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Division I

ANNEALING-TEMPERATURE EVALUATION OF TYPE 316 STAINLESS STEEL BASED ON MATERIAL TENSILE TEST

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ABSTRACT

Thermal elastic plastic analysis is widely used to estimate weld residual stress profiles in a welded structure. Temperature-dependent stress-strain relations are required as mechanical properties. It is important to clarify the annealing temperature, at which the effects of prior work hardening are removed, to simulate the stress history in a welded structure. In this study, we experimentally evaluated the annealing temperature of type 316L austenitic stainless steel. First, a tensile pre-strain load was applied to each tensile test specimen until the amount of stress on the cross section reached 450 MPa at room temperature, and the stress-strain curve in the pre-strain process was measured. The amount of strain when the stress reached 450 MPa was about 0.1. Then the pre-strain load was unloaded, the specimens were removed from the tensile test machine, and the specimens were subjected to heat treatment. Two temperature history conditions were set: Case A, in which the heating rate slowed just before reaching the maximum temperature, and Case B, in which the heating rate was constant. Then subsequent tensile loading was applied again on these pre-strained and heat-treated specimens, and the stress-strain curves were measured at room temperature. A tensile test without heat treatment was also carried out. When no heat was applied, plastic strain occurred when the stress reached 450 MPa, i.e., the subsequent yield stress was 450 MPa. In contrast, when heat was applied, the subsequent yield stress decreased. The subsequent yield stress was the initial yield stress when the maximum temperature was higher than 1200ºC and lower than 1300ºC. A linear interpolation was used to determine the annealing temperature at which the subsequent yield stress was equal to the initial yield stress, which was found to be 1240ºC.

INTRODUCTION

To estimate the reliability of welded structures, it is important to predict residual stress profiles. Thermal elastic plastic analyses have been widely used to determine the residual stress profiles (Ogawa, 2008, Yanagida et al., 2009). The stress-strain history is complex in the welding process of a structure. For example, during the heat-input process when a structure is being welded, compressive yield follows compressive stress around the heat-input region of the structure. Furthermore, during the cooling process after the heat-input, the compressive plastic strain generated by the yield results in tensile stress. Both processes, i.e., compressive yield and the following compressive plastic strain, that occur in the heat-input process and the tensile stress that occurs in the cooling process are repeated during the multi-pass welding process. To analyse residual stress profiles in such welded structures accurately, it is important to know the stress-strain relation (constitutive law) from room temperature to melting temperature. Tensile tests from room temperature to 800ºC were previously carried out on austenitic stainless steel to determine the stress-strain relation for thermal elastic plastic analysis (Yanagida, 2008). The material properties were determined for the mixed-hardening law, but the annealing temperature, at which the effects of prior work hardening are removed, was not examined in the previous study.

Muransky et al. (2015) investigated the sensitivity of plastic strain and weld residual stress profile predictions. The sensitivity of the numerical solution was examined when isotropic, kinematic, and isotropic-kinematic (mixed) plastic theory is used under identical high-temperature annealing conditions.

The annealing temperature, i.e., the temperature at which the subsequent yield stress is set to the initial yield stress, can be determined from the elevated temperature test. In this study, the annealing temperature of type 316L austenitic stainless steel was experimentally evaluated in terms of the subsequent yield stress change.

TESTED MATERIAL AND TENSILE TEST SPECIMEN

The material used for the test was type 316L austenitic stainless steel. The material composition listed in the mill test report is shown in Table 1. The material was held at 1060ºC for 2 minutes as solution heat treatment, followed by rapid cooling by water quenching. Tensile test specimens were taken from a pipe with an outer diameter of 268 mm and a thickness of 15 mm, with the direction of the center axis of the specimen coinciding with the direction of the center axis of the pipe, and the center axis of the specimen was centered in the thickness of the pipe.

The shape and the dimensions of the specimen are shown in Figure 1. Tensile test specimens with a parallel section diameter of 6 mm were fabricated. Two protrusions with a triangular cross section were formed on the parallel section, with a 30-mm distance between the protrusions. The displacement between the protrusions was measured with a differential displacement transducer during a pre-straining tensile test and a subsequent tensile test, and strain was determined by dividing the measured displacement by the initial distance between the protrusions. The tensile load on the tensile test specimen was also measured by a load cell, and stress was determined by dividing the measured load by the initial cross-sectional area of the tensile specimen.

