

RESEARCH ARTICLE

An Experimental Investigation on the Mechanical Behavior of Type-304 Stainless Steel at Cryogenic Temperatures

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ABSTRACT – An investigation of the mechanical behavior of AISI 304 steel at cryogenic temperatures, including the effects of plastic deformation-induced phase transformation, is essential for optimizing its use in deep cryogenic engineering applications. In this research, tensile experiments on AISI 304 steel were conducted at ambient and cryogenic temperatures using a liquid nitrogen setup, with various strain rates applied under quasi-static. The influence of heat treatment, strain rate, and testing temperature on the mechanical behavior is examined. The obtained results indicate a negative rate sensitivity in both ultimate strength and ductility of the steel under quasi-static conditions at room temperature, with heat treatment improving strength at low strain rates and significantly enhancing ductility at higher strain rates. Stress-strain behavior at cryogenic temperatures differs markedly from that at room temperature. The material exhibits secondary hardening and an increase in ultimate strength from 600 MPa at room temperature to about 1200 MPa at cryogenic temperatures. Meanwhile, the ductility remains largely unchanged at higher strain rates. XRD and microscopic examination indicate the presence of both austenite and martensite phases at room temperature, but at cryogenic temperatures, the austenite completely transforms into α' -martensite in areas of significant plastic deformation. This α' -martensitic transformation is crucial for enhancing strain hardening and ultimate strength at low temperatures. Importantly, the martensitic phase evolution does not increase hardness or reduce ductility, thereby improving the fracture characteristics of SUS304 steel at cryogenic conditions.

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1. INTRODUCTION

The development of liquefied natural gas (LNG) storage systems has advanced significantly, with advances in cryogenic storage tanks and LNG carriers enabling the efficient and safe transport of LNG at extremely low temperatures [1-2]. Modern LNG carriers and storage tanks are designed to withstand the harsh cryogenic environment, typically around -163°C [3-4], where material performance is vital to operational safety and reliability. Austenitic stainless steels, particularly types 304 and 316, are widely used in these fields due to their outstanding corrosion resistance and superior mechanical performance at cryogenic temperatures [5-8]. However, the mechanical behavior of these steels at such low temperatures differs significantly from that at ambient conditions [9-11]. Type 304 austenitic stainless steel is representative of the TRIP (transformation-induced plasticity) steel class, which exhibits a strain-induced martensitic transformation mechanism [12-14]. The formation of α' -martensitic phase during plasticity deformation plays a key role in enhancing both the material's strength and ductility [15-17]. Meanwhile, the phase transformation is highly dependent on the environmental temperature during plastic deformation [18-19]. The phase transformation is predicted to occur more prominently at low temperatures [20, 21], thereby enhancing the mechanical properties of the steel. Therefore, an investigation of the mechanical properties of AISI 304 austenitic stainless steel at cryogenic temperatures, along with consideration of phase transformations induced by plastic deformation, is essential for optimizing the use of 304 stainless steel in deep cryogenic engineering applications.

In recent years, numerous investigations have been conducted on the mechanical properties of 300-series austenitic stainless steel at low temperatures. The mechanical behavior of type-304 and 316 stainless steel obtained from uniaxial tensile tests at cryogenic temperature was examined by Lee et al. [22]. Then, Park et al. [23] indicated that austenitic stainless steel exhibits nonlinear hardening behavior below 223K. According to this study, the yield and ultimate strengths of some AISI 300 austenitic stainless steels increase with decreasing temperature. After that, the influences of pre-strain magnitude on the mechanical properties of AISI 304L at low temperatures were taken into account by Kim et al. [24]. Moreover, Kim et al. [25] also demonstrated the nonlinearity of the strain-hardening curve at low temperatures for AISI 316L, 321, and 347 stainless steel. In the study of Fernández-Pisón et al. [26], the flow and fracture of AISI 304L and 316L steel at liquid nitrogen temperature and at liquid helium temperature were examined. It was reported that a significant increase in flow stress can be obtained by decreasing the testing temperature. More recently, Li et al. [27] examined the flow behavior of 316H stainless steel over a wide range of cryogenic temperatures and found that the martensitic transformation is promoted at lower temperatures. Furthermore, the study by Pham et al. [28] indicated that although the role of heat treatment in the alteration of the hardness of this steel was not clearly observed, the stability of

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the austenitic phase before and after heat treatment exhibited a distinct change. Al-Bakri et al. [29] reported that heat treatment has an influence on the strength of type-304 stainless steel due to the stability of the parent phase. Consequently, it is predicted that heat treatment may affect the martensitic phase transformation during tensile testing, thereby altering the mechanical properties of the steel.

Although several studies have been conducted on the mechanical behavior of 300-series austenitic stainless steel in cryogenic temperature conditions, these studies primarily focus on the influence of experimental temperature on the strength and ductility of materials, with few providing evidence related to metallurgical aspects. As a result, the mechanism of the mechanical properties of the material at low temperatures has been insufficiently explained. There remains a critical research gap in understanding its behavior under cryogenic temperatures, particularly in relation to martensitic transformations occurring during plastic deformation. While prior heat treatment is known to considerably influence the stability of the parent phase, its specific effects on strain-induced martensitic transformation at low temperatures of type-304 stainless steel have not been comprehensively investigated. Addressing these gaps is essential to enhance the reliability and safety of AISI 304 stainless steel components used in cryogenic environments, such as liquefied natural gas carriers and cryogenic pressure vessels. Therefore, an investigation on the influence of martensitic transformation in type-304 steel under low-temperature conditions, combined with the effects of prior heat treatment, is inevitable.

The objective of this study is to conduct tensile experiments for both as-received and heat-treated specimens made of 304 steel under varying strain rates at both ambient and cryogenic temperatures in quasi-static loading conditions. Low-temperature tensile testing is performed in a liquid nitrogen environment. The effects of heat treatment, strain rate, and testing temperature on the strength and ductility of the material evaluated from the obtained stress - strain curves are discussed. The microstructural analysis using metallographic microscopy and scanning electron microscopy (SEM), as well as X-ray diffraction (XRD), is performed to evaluate the formation of martensitic phase during plastic deformation. Finally, the metallurgical observations are used to explain the mechanisms behind the observed mechanical properties of type-304 stainless steel.

