Review of specimen heating in mechanical tests at cryogenic temperatures

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At cryogenic temperatures near 4 K, a discontinuous deformation produces a large amount of specimen temperature rise and it might bring significant changes in mechanical properties. Authors had measured the specimen heating in tensile tests, fatigue test, and other tests in liquid helium for stainless steels and other materials. In this paper, results of the measurements in high-cycle and low-cycle fatigue tests for stainless steels are presented and testing conditions to keep the specimen at a specified temperature will be discussed.

INTRODUCTION

Specimen temperature is an important factor for mechanical testing.
Specimen temperature would be unknown at 4 K owing to the temperature rise caused by a small plastic deformation, because specific heat and thermal conductivity of the material become extremely low at that temperature.

We have reported the specimen temperature behavior in tensile tests at cryogenic temperatures and suggested that the strain rate during the tests should be lower than 3 x 10^{-3} s^{-1} for stainless steels.

We performed the measurements of internal specimen temperature rise during load-controlled and strain-controlled fatigue tests at liquid helium temperature.

We would like to present here the specimen temperature behavior, the magnitude of temperature rise, and some touchstone for the fatigue testing of stainless steels at 4 K.

Table 1. Chemical composition of the steels tested in this study (wt.%).

	C	Si	Mn	P	S	Ni	Cr	Mo	N
SUS 304L	0.016	0.67	1.52	0.027	0.009	10.03	18.24		
SUS 310S	0.04	0.79	0.93	0.020	0.001	19.20	25.18		
SUS 316LN	0.019	0.50	0.84	0.025	0.001	11.16	17.88	2.62	0.18

Table 2. Tensile properties of the steels

Material	Temperature (K)	0.2%Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Reduction in Area (%)
SUS 304L	4	505	1476	48.0	61.1
SUS 310S	4	783	1269	54.8	43.9
SUS 316LN	4	1072	1697	54.7	60.1

comments:
SUS304L: typical steels for cryogenic use, lower yield strength and higher work-hardening rate with martensitic transformation at low temperatures.
SUS310S: fully-stable austenitic stainless steel even at 4 K.
SUS 316LN: nitrogen-strengthened high strength stainless steel for cryogenic use.

Ref. ; T.Ogata, et al. : Adv. Cryog. Eng. -Mater., Vol.34 (1988), pp209-215

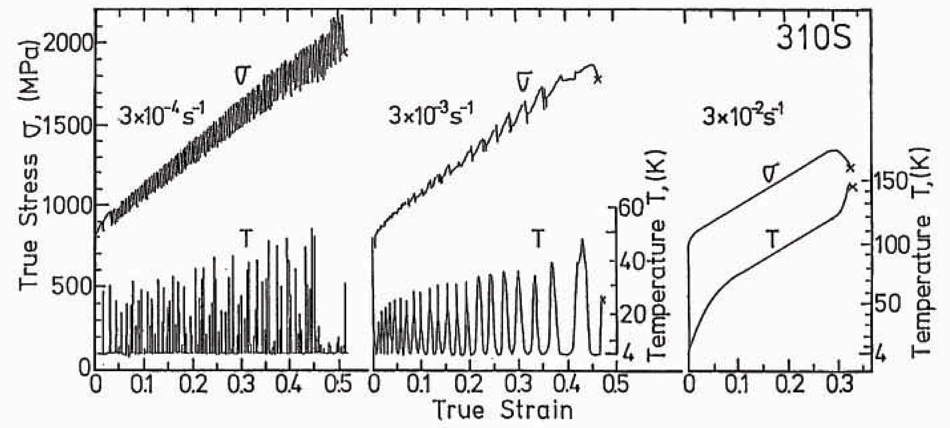
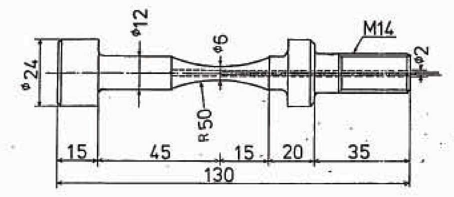
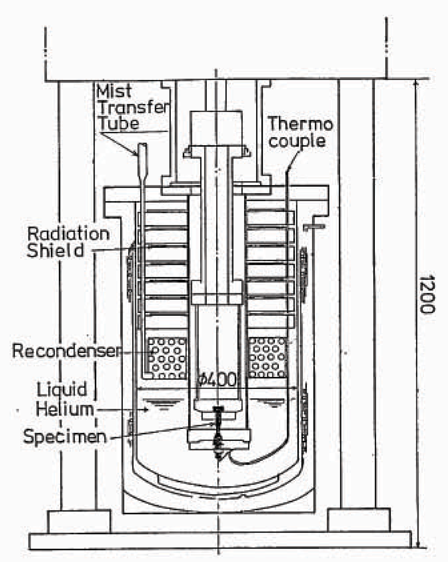


Fig. Load-displacement curves and specimen temperature (T) for SUS310S.





