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Effects of Cold-work on the Mechanical Properties of TP304 Stainless Steel and Its Weldment under Monotonic and Cyclic Loads

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ABSTRACT

In this study, SA240 TP304 stainless steel (SS) base and weld metals were cold-worked under various rolling conditions (5,15, 22, 35% CW), and monotonic and cyclic failure tests were performed using these materials. Monotonic tests showed that, as the cold-work rate increased, the strength of SA240 TP304 SS base and weld metals increased almost linearly and the ductility decreased, regardless of the test material and temperature. In particular, an increase in yield strength and a decrease in uniform elongation were considerable. Also, the change in strength and ductility due to cold-working was more significant in the base metal than in the weld metal and was greater at 316℃ that at RT. Cyclic tests showed a significant reduction in cyclic hardening due to cold-work, with cycle softening occurring at 15% or more cold-work. The reduction in cyclic hardening was greater in the base metal than in the weld metal. Irrespective of the test material and temperature, cold-work reduced the number of cycles to failure, and the reduction was attributed to loss of ductility due to cold-work.

INTRODUCTION

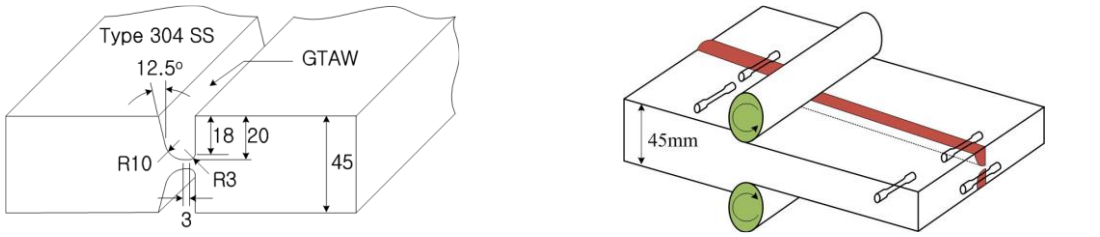
Austenitic stainless steels (SSs) are commonly used as structural materials for system, structure, and components (SSCs) of nuclear power plants (NPPs) due to their excellent corrosion resistance and mechanical properties (Das (2019)). They are also used as materials for hydrogen storage and transfer vessels due to their high ductility and low brittleness in hydrogen atmospheres (Chen et al. (2018), Sezgin et al. (2019)). Austenitic SSs are typically used in the annealed condition, but they can be locally deformed during fabrication or intentionally cold-worked to increase the strength. Generally, during plastic deformation or cold-work, the mechanical properties of metals are changed by grain boundary deformation, increase in dislocation density, and twinning (Sezgin et al. (2019), Paul et al. (2018)). In addition, in SSs with metastable austenitic phases (γ), strain-induced martensite is produced during cold working, which changes the mechanical properties (Paul et al. (2018), Milad et al. (2008)). Therefore, when evaluating the structural integrity of SSCs made of austenitic SSs, it is necessary to identify the changes in mechanical properties due to deformation and cold-work and to reflect them in the evaluation. In particular, it is important to understand the mechanical properties of cold-worked austenitic SSs not only under monotonic loads but also under cyclic loads, because the micro-structure and density of dislocations are also varied due to repeated plastic deformation (Das (2019), Paul et al. (2018), Murasaki et al. (2009), Kundu et al. (2019), Paul et al. (2011)).

In this study, SA240 TP304 SS that is an austenitic SS widely used as an industrial material and its weld metal were cold-worked under various rolling conditions, and monotonic and cyclic tests were performed using these materials. Engineering stress-strain curves and tensile properties were obtained from the monotonic tests, and hysteresis loop, peak load-cycles, and number of cycles to failure were obtained from the cyclic tests. Based on these experimental results, the effect of cold-work on the deformation and failure behaviors of SA240 TP304 SS base and weld metals under monotonic and cyclic loads was investigated.

