclusion

This work investigated systematically the effect of optimized heat treatment methods on Incrementally Formed Stainless Steel 304 sheets' formability. Optimized annealing temperatures and tempering at 500°C significantly enhanced material ductility, geometric accuracy, and surface quality. Experimental results showed that pre-forming heat treatment greatly reduced forming forces, minimized springback, and enhanced formability. The best performance was obtained in sheets annealed at 700°C, which possessed the maximum forming limits and minimum surface defects, and additional improvement in surface roughness was observed upon tempering at 500°C.

Under different conditions of annealing, it was found that reduction in temperatures results in partial recrystallization and greater temperatures result in excessive grain growth, thus weakening the strength. Reduction of the tool force when specimens are subjected to heat highlights the greater flow of material and reduced work hardening effects, making the process more efficient and sustainable. In addition, geometric accuracy analysis demonstrated that controlled heat treatment reduces shape deviations, and hence ISF is more viable for industrial applications.

These findings provide valuable information to improve ISF processes for stainless steel to make them more suitable for aerospace, automotive, and biomedical applications. Additional research needs to focus on integrating real-time process monitoring, advanced forming techniques, and AI-based optimization techniques to enhance the process efficiency and industrial relevance of Incremental Sheet Forming for stainless steel materials.

Acknowledgements

I sincerely acknowledge Feri Ferdiansyah Lab Attendant for their valuable assistance in conducting the experiments.

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