2. METHODOLOGY

The chemical composition of the type-304 stainless steel employed in this research is presented in Table 1. There are two different types of specimens used for microstructural observation and for tensile testing. The former type is in the form of a rectangular block with dimensions of 20x20x10 mm. Figure 1 indicates dimensions of specimens used in the tensile test, following the ASTM-E28/E8M-09 standard. The specimens are cut from sheet metal using an electrical discharge machining wire cut.

Table 1. Chemical composition (wt%)

Chemical element	C	Cr	Ni	Si	Mn	Co	N	V
Wt. (%)	0.053	18.8	8.03	0.31	1.17	0.22	0.113	0.103
Chemical element	P	Al	Cu	S	Mo	Ti	W	Fe
Wt. (%)	0.023	0.001	0.02	0.004	0.007	0.001	0.007	Blan.

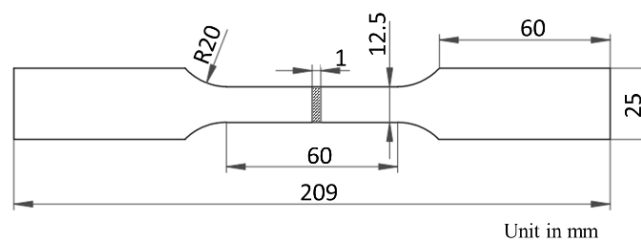


Figure 1. Specimen used in tensile test

According to previous studies [12, 28], the heating temperature for heat treating type-304 stainless steel is 1050°C, followed by water quenching. With this heat treatment process, the resulting microstructure is a homogeneous austenite phase, which tends to favor transformation into martensite through the strain-induced phase transformation mechanism during subsequent plastic deformation. Therefore, this heat treatment process was applied in the current study for the same material. The heat treatment of the investigated steel was carried out by heating to 1050°C in an electrical resistance furnace (Nabertherm model LT5/14/B410), followed by a 30-minute holding time and quenching in water. The specimens were ground, polished, and etched with an acid solution of HCl and HNO₃ with a ratio of 1:3, respectively, for microstructural observation using a metallographic microscope GX41. The fracture morphology of the specimen after tensile testing was analyzed by electron scanning technique (SEM TM4000Plus). A X-ray analysis equipment (XRD, X'Pert Pro) was used to investigate the phase composition of the steel after tensile testing. The hardness measurement is achieved by using a hardness tester, Rockwell Mitutoyo model HR-430MR.

The tensile test is performed by the WA-1000C conventional tensile testing machine. The experimental setup for tensile testing under deep cryogenic conditions is shown in Figure 2. The specimen is placed inside a liquid nitrogen chamber. Liquid nitrogen from a container is delivered into the chamber through a piping and valve system. After securing the specimen in the liquid nitrogen chamber and closing the chamber lid, the specimen is firmly clamped at both ends using the hydraulic clamping grips of the tensile testing machine. Liquid nitrogen is introduced into the chamber to ensure that both the experimental sample and the interior of the chamber are uniformly cooled for approximately 10 minutes prior to the tensile test. Temperature measurement of the specimen inside the liquid nitrogen chamber was conducted using a thermocouple device of the TK62 model to monitor the temperature throughout the experiment. During the tensile test, liquid nitrogen was continuously supplied through a valve system into the chamber to maintain the testing temperature of -195°C within the furnace chamber. The experiment is conducted at various crosshead displacement speeds of 5, 25, 50 and 150 mm/min. Then, the strain rates are converted to 0.0014, 0.0069, 0.0139 and 0.0417 s^{-1} , respectively. The testing arrangement is described in detail in Table 2.

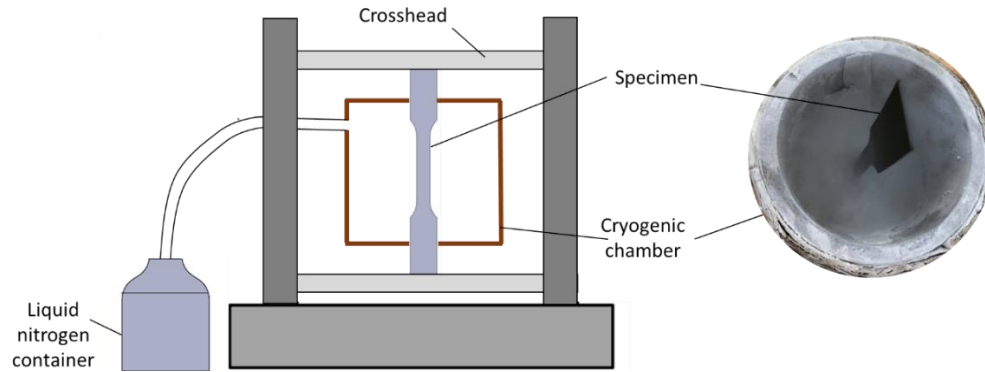


Figure 2. Experimental arrangement for tensile test at cryogenic temperature

Table 2. Testing conditions

Specimen symbol	Heat treatment	Tensile test temperature
HT-room	Yes	Room temperature
noHT-room	No	Room temperature
HT-cryogenic	Yes	Cryogenic temperature
noHT- cryogenic	No	Cryogenic temperature

3. RESULTS AND DISCUSSION

3.1 Mechanical Behavior

Mechanical tensile tests were carried out at multiple strain rates for specimens that underwent heat treatment at room and deep cryogenic temperatures. Experiments were repeated at least three times to validate the experimental outcomes. Figure 3 illustrates the engineering stress–engineering strain curves obtained at a representative strain rate of 0.0069 s^{-1} under room-temperature and cryogenic conditions for the specimen without heat treatment. The repeatability of the experimental results can be illustrated in this figure. Moreover, the result of the engineering stress–engineering strain curve for SUS304 stainless steel is quite similar to that in the investigation of Kundu et al. [30] conducted under comparable strain rate conditions at ambient temperature. As a result, the reliability of the experiment can be confirmed.