EXPERIMENT

Test Materials and Specimens

SA240 TP304 SS base metal in the form of a plate (t=45 mm) and weld metal welded by manual gas tungsten arc weld (GTAW) method by machining grooves designed as shown in Figure 1(a) on both sides of the plate were used for monotonic and cyclic tests. ER308L SS filler metal were used for welding, and multi-pass (24 passes) welding were performed for each groove. Table 1 summarizes the chemical composition of the base metal and filler metal. The cold-worked material was obtained by cold rolling the base metal and weldment to 5, 15, 22, and 35%, respectively (Figure 1(b)). Round bar specimens with a diameter of 2.5mm and a uniform length of 13.0mm were used for the monotonic test, and hourglass type round bar specimens with a minimum diameter of 2.5mm were used for the cyclic tests. Both specimens were designed according to ASTM E8/E8M (ASTM (2016)) and ASTM E606 (ASTM (1998)) standards. Figure 2 shows photographs of the specimen.

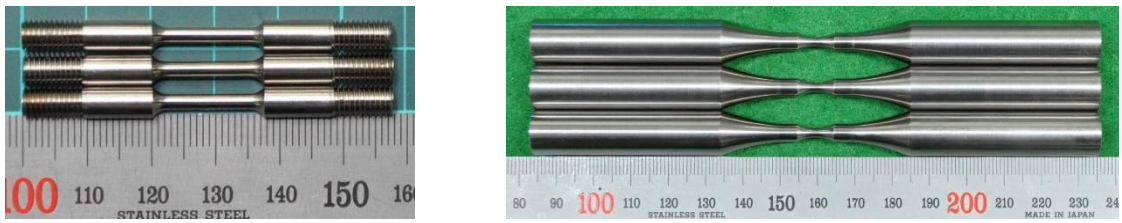


(a) Weld groove (b) Cold rolling and machining of specimens

Figure 1. Test materials and specimens.

Table 1. Chemical compositions of SA240 TP304 SS base and weld metals used for the experiment (wt.%)

Material	C	Si	Mn	P	S	Cr	Ni	Mo	N	Co	Cu	Bal.
Base metal	0.017	0.36	1.62	0.031	0.002	18.15	8.06	0.12	0.069	0.19	0.23	Fe
Weld metal	0.020	0.40	1.90	0.024	0.010	19.64	10.79	0.03	-	-	-	Fe



(a) Monotonic test (b) Cyclic tests

Figure 2. Specimens for monotonic and cyclic tests

Experimental Procedure

Monotonic tests were conducted at room temperature (RT) and 316°C at a quasi-static rate ($\dot{\varepsilon} = 5.77 \times 10^{-4}/s$). In all tests, a motor-driven universal testing machine installed a 10 kN load-cell and a high-temperature extensometer with a 12.5 mm gauge length were used.

Cyclic tests were performed at quasi-static rate at RT and 316°C. In the tests, displacement-controlled fully-reversed cyclic loads with constant amplitude were applied, and two displacement amplitudes ($\delta_a =$ 0.8% and 1.2%) were considered. Here, δ_a is displacement amplitude normalized with respect to the gage length (12.0 mm). The displacement amplitude was measured from a dynamic extensometer mounted outside the hourglass section of the specimen. Therefore, considering that the strain is concentrated in the mid-section of the hourglass shape, the strain amplitude at the center of the specimen might be greater than 0.8% and 1.2%. The test was terminated when the peak load of the specimen decreased to 75% or less of the maximum peak load, and the number of cycles to failure (*i.e.*, failure cycles) was defined as the number of cycles the test was terminated. A hydraulic universal testing

machine with a 25 kN load-cell and a high-temperature dynamic extensometer with a gauge length of 12.0 mm were used.

RESULT and DISCUSSION

Monotonic tests

Monotonic tests were performed at RT and 316°C. Figure 3 shows the engineering stress-strain curves of cold-worked SA240 TP304 SS base and weld metals tested at RT. As shown in Fig. 3, regardless of the test material, the strength increased and ductility decreased as the cold-work rate increased. The same cold working effect was also observed at 316°C.