Testing conditions

Temperature: liquid helium temperature, 4K
Machiene: servo-controlled testing system

1. load-controlled
   a) tension-tension, R=0.01
      frequency: 0.05, 0.1, 0.5, 1, 5,10 Hz
      stress: SUS 310S 0.5 - 1.5 $\sigma_{0.2}$
      SUS 304L 0.5 - 4 $\sigma_{0.2}$

   b) tension-compression, R=-1
      frequency: 0.05, 0.1, 0.5, 1, (5) Hz
      stress: SUS 310S 0.5 - 1.2 $\sigma_{0.2}$
      SUS 304L 0.5 - 3 $\sigma_{0.2}$

2. strain-controlled (axial)
   tension-compression, R=-1
   triangular wave
   frequency: 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2, 5 Hz
   strain range: 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6
   1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2 %

load-controlled fatigue tests

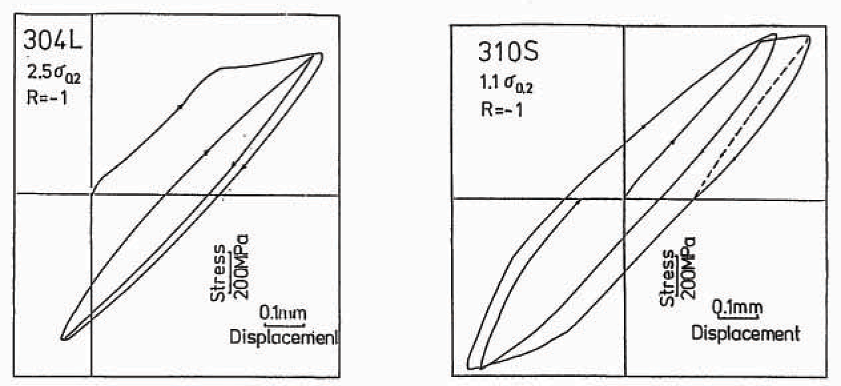
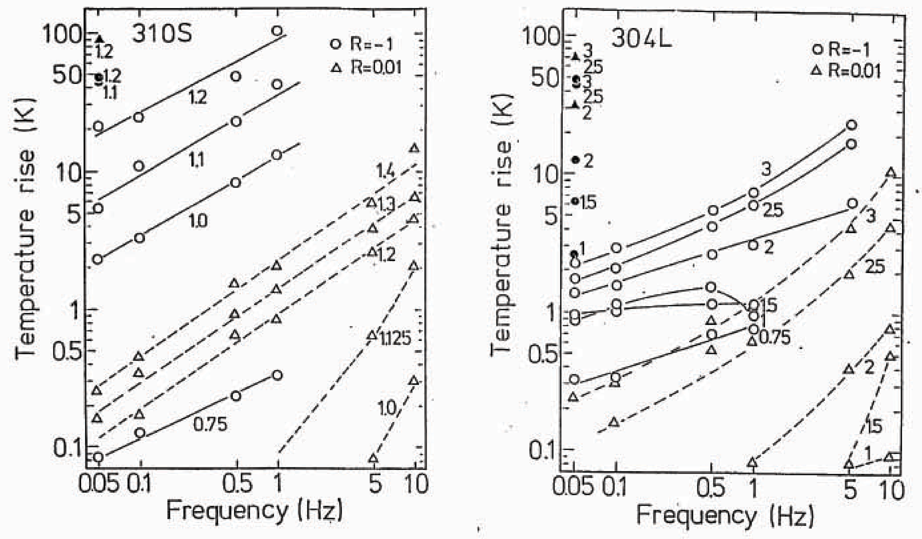
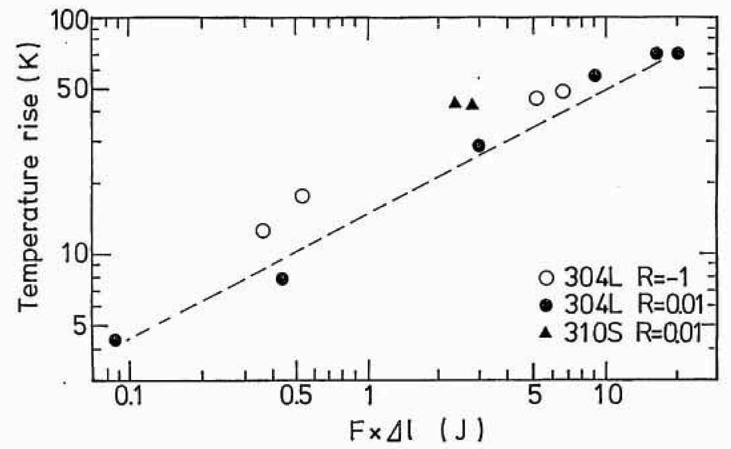
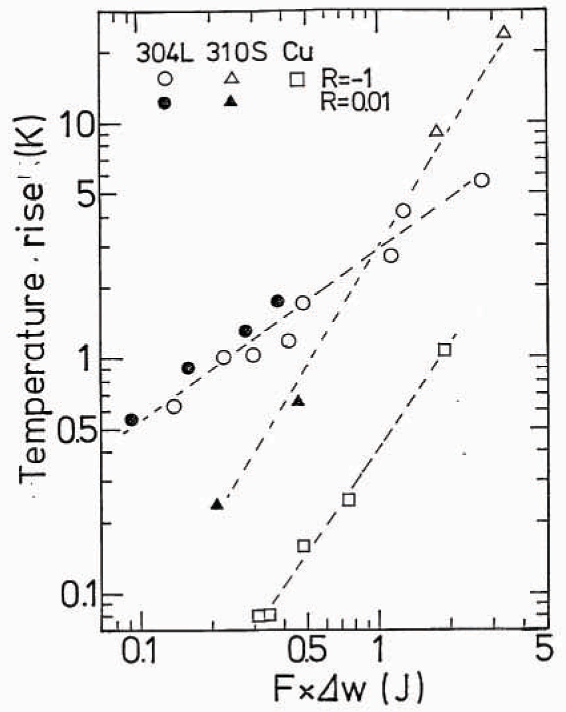