Table 1: Listed value on mill test report of type 316L austenitic stainless steel test specimen.

Alloying elements	C	Si	Mn	P	S	Cr	Ni	Mo	B	N	C+N
Wt%	0.015	0.47	1.41	0.019	0.001	18.00	11.56	2.11	0.015	0.11	0.12

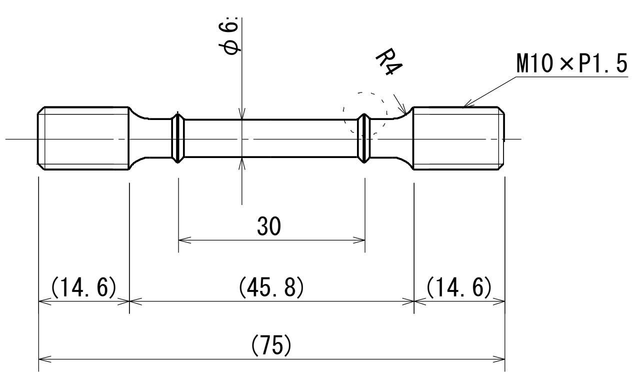


Figure 1. Shape and dimensions of tensile test specimen.

MATERIAL TEST CONDITIONS

In this study, the annealing temperature was evaluated through tensile tests. The annealing temperature is the maximum temperature of the heat treatment in which the subsequent yield stress increased by plastic deformation is reset to the initial yield stress. To determine the annealing temperature, pre-straining by a tensile loading and heat-treatment were carried out on the specimens, and then the tensile tests were carried out. The details of the procedure are described below.

First, the tensile specimens were pre-strained at room temperature, which increases their yield stress. The increased yield stress after pre-straining is called the subsequent yield stress, in contrast to the initial yield stress before pre-straining. Then the tensile specimen was removed from the tensile testing machine and heat-treated by rapid heating and rapid cooling under stress-free conditions. The tensile test was then carried out again at room temperature by applying a tensile load until the specimen ruptured. The annealing temperature was evaluated by comparing the initial yield stress measured during the pre-straining process with the subsequent yield stress measured during the subsequent tensile test which was carried out after the heat treatment.

Nine test conditions were set. One test specimen was prepared for each condition. First, a tensile load was applied to each tensile specimen until the nominal stress reached 450 MPa at room temperature. The resulting plastic strain applied as pre-strain was about 0.1. Then each tensile test specimen was removed from the tensile test machine after unloading, and heat treatments were carried out, the conditions of which are listed in Table 2.

One of the nine tensile specimens was not heat treated and is marked "No heating" in Table 2. In this condition, after pre-straining, the specimen was subjected to tensile load until it ruptured at room temperature. The other eight tensile specimens were subjected to heat treatment under rapid heating conditions in which the maximum temperature ranged from 900ºC to 1300ºC, followed by rapid cooling. In the heat-treatment process, two temperature history conditions were set, shown as Case A and Case B in Table 2. Figures 2(a) and 2(b) schematically show the temperature histories of Case A and Case B, respectively.

In Case A, the maximum temperature was set to five conditions from 900ºC to 1300ºC at intervals of 100ºC. In this study, controlling the maximum temperature is crucial, so in each condition, the heating rate was set to 70ºC/s until the temperature was lower than 100ºC of the set maximum temperature during the heating process, and then the heating rate was set to 15ºC/s so that cooling could start without fail when the temperature reached the set maximum temperature. The effect of annealing became more pronounced because of the longer time (about 6.7 seconds) due to a decrease in the heating rate. The cooling rate was set to -140ºC/s during the cooling process.

In Case B, the maximum temperature was set to three conditions from 1100ºC to 1300ºC at intervals of 100ºC. In each condition, the heating rate was 70ºC/s up to the maximum temperature during the heating process. In Case B, the maximum temperature was reached within 10ºC in the actual heat-treatment process, although there was a concern that the temperature would not match the set maximum temperature. The cooling rate was set to -140ºC/s during the cooling process.