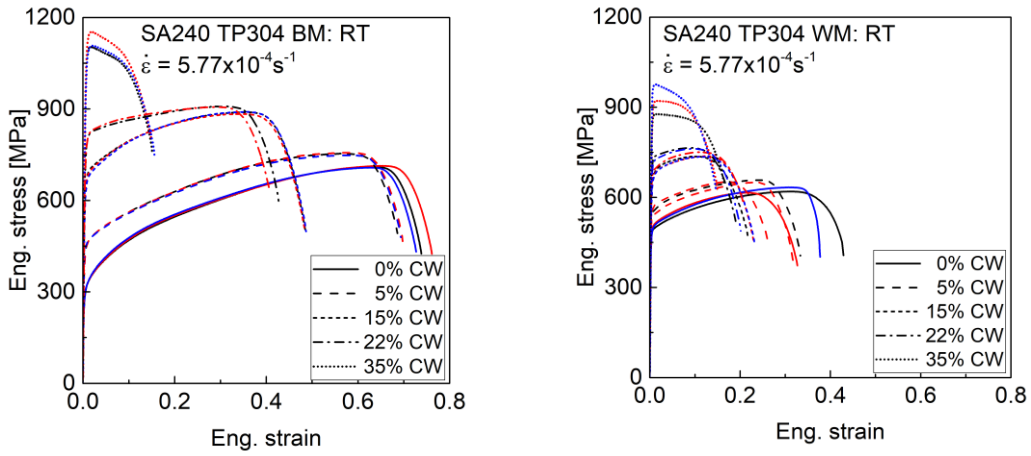
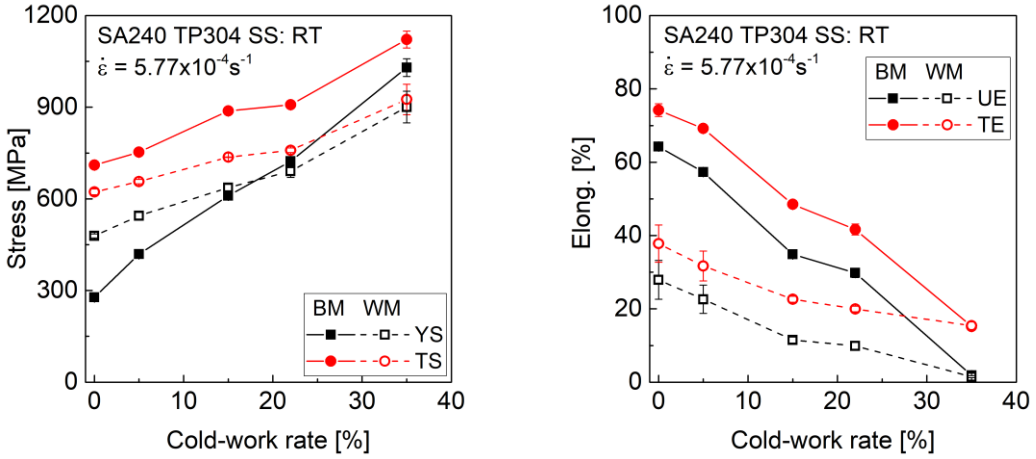


Figure 3. Engineering stress-strain curves of cold-worked SA240 TP304 SS base and weld metals at RT