Fig. Stress-displacement curves obtained in tension-compression fatigue test.







load-controlled fatigue tests

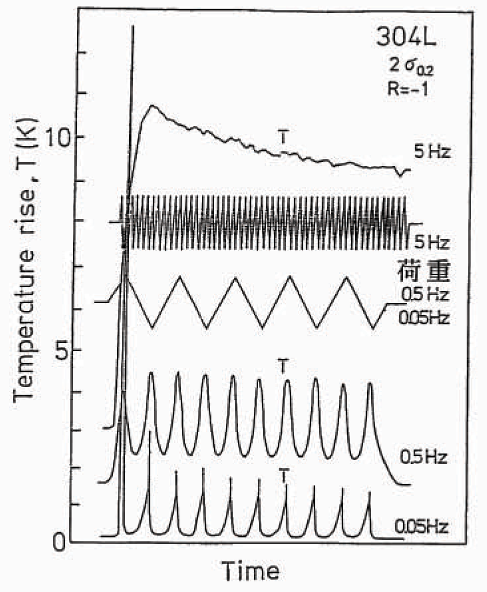
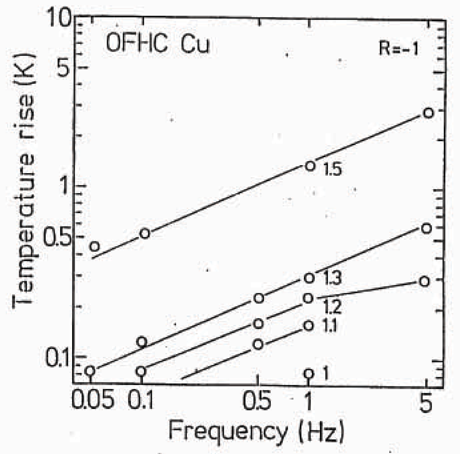


Fig. Temperature rise curves in tension-compression tests as a function of time for 304L steels at $2\sigma_{0.2}$.