Rapid heating was performed by induction heating while monitoring the temperature of the specimen, and rapid cooling was performed by gas injection immediately after induction heating was stopped. The conditions of Case A and Case B were set as the maximum possible value of the machine settings used for the heat treatment.

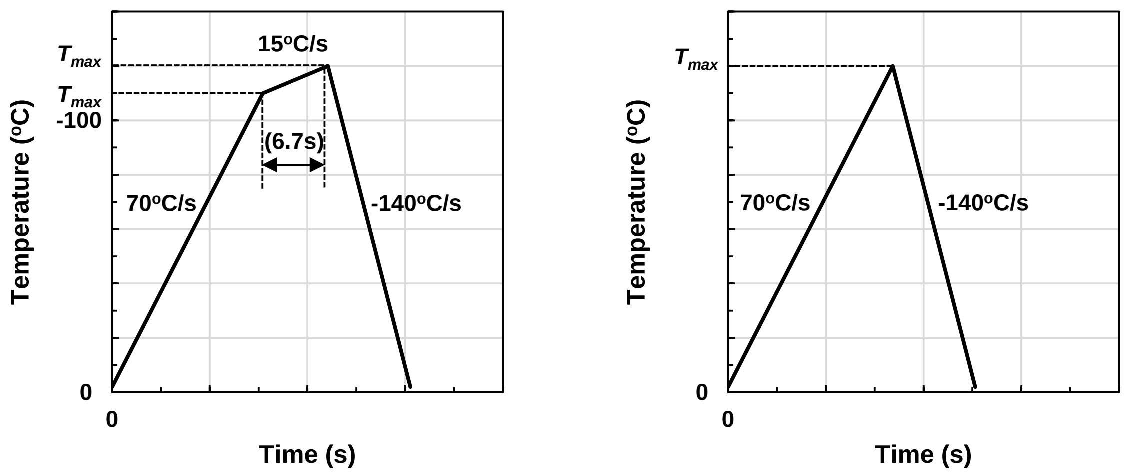
After the pre-strained specimens were treated with heat, the subsequent tensile test was carried out. The displacement between the protrusions of the tensile test specimen was measured with a displacement meter, and the strain was calculated. Strain was also measured using strain gauges in the subsequent tensile tests. Tensile load on the tensile test specimens was also measured by a load cell of the tensile test machine. The stress on the cross section of the tensile test specimen was calculated. The subsequent yield stress was determined as 0.2% proof stress on the measured stress-strain curves.

The annealing temperature of steel is known to be affected by the magnitude of the applied plastic deformation, the maximum applied temperature, and the holding time at the maximum temperature. In our study, we only assumed one pre-strain condition. The effect of the amount of pre-strain will be investigated in future work. In addition, material properties such as metallurgical structure and hardness of the tensile specimens after pre-straining, heat treatment, and rupture by subsequent tensile test are also important in clarifying annealing behaviour but were not examined in this study. The evaluation of these effects is also a future issue.

Table 2: Heat treatment conditions for pre-strained tensile test specimens.

Maximum temperature: T_{max} (°C)		20	900	1000	1100	1200	1300
Heat process condition	No heating	✓	−	−	−	−	−
	Case A	−	✓	✓	✓	✓	✓
	Case B	−	−	−	✓	✓	✓