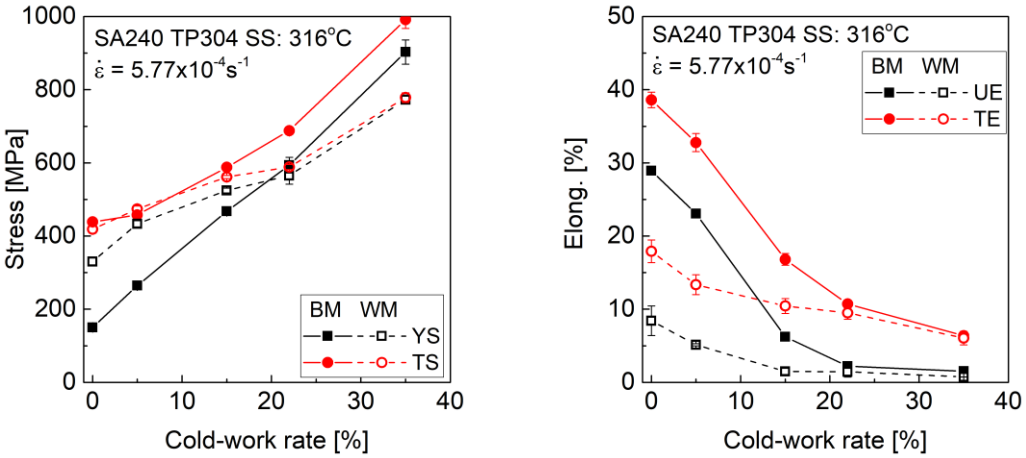
Figures 4 and 5 show the tensile properties (yield strength (YS), tensile strength (TS), uniform elongation (UE), and total elongation (TE)) of cold-worked SA240 TP304 SS base and weld metals tested at RT and 316°C, respectively, as a function of cold-work rate. YS and TS of the base metal and weld metal at RT increased almost linearly with increasing cold-work rate, and the increase in YS was more pronounced compared to TS. UE and TE decreased with similar slopes as the cold-work rate increased. Comparing the base metal and weld metal, the cold work effect on the strength and elongation was greater for the base metal than for the weld metal. At 316°C, also, YS and TS increased and UE and TE decreased with increasing cold-work rate, and the increase in strength and decrease in elongation with cold-work was greater for the base metal than for the weld metal (Figure 5). Compared to RT, the increase in strength and decrease in elongation due to cold-work was more pronounced at 316°C. In addition, the decrease in elongation tended to be saturated in the cold working over 22% for the base metal and in the cold working over 15% for the weld metal.

In figures 4 and 5, regardless of test temperature, the increase in strength and decrease in ductility due to cold working were more pronounced in the base metal compared to the weld metal. This is related to strain-induced martensite transformation of the SA240 TP304 SS base metal by cold working. Cold working increases the dislocation density in most metals and forms strain-induced martensite in some metals, such as TP304 austenitic SS (Paul et al. (2018), Milad et al. (2008), Murasaki et al. (2009)). Thus, the increase in dislocation density and formation of martensite are dominant mechanism of strength increase and ductility decrease of cold-worked metals (Paul et al. (2018), Milad et al. (2008)). According to the microstructure of base and weld metals, strain-induced martensite was formed in the cold-worked base metal and the fraction of martensite was almost proportional to the cold-work rate, whereas it was not observed in the cold-worked weld metal. Therefore, the greater cold work effect in the base metal compared to the weld metal is related that cold working not only increases dislocation density but also forms martensite.



(a) Yield and tensile strengths (b) Uniform and total elongation

Figure 4. Effect of cold working on tensile properties of SA240 TP304 SS base and weld metals at RT