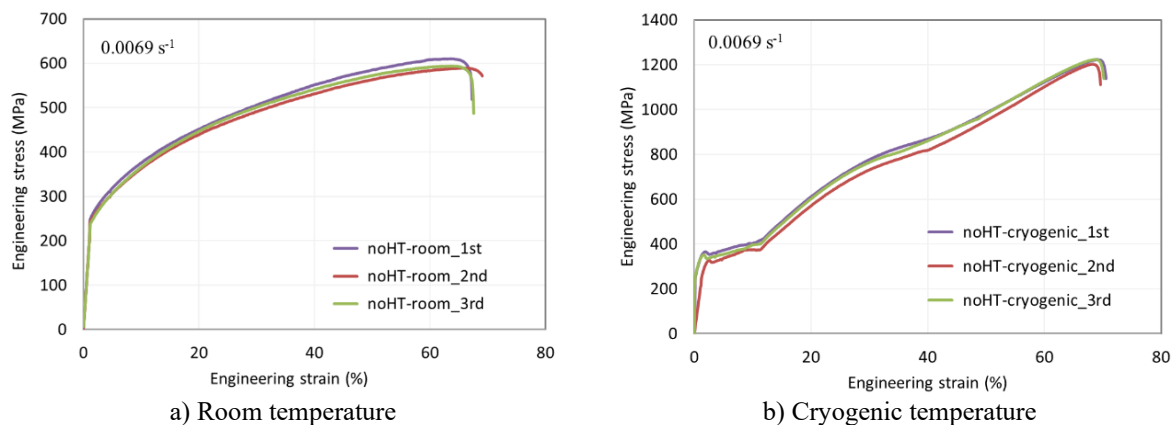


Figure 3. The repeatability of experimental results for engineering stress – engineering strain curve obtained in tensile test at room and cryogenic temperatures

Figure 4 shows the engineering stress – engineering strain obtained at different strain rates in the testing environment of room temperature for specimens without and with heat treatment. The influence of strain rate on the elastic limit is not clearly observed. Meanwhile, a significant difference can be seen in the value of the maximum stress values and the strain at maximum stress at various strain rates. Remarkably, the highest strain measured at the lowest applied strain rate surpasses that at increased strain rates for samples regardless of heat treatment. The ductility of the material can be discussed through the maximum value of the engineering strain. Therefore, from this figure, the ultimate strength as well as ductility of the material decrease at higher strain rates within the investigated range of strain rates for the cases with or without heat treatment. This phenomenon can be attributed to the higher martensite volume fraction observed at the lowest strain rate, facilitated by the strain-induced phase transformation mechanism during tensile testing of AISI 304 stainless steel. The rise in temperature associated with plastic deformation at higher strain rates may suppress martensite formation, thereby lowering its volume fraction. The formation of the martensite phase enhances both the ductility and strength of the material. Consequently, the highest value of strain as well as ultimate strength is observed at the lowest strain rate within the investigated range.

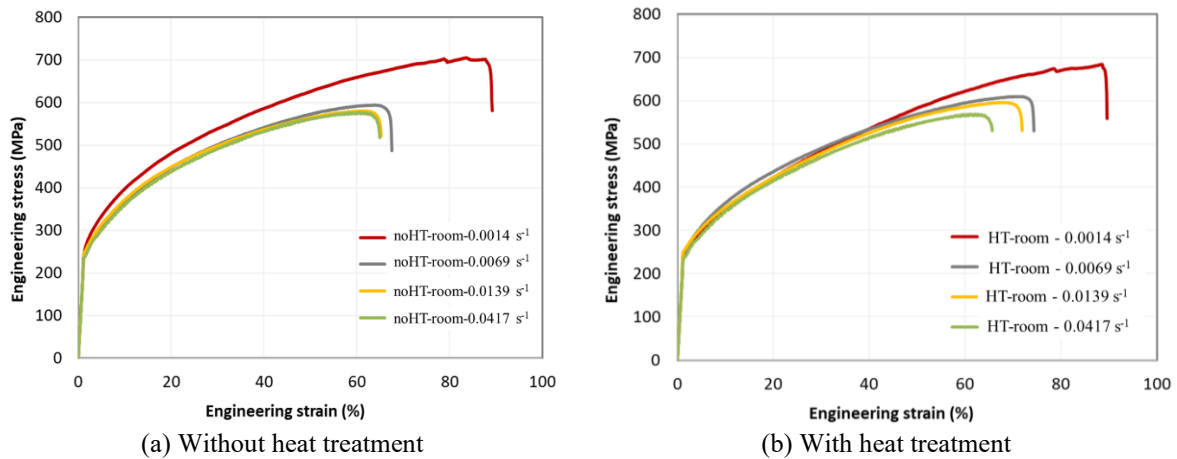


Figure 4. Engineering stress – engineering strain curve obtain in tensile test at room temperature at different displacement rates before and after heat treatment

Table 3 summarizes the mean values and standard deviations of ultimate strength and maximum strain derived from three tests conducted at room temperature, as illustrated by the stress-strain curves.

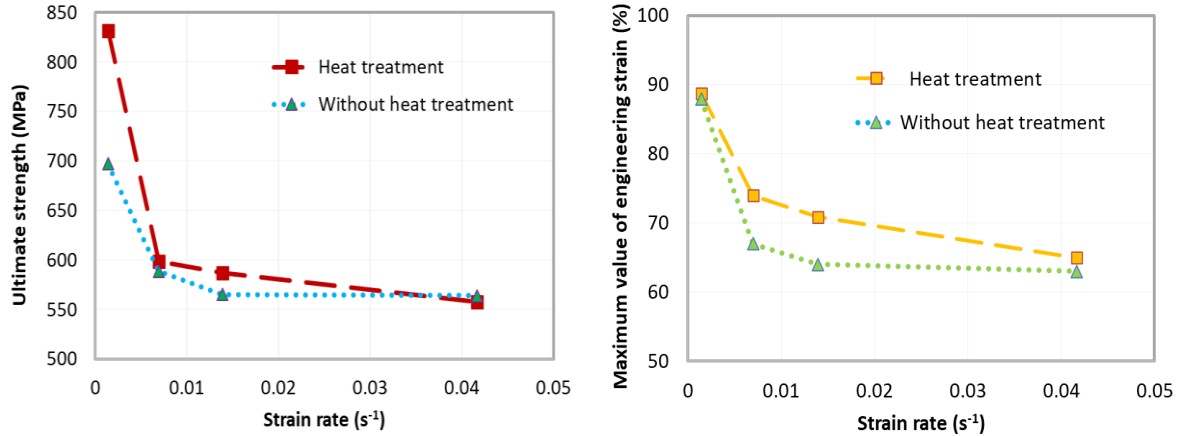
Table 3. Average values of three tests and the standard deviation of ultimate strength and maximum strain at room temperature

Strain rate (s ⁻¹)	With heat treatment		Without heat treatment	
	Ultimate strength (MPa)	Maximum strain (%)	Ultimate strength (MPa)	Maximum strain (%)
0.00139	831.2±0.51	88.76±1.18	697±8.71	87.92±1.19
0.00694	598.5±3.88	73.93±0.75	588.75±10.96	67±1.52
0.01389	586.97±8.20	70.86±1.51	565±8.42	64±1.57
0.04167	557.6±5.48	64.94±0.87	564±5.24	63±0.64