✓: tensile test was carried out, −: tensile test was not carried out



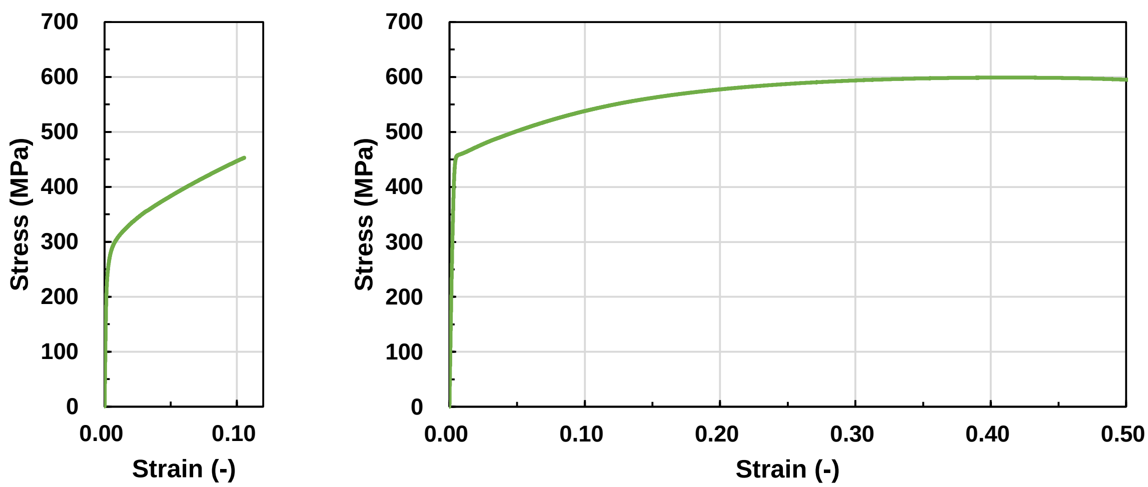
(a) Heating condition: Case A (b) Heating condition: Case B

Figure 2. Temperature histories during heating process of pre-strained specimens.

MATERIAL TEST RESULTS

Pre-straining and subsequent tensile test results under no heating condition

Figure 3 shows the measurement results of a stress-strain curve under the no heating condition listed in Table 2, in which no heat treatment was carried out after the pre-straining process. Figure. 3(a) shows the stress-strain curve during the pre-straining process in which the applied stress increased to 450 MPa. Tensile loading was stopped when the stress reached 450 MPa and unloaded until the specimen reached a stress-free state. Figure 3(b) shows the stress-strain curve during the subsequent tensile test. The strain value at the start of the subsequent tensile loading is shown as zero. Plastic deformation occurs when the stress reaches 450 MPa after the start of subsequent tensile loading. Then the increment of the strain for the increment of the stress increased substantially. In other words, if no heat treatment was carried out after pre-straining, the subsequent yield stress, which was measured in the subsequent tensile test, is equal to the stress value at the start point of the unloading during the pre-straining process.

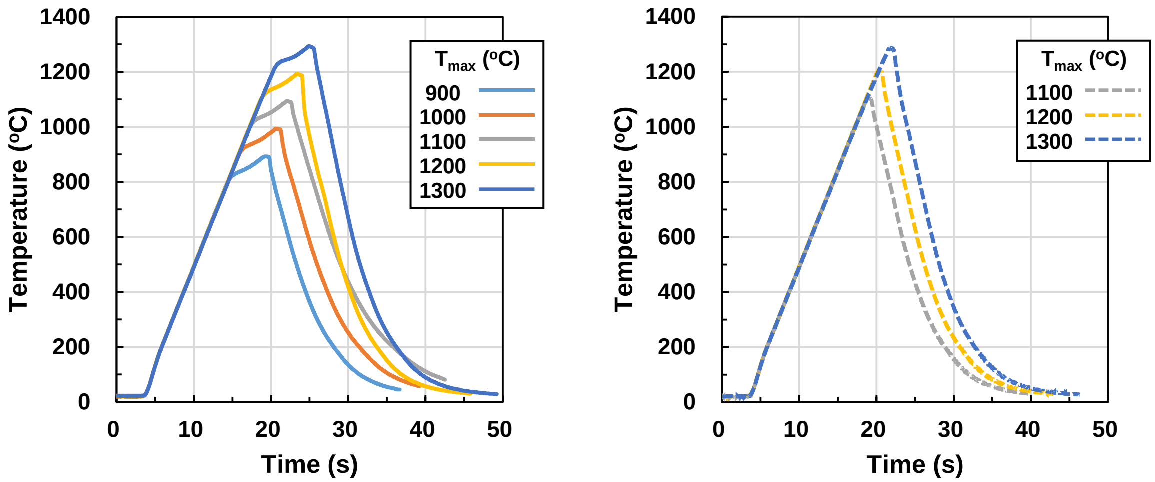


(a) Pre-straining process (b) Subsequent tensile test process

Figure 3. Stress-strain curve in no heating condition.