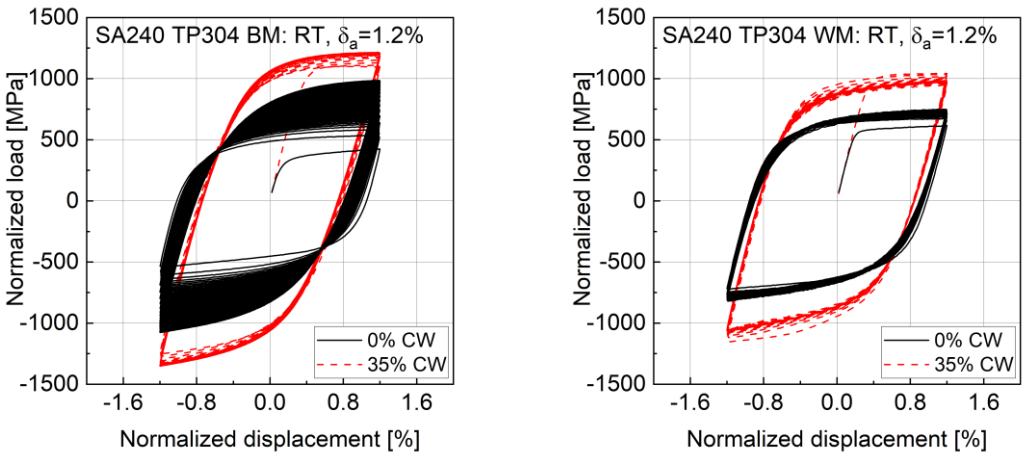


(a) Yield and tensile strengths (b) Uniform and total elongation

Figure 5. Effect of cold working on tensile properties of SA240 TP304 SS base and weld metals at 316°C

Cyclic tests

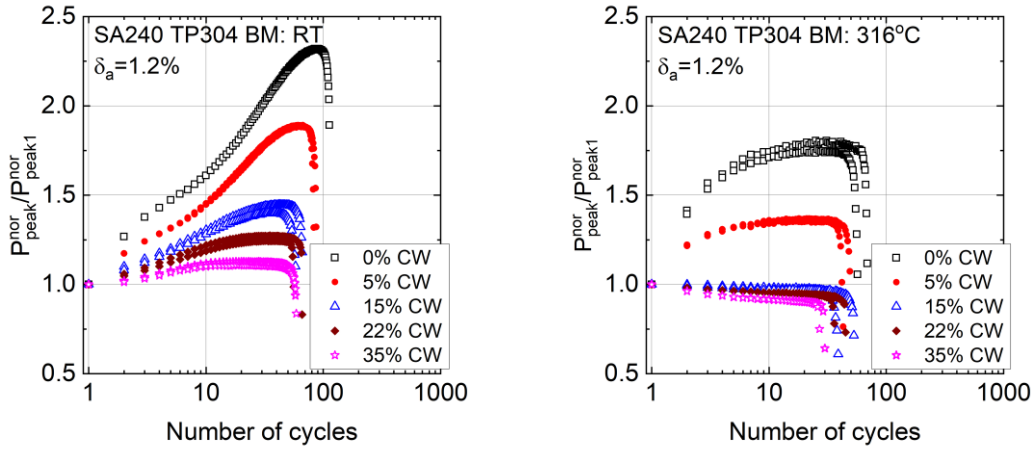
Cyclic tests were performed on the cold-worked SA240 TP304 SS base and weld metals at displacement amplitudes of δ_a =0.8% and 1.2%. Figure 6 shows the normalized load-displacement hysteresis curves of 0% cold-worked (0% CW) and 35% cold-worked (35% CW) base metal and weld metal tested at δ_a =1.2% and RT. Regardless of type of test material, the normalized load of 35% CW was much higher than that of 0% CW, and the plastic displacement range of 35% CW was smaller than that of 0% CW. For the base metal, the change in load with cyclic loading was evident in the 0% CW specimen, but the change was relatively small in the 35% CW specimen. In the case of weld metal, also, the change in the load with cyclic loading was smaller for the 35% CW specimen compared to the 0% CW specimen; however, for weld metal, the load change was insignificant even for the 0% CW specimen. Such trend in the hysteresis curves was similar regardless of the test temperature and displacement amplitude. The different hysteresis behavior is caused by the different cyclic hardening characteristics of the base and weld metals, as well as changes in hardening characteristics due to cold working.