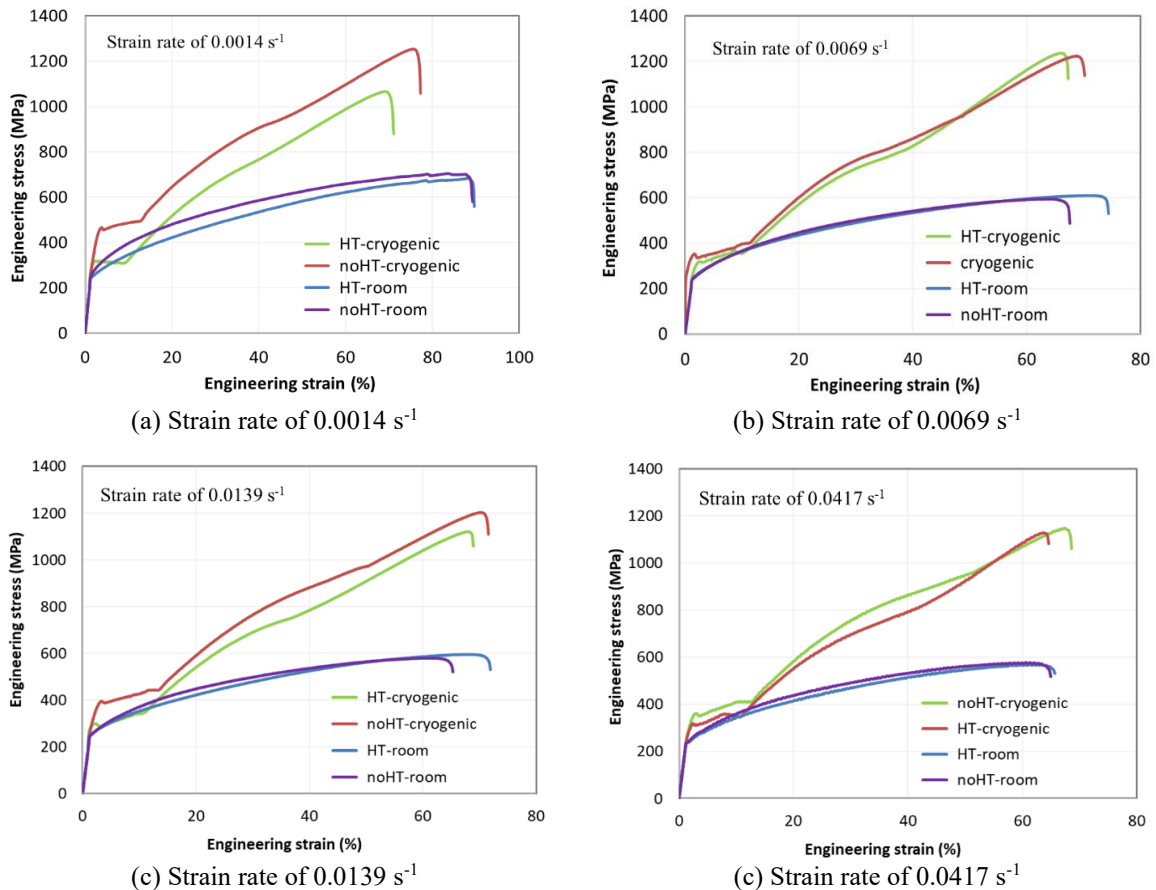
From the results of Table 3, the rate-sensitivity of the mechanical properties of SUS304 stainless steel at room temperature with heat treatment effect can be obtained in Figure 5. A negative rate-sensitivity in the ultimate strength as well as the maximum value of the engineering strain is indicated in this figure. At a low strain rate of 0.0014 s⁻¹, the effect of heat treatment on the ultimate strength is clearly noticeable. Meanwhile, the ultimate strength values obtained at higher strain rates seem to be independent of heat treatment. On the other hand, the ductility of the material at the lowest strain rate in both cases, before and after heat treatment, is quite similar. As the strain rate increases, the heat-treated cases show a slight increase in the maximum value of engineering strain. Overall, the strength of the steel might be improved through the heat treatment at very low strain rates, while a considerable enhancement of the ductility because of the heat treatment process can be observed at higher strain rates in quasi-static conditions.

Figure 6 presents the engineering stress – engineering strain curve at different strain rates obtained in tensile test at room and cryogenic temperatures with the influence of the heat treatment. In general, the stress-strain curves obtained at cryogenic temperatures have a significant difference from those at room temperature. The phenomenon of secondary hardening can be observed at low temperatures in the examined range of strain rate, as found in past studies [24, 25] for other grades of 304-series of austenitic stainless steel. Obviously, the yield strength of the material is significantly improved when the material is tested at cryogenic temperatures compared to results at room temperature. This enhancement is most pronounced at low strain rates without heat treatment. Meanwhile, the strain hardening of the

material increases substantially as the testing temperature decreases, resulting in a significant improvement in the ultimate strength of SUS304 steel. All cases of investigated strain rate show an almost double value of the ultimate strength compared to that at room temperature. At the same time, the ductility of the material, which can be discussed through the maximum value of engineering strain, shows an inconsiderable difference in the results tested at different temperatures for each strain rate, except for the case of a strain rate of 0.0014 s^{-1} . A significant decrease in ductility when tested at cryogenic temperature can be observed compared to ductility at room temperature at the lowest strain rate within the examined range of strain rate, especially for the material after heat treatment.



(a) Rate-sensitivity of ultimate strength (b) Rate-sensitivity of ductility
 Figure 5. Rate-sensitivity of mechanical behavior of SUS304 stainless steel at room temperature



(a) Strain rate of 0.0014 s^{-1} (b) Strain rate of 0.0069 s^{-1}
 (c) Strain rate of 0.0139 s^{-1} (c) Strain rate of 0.0417 s^{-1}
 Figure 6. Engineering stress – engineering strain curve at different strain rates obtained in tensile test at room and cryogenic temperatures

Figure 7 shows the relationship of engineering stress – engineering strain in tensile test at cryogenic temperature at different displacement rates before and after heat treatment. The influence of strain rate on the mechanical properties of steel can be clearly observed in both heat-treated and non-heat-treated cases at a cryogenic environment. Within the examined strain rate range, the case of the lowest strain rate shows the highest values of both ductility and strength, including yield strength and ultimate tensile strength for the non-heat-treated specimen. In contrast, for the heat-treated

steel, a lower value of ultimate tensile strength is observed at the lowest strain rate. In the case of heat treatment, the ultimate tensile strength is highest at a strain rate of 0.0069 s⁻¹ in cryogenic temperature conditions.