Temperature history measurement results during heat-treatment process

Figure 4 shows the resulting temperature measurements of the pre-straining tensile test specimens during the heat-treatment process of the rapid heating and the rapid cooling in the stress-free condition. Figure 4(a) shows the measurement results of Case A. The heating rate was 70°C/s until the temperature was lower than 100°C of the set maximum temperature during the heating process, and then the heating rate was set to 15°C/s up to the maximum temperature of each specimen. Then the cooling rate was set to -140°C/s during the cooling process. The temperature histories based on the conditions of Case A were attained in this heat treatment process. Figure 4(b) shows the measurement results of Case B. The heating rate was 70°C/s during the heating process, and the cooling rate was set to -140°C/s during the cooling process. The temperature histories based on the conditions of the Case B were also attained in this heat treatment process.



(a) Heating condition A

(b) Heating condition B

Figure 4. Temperature histories during heat-treatment process of pre-strained specimens.

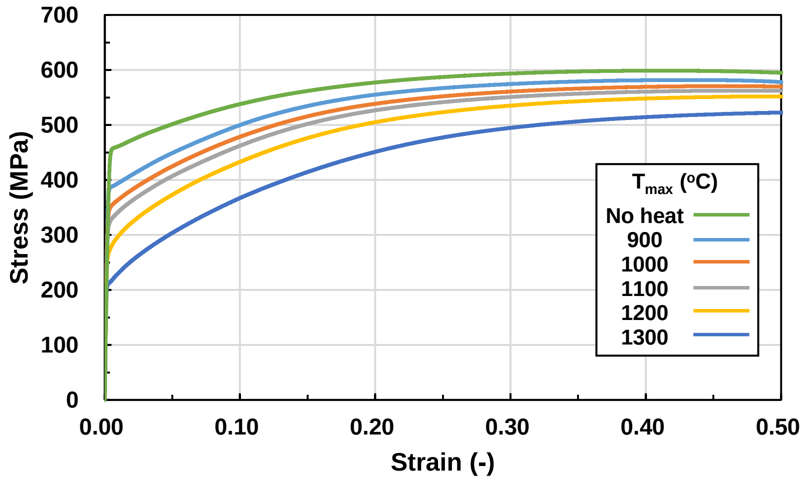
Subsequent tensile test results and annealing temperature evaluation

The results of the subsequent tensile test using the pre-strained tensile specimens subjected to heat treatment are shown in Figure 5. Figure 5 (a) shows the measurement results of the test specimens subjected to the heat-treatment conditions of Case A. Figure 5 (b) shows the measurement results of the test specimens subjected to heat-treatment of Case A and Case B with a maximum temperature of 1100ºC, 1200ºC, and 1300ºC. In each measurement result, the subsequent yield stress was lower than the 450 MPa, which is the stress at the start point of unloading during the pre-straining process.

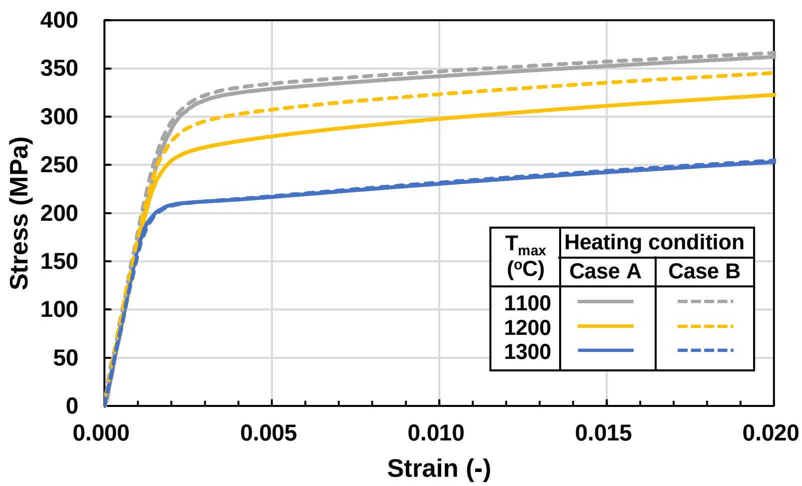
Both stress-strain curves during the pre-straining process and that during the subsequent tensile test process are shown in Figure 6. The subsequent yield stress was higher than the initial yield stress when the maximum temperature was 1100ºC as shown in Figures 6(1-a) and 6(1-b). Similarly, the subsequent yield stress was higher than the initial yield stress when the maximum temperature was 1200ºC as shown in Figures 6(2-a) and 6(2-b), but the difference is smaller than that shown in Figures 6(1-a) and 6(1-b). On the other hand, the subsequent yield stress was lower than the initial yield stress regardless of the heat-treatment condition when the maximum temperature reached 1300ºC as shown in Figures 6(3-a) and 6(3-b).