(a) Base metal (b) Weld metal

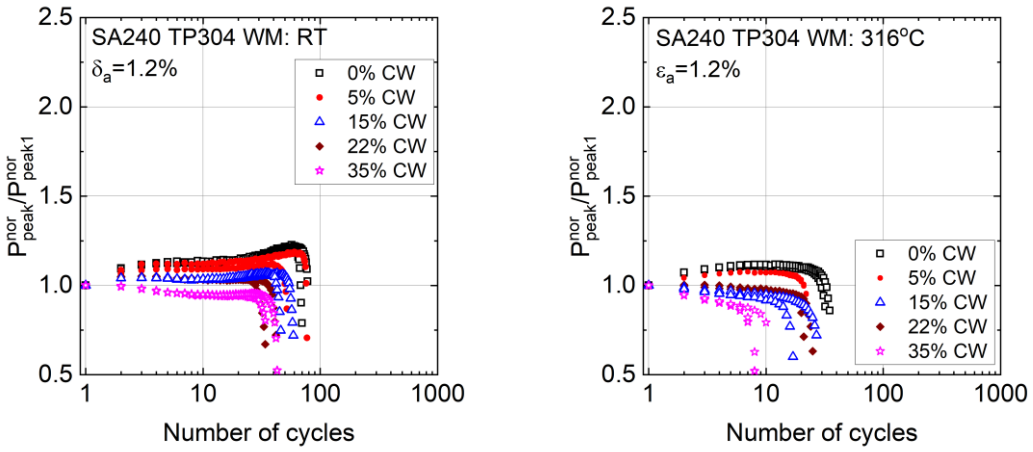
Figure 6. Normalized load-displacement hysteresis curves of cold-worked SA240 TP304 SS base and weld metals at RT

To investigate the effect of cold-work on the cyclic hardening/softening behaviors of base and weld metals, the variation of peak load with the number of cycles at each displacement amplitude condition was examined. Figures 7 and 8 show $P_{peak}^{nor}/P_{peak1}^{nor}$ for the cold-worked SA240 TP304 SS base and weld metals, respectively, tested at $\delta_a = 1.2\%$. Here, P_{peak}^{nor} is the normalized peak load of each cycle and P_{peak1}^{nor} is the normalized peak load of the first cycle. In figures 7 and 8, thus, $P_{peak}^{nor}/P_{peak1}^{nor} > 1.0$ means that the material is hardened by cyclic loads, and $P_{peak}^{nor}/P_{peak1}^{nor} < 1.0$ means that the material is softened by cyclic loads. For the base metal, regardless of the test temperature, a large cyclic hardening was observed for small cold-work rates (0% CW and 5% CW), and a secondary hardening was observed after an initial hardening at RT. The cyclic hardening decreased significantly as the cold-work rate increased, and cyclic softening occurred at large cold-work rates (> 15% CW) for 316°C. In the weld metal (in Figure 8), the cyclic hardening was also reduced by cold working, and cyclic softening occurred at large cold-work rates for both test temperatures (> 22% CW for RT and > 15% for 316°C). Compared to the base metal, however, the weld metal showed relatively small change in cyclic hardening/softening behavior with cold working.



(a) RT (b) 316°C

Figure 7. Variation in normalized peak load with the number of cycles for cold-worked SA240 TP304 SS base metal



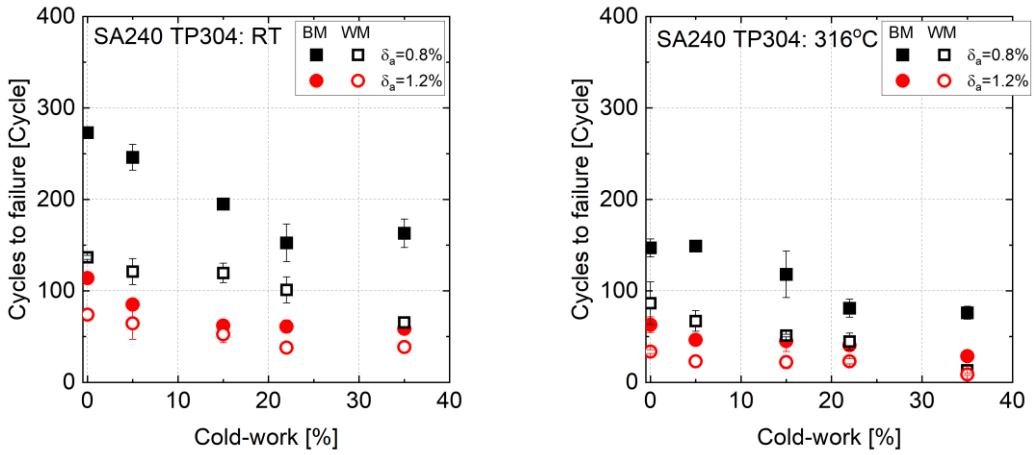
(a) RT (b) 316°C

Figure 8. Variation in normalized peak load with the number of cycles for cold-worked SA240 TP304 SS weld metal