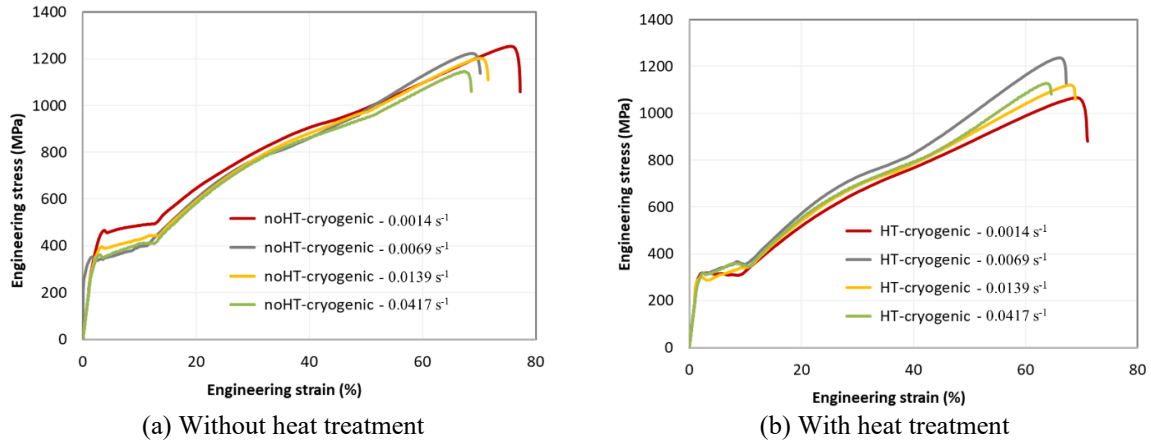


Figure 7. Engineering stress – engineering strain curve obtained in tensile test at cryogenic temperature at different strain rates without and with heat treatment

The data in Table 4 represent the mean and standard deviation of maximum strain recorded during tensile testing at cryogenic temperature, based on three repetitions.

Table 4. Average values of three tests and the standard deviation of maximum strain at cryogenic temperature

Strain rate (s ⁻¹)	Without heat treatment	With heat treatment
0.00139	76.4±1.45	70.13±0.18
0.00694	69.19±0.88	66.72±1.34
0.01389	70.96±1.12	68.71±1.12
0.04167	68.06±0.21	64.22±1.07

From the results of Table 4, the rate-sensitivity of the maximum value of engineering strain at cryogenic temperature at different displacements without and with heat treatment is presented in Figure 8. A similar tendency can be observed in both heat-treated and non-heat-treated material. The value of strain at maximum stress shows a negative-rate sensitivity, except for the case of a strain rate of 0.0139 s⁻¹.

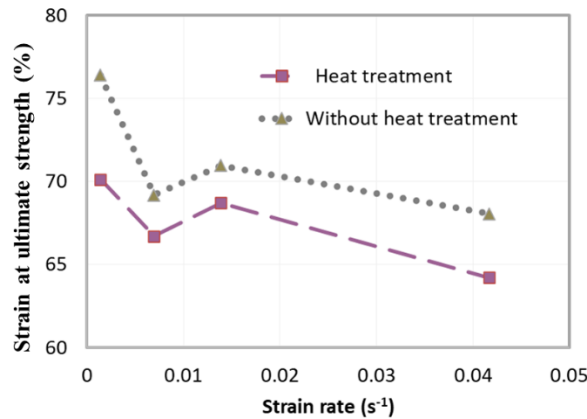


Figure 8. Rate-sensitivity of strain at ultimate strength at cryogenic temperature at different displacements without and with heat treatment

Figure 9 illustrates the specimen after tensile testing and the locations for hardness measurements. The hardness of the material was measured at two positions, 1 and 2, corresponding to the location where the specimen is clamped on the clamping grip of the tensile testing machine and the region near the fracture, respectively. At position 1, the specimen is tightly clamped and experiences almost no displacement during the tensile testing process. Meanwhile, a significant plastic deformation occurs during the tensile test at position 2.

The result of hardness measurement at various strain rates in ambient temperature and cryogenic conditions, along with the influence of heat treatment, is shown in Figure 10. From this figure, it is observed that the hardness results for various strain rates are quite similar to each other. The hardness values at positions 1 and 2 have a significant difference, with the higher values belonging to the latter case. At room temperature, the hardness at position 2 is approximately 20 HRA higher than at position 1. At the same time, the hardness difference between the two positions is around 10 HRA

for tensile testing in a cryogenic environment. The variation in hardness between the two measurement positions can be explained by the work-hardening phenomenon due to the plastic deformation of the material. Additionally, it is predicted that the martensite phase transformation might be more pronounced in the central region of the specimen, where significant plastic deformation occurs due to the strain-induced martensitic transformation mechanism. The formation of the martensitic phase in this region may be the cause of the increase in the hardness of 304 stainless steel.

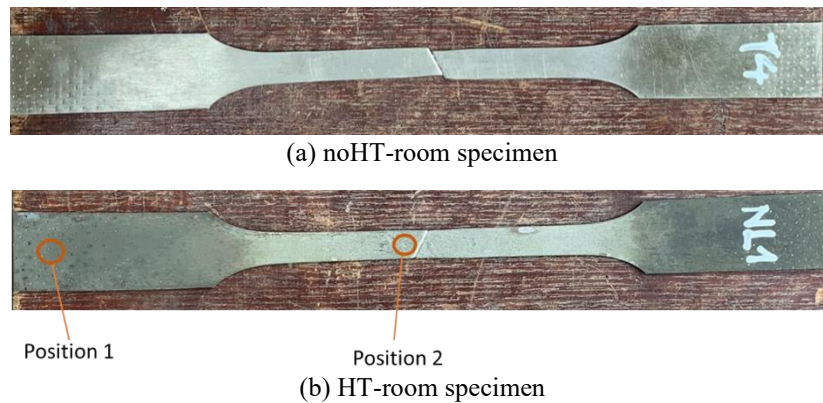


Figure 9. Photograph of specimen after tensile test: (a) noHT-room specimen, (b) HT-room specimen with the position for hardness measurement