A comparison of the subsequent yield stress measured from the tensile tests after heat treatment is shown in Figure 7. The initial yield stress measured during the pre-straining process was 267 MPa. As mentioned above, the subsequent yield stress measured from the subsequent tensile test was higher than the initial yield stress at the maximum temperature of 1200ºC. In contrast, the subsequent yield stress measured from the tensile test after heat treatment was lower than the initial yield stress at the maximum temperature of 1300ºC. Accordingly, the temperature at which the subsequent yield stress is equal to 267 MPa would be between 1200ºC and 1300ºC. By applying a linear interpolation, we obtained the annealing temperature of 1210ºC for Case A and 1240ºC for Case B, respectively.

Since welding involves rapid heating and cooling, the temperature history of the weld is considered to be closer to that of the welded structure in Case B than in Case A. Therefore, to evaluate weld residual stress profiles by thermal elastic plastic analysis, it is reasonable to set the annealing temperature to 1240ºC. The factors that caused the difference in Case A and Case B are discussed in the next section.

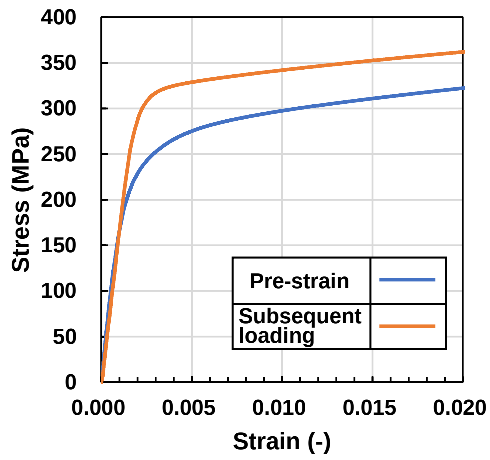


(a) Comparison between no heating condition and heating condition of Case A

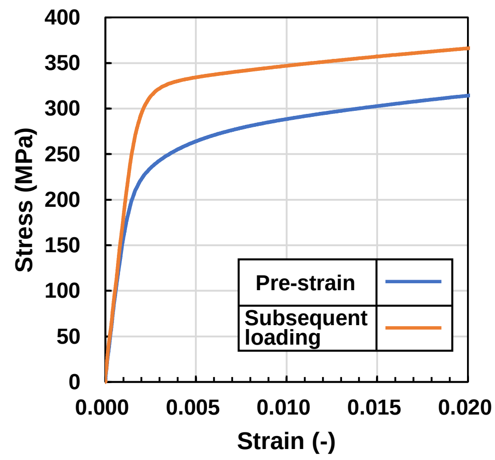


(b) Comparison of heating condition of Case A and condition of Case B

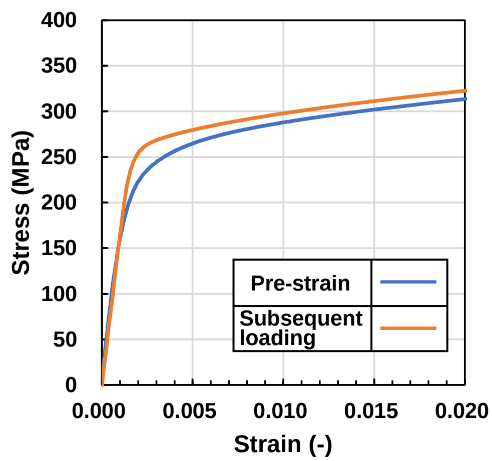
Figure 5. Subsequent tensile test results.