Previous studies have shown that primary hardening of austenitic SSs is related to an increase in dislocation density due to cyclic plastic deformation, while softening is related to rearrangement and disappearance of dislocations (Paul et al. (2018), Milad et al. (2008), Kunda et al. (2019), Paul et al. (2011)). In addition, secondary hardening of TP304 SS is known to occur by the formation of strain-induced martensite under cyclic deformation at RT (Paul et al. (2018), Colin et al. (2011)). In the case of cold-worked austenitic SSs, the dislocation density and martensitic fraction are initially high, so the dislocations are rearranged and disappear from the beginning of the cyclic loading. Also, it is known that the fraction of strain-induced martensite continues to increase with increasing the number of cycles (Paul et al. (2018)). Therefore, regardless of the test temperature, the reduction of the cyclic hardening in the cold-worked SA240 TP304 SS base and weld metals is because the softening effect due to the rearrangement and disappearance of dislocations overcomes the hardening effect due to strain-induced martensite transformation. In addition, even if the cyclic hardening phenomenon is reduced by cold-work at RT, it still exhibits hardening behavior due to secondary hardening by the production of strain-induced martensite. On the other hand, regardless of the material, the cyclic softening behavior at large cold-work rates (> CW 15%) at 316°C is because strain-induced martensite is not produced at higher temperatures (Paul et al. (2018)).

Figure 9 shows the number of cycles to failure for each material as a function of cold-work rate. As shown in figure 9, the number of cycles to failure tended to decrease with increasing cold-work rate regardless of the test material and temperature. In the case of base metal, the number of cycles to failure of 35% CW specimen was reduced by about 45% compared to 0% CW specimen regardless of the test temperature. For the weld metal, the number of cycles to failure of 35% CW specimen was reduced by about 48% at RT and about 74% at 316°C compared to the number of cycles to failure of 0% CW specimen. In addition, the number of cycles to failure of the weld metal was about 50% shorter than that of the base metal at both RT and 316°C, and both metals showed a shorter failure cycle at 316°C than at RT regardless of the cold-work rates.

In the low-cycle fatigue regime, the number of cycles to failure under cyclic loading depends on the ductility of the metals, but it depends on the strength of the metals in the high-cycle fatigue regime, depending on the strain amplitude applied to the specimen (Colin et al. (2011), Stephens et al. (2000)). In this study, all the specimens were tested in the low-cycle fatigue regime. Therefore, the decrease in the number of cycles to failure with increasing cold-work rate is associated with the decrease in ductility due to cold-work as indicated from the tensile test results in figures 4 and 5. Also, the shorter failure cycles for the weld metal than for the base metal and at 316°C than at RT can be explained by the smaller ductility of the weld metal and at 316°C compared the base metal to RT.



(a) RT (b) 316°C

Figure 9. Effect of cold-work on failure cycle of SA240 TP304 SS base and weld metal

CONCLUSION

In this study, to investigate the effect of cold working on the mechanical properties of SA240 TP304 SS base and weld metals, monotonic and cyclic tests were performed at room temperature (RT) and 316°C using specimens cold-worked at various rolling rates. From the results, the following conclusions were obtained;

1) Under monotonic load, strength increased and ductility decreased with increasing cold-work rate regardless of test temperature and material, and the increase in strength and decrease in ductility were more pronounced in the base metal than in the weld metal and at RT than at 316°C.
2) Regardless of the test temperature, the cyclic hardening of the base and weld metals was clearly reduced by cold-work, and the reduction in cyclic hardening was observed to be greater in the base metal compared to the weld metal. Even severe cold-worked specimens were cyclic softened at 316°C.
3) Regardless of the test temperature, the number of cycles to failure of both base and weld metals was reduced as cold-work rate increased, and this was associated with the reduction of ductility of materials by cold-work.

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