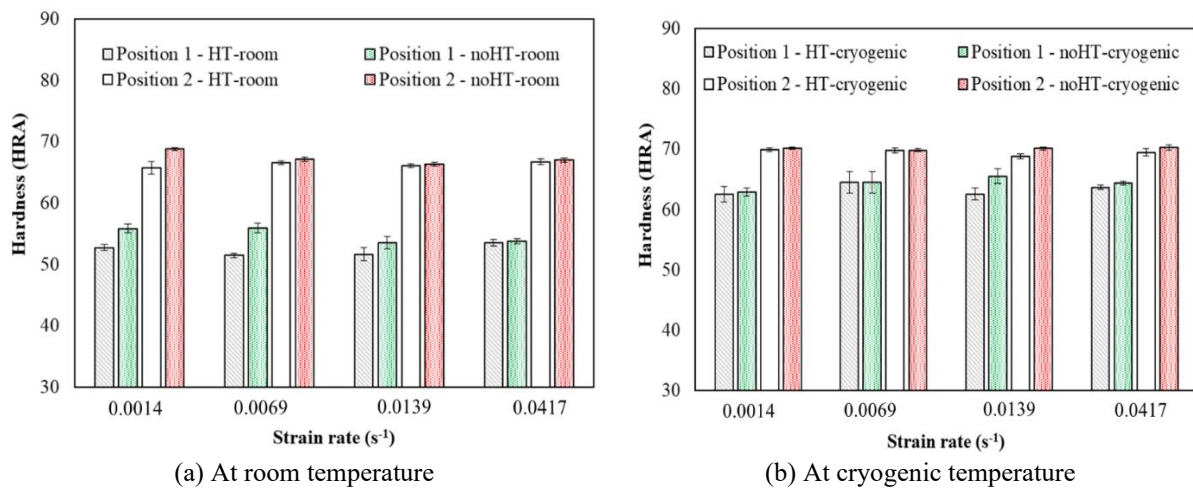


Figure 10. Hardness of the material at different positions after tensile test

3.2 Microstructure Evolution

Microstructures of type-304 austenitic stainless steel as-delivered and after heat treatment before the tensile test are presented in Figure 11. The microstructure of the steel in the as-delivered state mainly consists of the austenite phase. Additionally, the presence of the ferrite phase and several slip bands is observed. The austenite phase exhibits indistinct grain boundaries and a nonuniform grain size distribution in the microstructure before heat treatment. In contrast, after heat treatment, the steel displays a homogeneous microstructure composed entirely of the austenite phase, with austenite grains that have well-defined grain boundaries and significantly larger grain sizes compared to before heat treatment. Some slip bands are also observed. The presence of these slip bands can be explained by plastic deformation of the surface layer during polishing for microstructure observation. Notably, the ferrite phase no longer appears in the microstructure of the steel after heat treatment. This is explained by the dissolution of ferrite into austenite during the heating of the steel up to 1050°C during heat treatment. Consequently, martensite formation is prevented during quenching as a result of the stable austenite phase. These findings are consistent with previous studies on stainless steel [28]. Although the heat treatment process does not induce a phase transformation, the morphology and grain size of austenite change significantly compared to the pre-heat treatment state. According to the study by Takaki et al. [31], larger austenite grain sizes promote the martensitic phase transformation during plastic deformation. Therefore, despite the absence of new phase formation during heat treatment, this process is predicted to be necessary to facilitate the martensitic phase transformation due to the strain-induced martensitic transformation mechanism during subsequent plastic deformation. Indeed, thanks to the more favorable martensitic phase transformation during the tensile test, the heat-treated cases generally exhibited better strength and ductility compared to the non-heat-treated case, as observed in Figure 5.

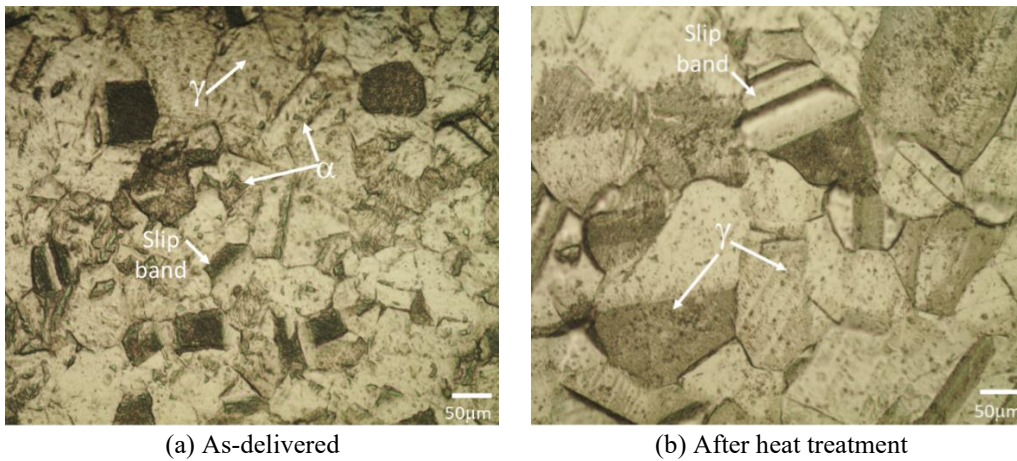


Figure 11. Microstructure of the steel as-delivered and after heat treatment before tensile test

Microstructure of the steel after tensile test at ambient condition at position 2 in the cases without and with heat treatment is indicated in Figure 12 at a strain rate of 0.0069 s^{-1} . A significantly larger amount of α' - martensitic phase after tensile test with large plastic deformation can be observed compared to before plastic deformation, as shown in Figure 11. Furthermore, after tensile testing at room temperature, the material still exhibits an austenitic phase, despite undergoing plastic deformation. Thus, it can be considered that during tensile testing at room temperature, the austenitic phase in SUS304 steel might transform into martensite due to the mechanism of strain-induced martensitic transformation. The presence of the martensitic phase at position 2 leads to a slight increase in hardness in this region compared to position 1, where the steel undergoes minimal plastic deformation.