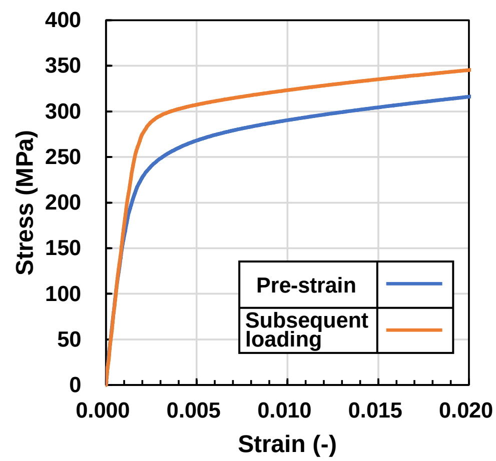
(1-a) Heating condition A of T_{max}=1100ºC



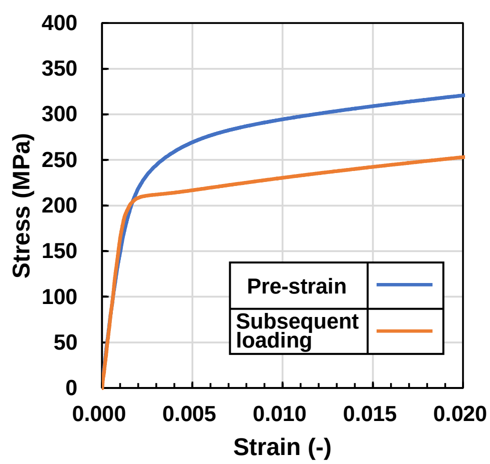
(1-b) Heating condition B of T_{max}=1100ºC



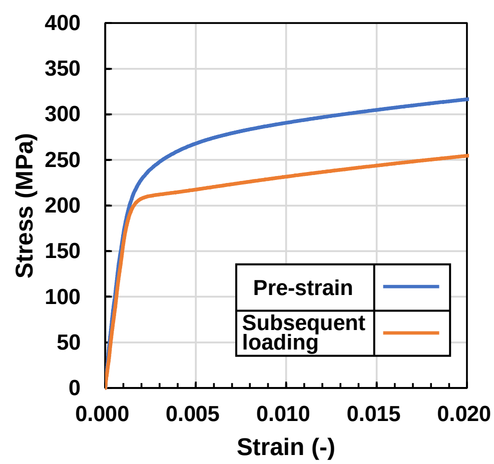
(2-a) Heating condition A of T_{max}=1200ºC



(2-b) Heating condition B of T_{max}=1200ºC



(3-a) Heating condition A of T_{max}=1300ºC



(3-b) Heating condition B of T_{max}=1300ºC

Figure 6. Comparison of stress-strain relations between pre-strain and subsequent tensile test process.

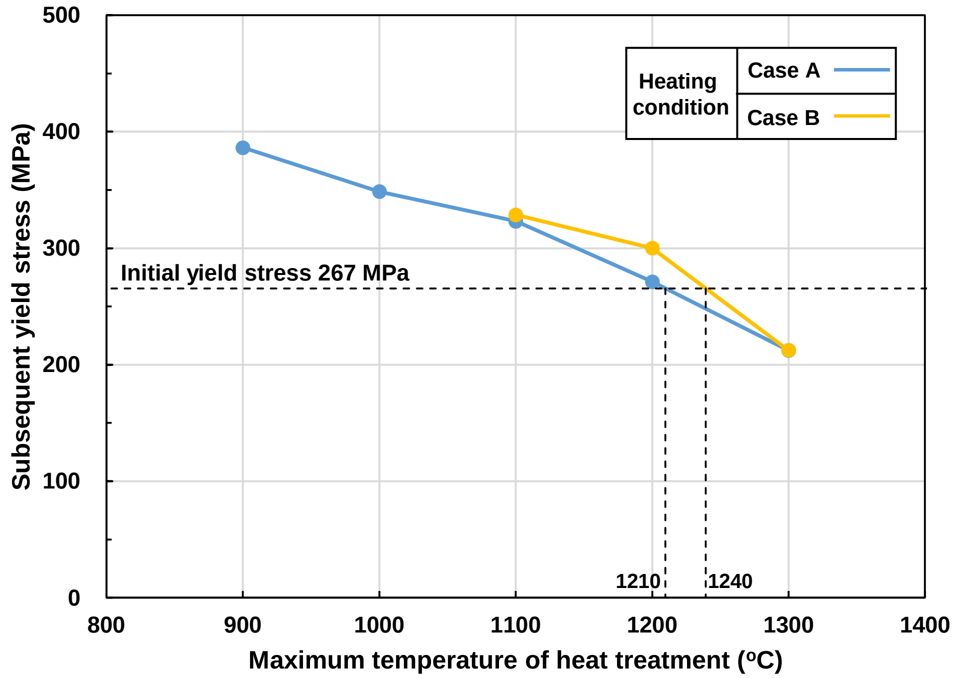


Figure 7. Comparison of subsequent yield stress versus maximum temperature of heating process.