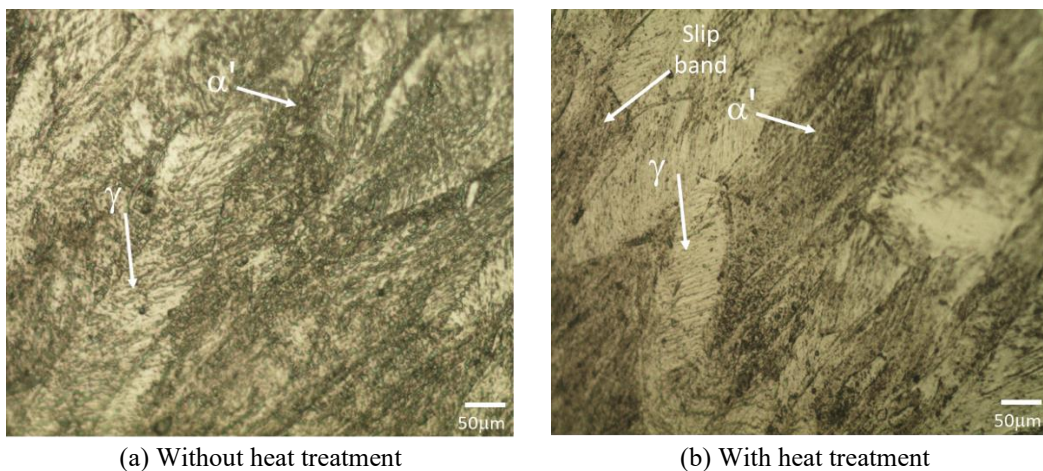


Figure 12. Microstructure of the steel after tensile test at ambient conditions at position 2 in the cases without and with heat treatment

Figure 13 presents the microstructure of the steel at position 2 after a tensile test at cryogenic temperature in the cases without and with heat treatment at a strain rate of 0.0069 s^{-1} . This figure shows that only the martensitic phase can be observed at position 2 when the specimen is subjected to tensile testing at low temperature. The martensitic phase can be formed on slip bands that are clearly oriented in the direction of the tensile load. Hence, the phase change to martensite due to plastic deformation in SUS304 steel tends to be more favorable under low-temperature conditions. As a result, the mechanical properties of the steel, particularly the strain hardening as well as ultimate strength, are significantly improved at cryogenic temperatures, as presented in Figure 6. Meanwhile, the α' - martensitic phase does not significantly increase the hardness of the material, as can be seen from Figure 10. Interestingly, despite the notable enhancement in the amount of martensitic phase formed during low-temperature tensile testing, which markedly enhances the strength of the material, this martensitic phase does not reduce the ductility, as shown in Figure 6. As a result, it is predicted that the fracture toughness of the steel might be considerably improved, as its strength increases while its ductility remains largely unaffected.

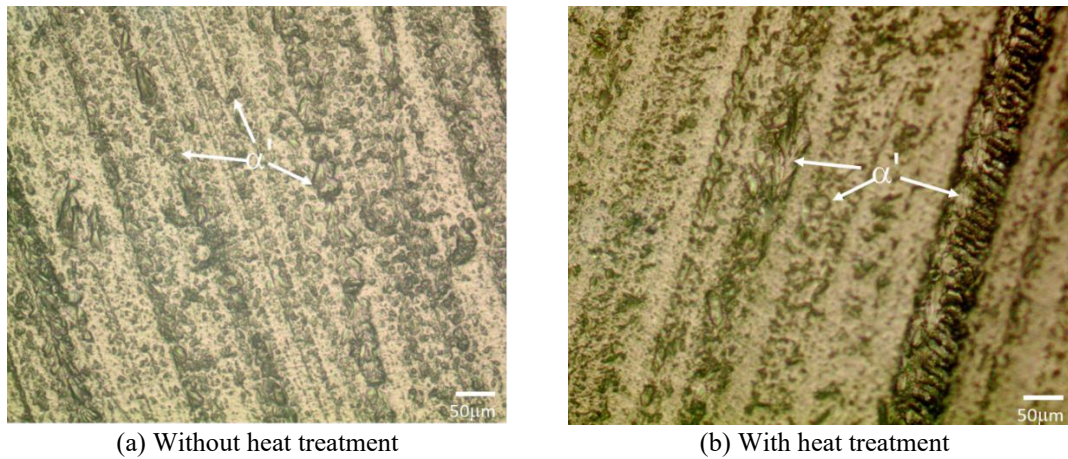


Figure 13. Microstructure of SUS304 at position 2 after tensile test at cryogenic temperature in the cases without and with heat treatment

Figure 14 shows the XRD results for the specimen after the tensile test at different environmental temperatures at position 2 at a strain rate of 0.0069 s^{-1} . The X-ray diffraction pattern indicates the presence of both austenite and martensite phases in the specimen tested at room temperature. Meanwhile, only α' -martensite phase is observed at the location of a significant amount of plastic deformation in the low-temperature tensile test. From this result, the entire austenite phase in SUS304 stainless steel has completely transformed into martensite during the tensile test at cryogenic temperature in both heat treatment and no heat treatment cases. There is a notable consistency between the XRD results and the observed microstructure for the specimen tested at room temperature and cryogenic temperature, as presented in Figures 12 and 13, respectively.

From the obtained results, it is evident that the effect of cryogenic temperature on the microstructure and mechanical properties of SUS304 austenitic stainless steel can be clearly observed. At cryogenic temperatures, the austenite phase completely transforms into α' -martensite, particularly in regions experiencing significant plastic deformation during tensile testing. This martensitic transformation contributes to secondary hardening, resulting in an almost twofold increase in ultimate tensile strength compared to room temperature. Despite this substantial strength improvement, the ductility of the material remains largely unaffected at higher strain rates. Additionally, the presence of the martensitic phase enhances strain hardening without significantly increasing hardness or diminishing ductility, which collectively leads to improved fracture behavior under cryogenic conditions.

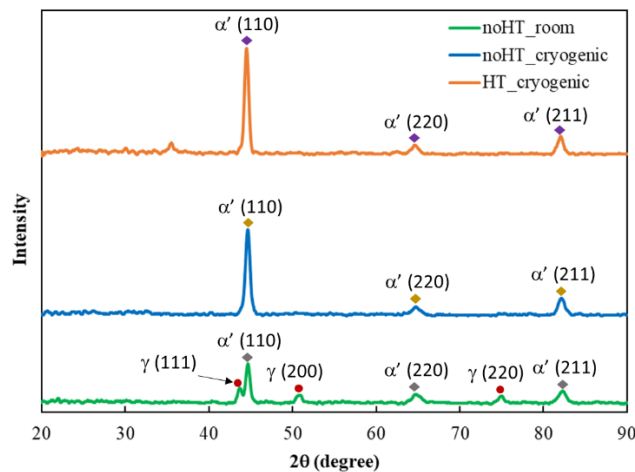


Figure 14. X-ray diffraction pattern of 304 stainless steel after tensile test at position 2

Figure 15 indicates SEM observation of the fracture surface after tensile test at different temperatures at a strain rate of 0.0069 s^{-1} . The ductile dimples and some voids can be clearly seen in the fracture surface in all investigated cases. Therefore, it can be considered that the fracture mechanism of type-304 austenitic stainless steel under tensile stress is ductile fracture. Interestingly, as demonstrated by X-ray diffraction results and microstructural observations above, specimens tested under deep cryogenic temperatures, which were entirely composed of martensitic phase, still exhibited ductile fracture. This indicates that martensite is generated from austenite in tensile testing, which might not affect the ductility of the material. This result can be used to explain the slight changes in ductility when testing at low temperatures compared to testing at room temperature. As a result, the transformation to martensite occurring at cryogenic temperature in the studied steel not only significantly enhances the ultimate strength and strain hardening but also does not adversely affect its ductility, leading to a significant improvement in the fracture characteristics.

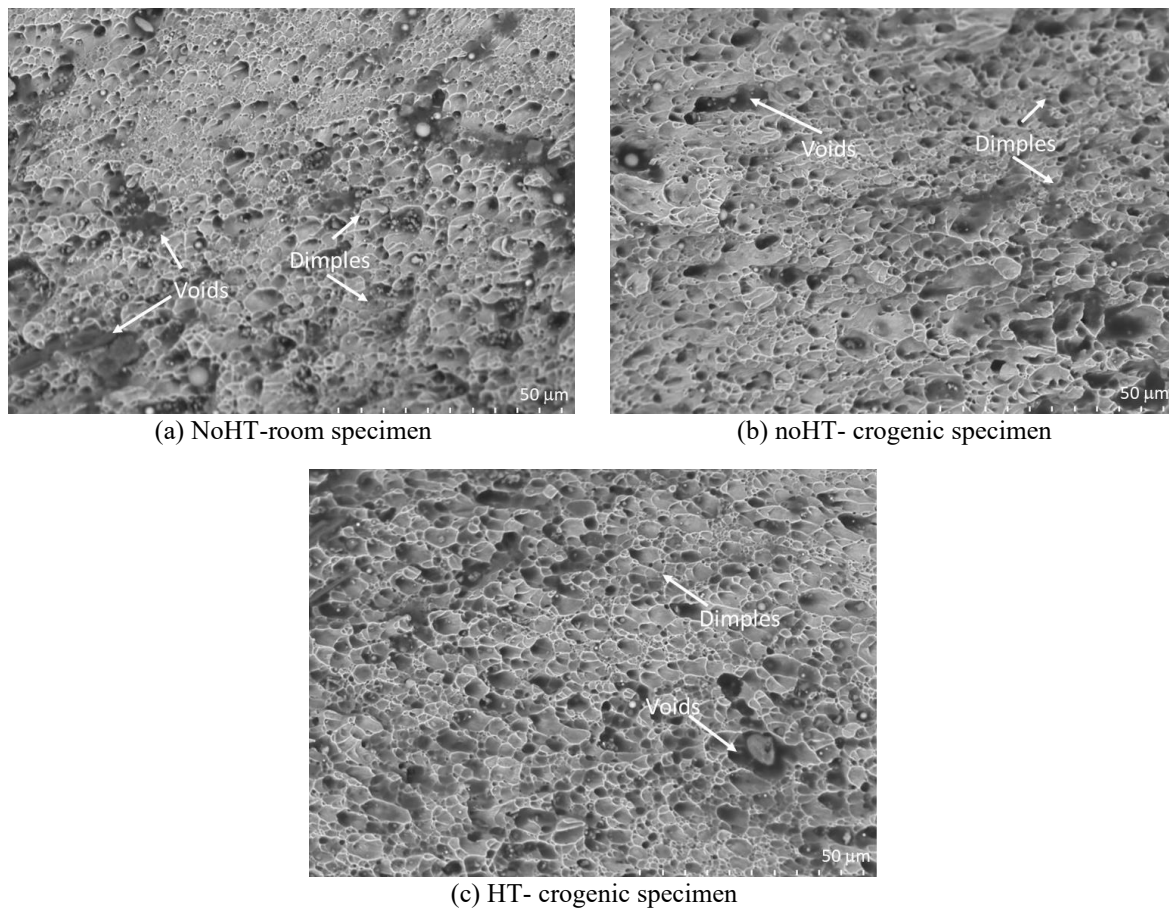


Figure 15. SEM observation of the fracture surface after tensile test at different temperatures

4. CONCLUSIONS

In this study, tensile tests were performed on SUS304 austenitic stainless steel in both as-received and heat-treated conditions, at ambient and cryogenic temperatures in liquid nitrogen, and at different strain rates under quasi-static loading. The conclusions can be summarized as follows.

- Negative rate sensitivity in the ultimate strength and ductility of the investigated material can be observed in quasi-static testing at room temperature. The strength of the steel can be improved through heat treatment at very low strain rates, while a significant enhancement in ductility can be observed at higher strain rates during tensile tests conducted at room temperature.
- The stress-strain curves obtained at cryogenic temperatures differ significantly from those at room temperature. The phenomenon of secondary hardening can be observed in 304 stainless steel at low temperatures. Moreover, all cases of investigated strain rate show an almost double value of the ultimate strength compared to that at room temperature. At the same time, the material's ductility shows an insignificant difference in results obtained at different temperatures at a higher strain rate.
- The tensile specimen examined at ambient temperature exhibits coexistence of the austenite and martensite phases, as indicated by XRD and microscopic studies. Meanwhile, only the martensite phase is observed at the location of significant plastic deformation during the tensile test at cryogenic temperature. Obviously, the entire austenite phase in SUS304 stainless steel has completely transformed into α' - martensite during the tensile test at cryogenic temperature in both heat-treated and as-received states. The formation of α' - martensitic phase in the steel significantly contributes to improving the mechanical characteristics, notably enhancing its work hardening as well as ultimate strength at cryogenic temperatures. Meanwhile, the α' - martensitic phase does not significantly increase the hardness nor reduce the ductility of the steel, leading to a significant improvement in the fracture characteristics.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

Hang Thi Pham– Conceptualization, Methodology, Writing - review and editing, Supervision.

Thong Chung Nguyen– Data curation, Formal analysis and investigation.

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