DISCUSSION

In type 316L austenitic stainless steel, plastic deformation introduces dislocations (line defects) and vacancies (point defects), which are lattice defects in the crystal grains, and the subsequent yield stress increases accordingly. However, when type 316L austenitic stainless steel which has been subjected to plastic deformation is heated, recrystallization begins to occur around 900°C to 950°C, and new crystal grains (recrystallized grains) are generated within the crystal grains. Since lattice defects are eliminated in the recrystallized grains, the subsequent yield stress decreases. The recrystallization is most pronounced at around 1050°C to 1200°C. In temperatures above 1200°C, the recrystallized grain grows, and the grain size increases considerably. As a result, the subsequent yield stress decreases. The generation and the growth of recrystallized grains also depend on the heating time, and the growth rate increases as heating time increases.

In the measurement results of Case B, the subsequent yield stress decreased as the maximum temperature increased. This may be due to the accelerated recrystallization that occurs at higher temperatures. Comparing Case A and Case B, the subsequent yield stress was lower in Case A at 1100°C and 1200°C than in Case B because Case A was held at higher temperatures for a longer time than Case B. The effect of holding time is larger at higher temperatures, resulting in a larger difference in subsequent yield stress between Case A and Case B at 1200°C. On the other hand, at 1300°C, the increased grain size due to the growth of recrystallized grains had a significant effect, resulting in a marked decrease in the subsequent yield stress. In addition, at 1300°C, the time difference around the maximum temperature between Case A and Case B (about 6.7s) did not have a noticeable effect on the amount of increase in grain size.

Note that the subsequent yield stress was lower than the initial yield stress in the measurement results at the maximum temperature of 1300°C. In this study, no plastic deformation occurred in the tensile specimens during cooling from 1300°C to room temperature because heat treatment was performed under stress-free conditions. Therefore, the specimens maintained the lower subsequent yield stress until room temperature due to the increased grain size.

When the annealing temperature was set to 1240°C in the thermal elastic plastic analysis code, the subsequent yield stress was reset to the initial yield stress and was not lower than the initial yield stress even when the maximum temperature reached 1300°C. We plan to conduct a sensitivity analysis and evaluate the results to determine the effect of such analytical treatment on annealing temperature in the future. The region heated above 1300°C in HAZ will likely be subject to plastic deformation due to deformation constraints from the surroundings during the cooling process after weld heat input. After reaching room temperature, the subsequent yield stress increases depending on the plastic deformation that occurs during the cooling process, and the subsequent yield stress at room temperature should not be lower than the initial yield stress.

CONCLUSION

Material tests were carried out on type 316L austenitic stainless steel to evaluate the annealing temperature at which the subsequent yield stress is reset to the initial yield stress. First, the tensile test specimens were subjected to tensile plastic strain at room temperature. Then the pre-strained specimens were heat treated by rapid heating followed by rapid cooling under stress-free conditions. Afterwards, subsequent tensile tests were carried out. The stress-strain curve was measured for each specimen, and the subsequent yield stress was determined. The subsequent yield stress was compared to the initial yield stress and the annealing temperature was examined.

Under the no heating condition, no heat treatment was applied to the pre-strained tensile test specimen. The subsequent yield stress measured in the subsequent tensile test was equal to the stress value at the start point of unloading during the pre-straining process. The subsequent yield stress did not decrease in this condition.

When the pre-strained tensile specimen was treated with heat, the subsequent yield stress was lower than the stress value at the start point of unloading during the pre-straining process. The subsequent yield stress measured from the subsequent tensile test was higher than the initial yield stress at the maximum temperature of 1200°C and lower than that at 1300°C. Through linear interpolation, the annealing temperature was determined to be 1240°C.

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