Relations between ΔT and f

AISI310S R=-1
$\Delta T = 10(\sigma/\sigma_{0.2})^{12} f^{0.5}$

R=0.01 $\sigma > 1.1\sigma_{0.2}$
$\Delta T = 0.27(\sigma/\sigma_{0.2})^{6} f^{0.66}$

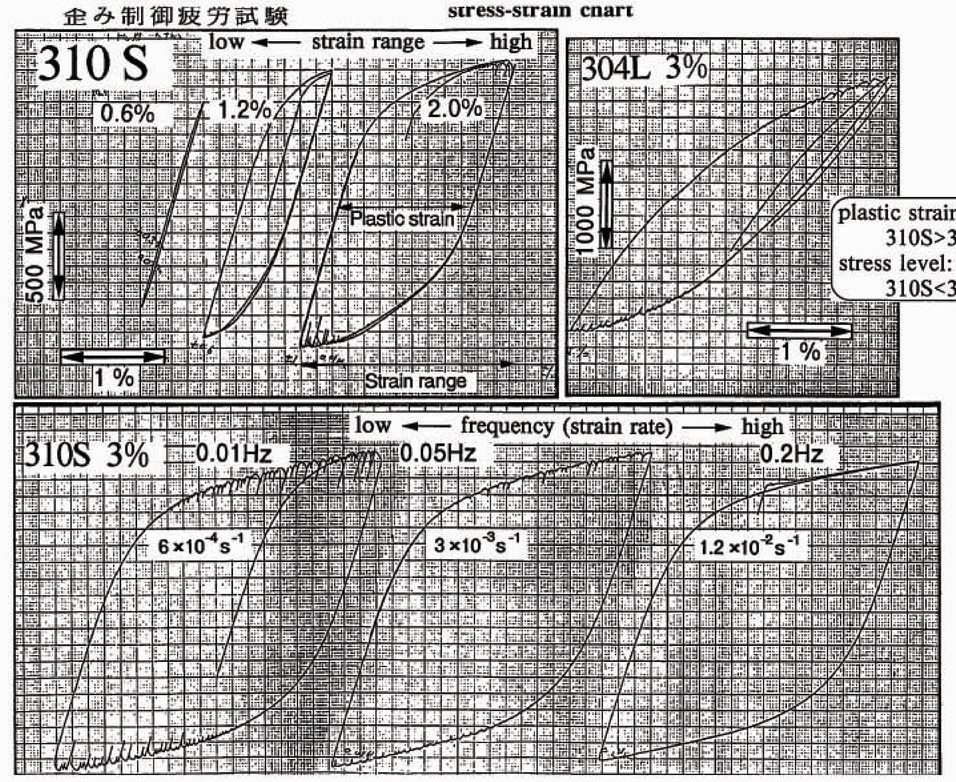
AISI304L R=0.01 $\sigma_{0.2} \leftarrow 2\sigma_{0.2}$
R=-1 $\sigma_{0.2} \leftarrow 3\sigma_{0.2}$

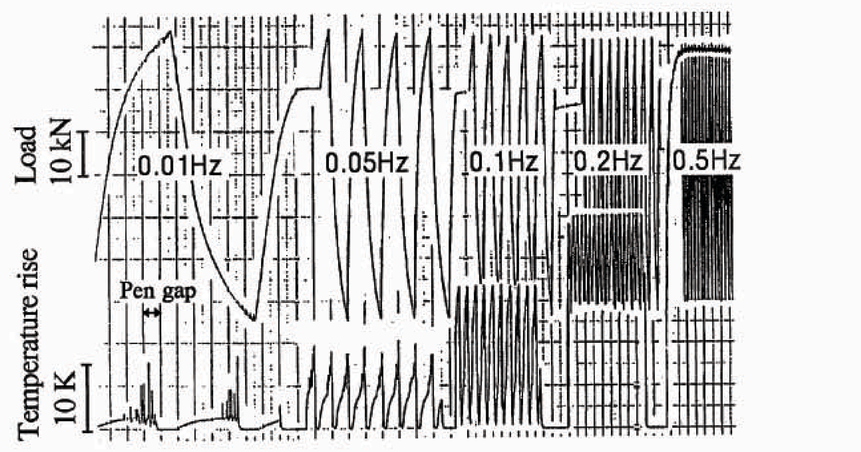
OFHC Cu $\Delta T = 0.1(\sigma/\sigma_{0.2})^{6} f^{0.44}$

Upper limit of frequency

R=0.01 5Hz
R=-1 0.1Hz (max. 1Hz)

stress-strain chart





strain-controlled fatigue tests

304L-HighData 304L-LowData

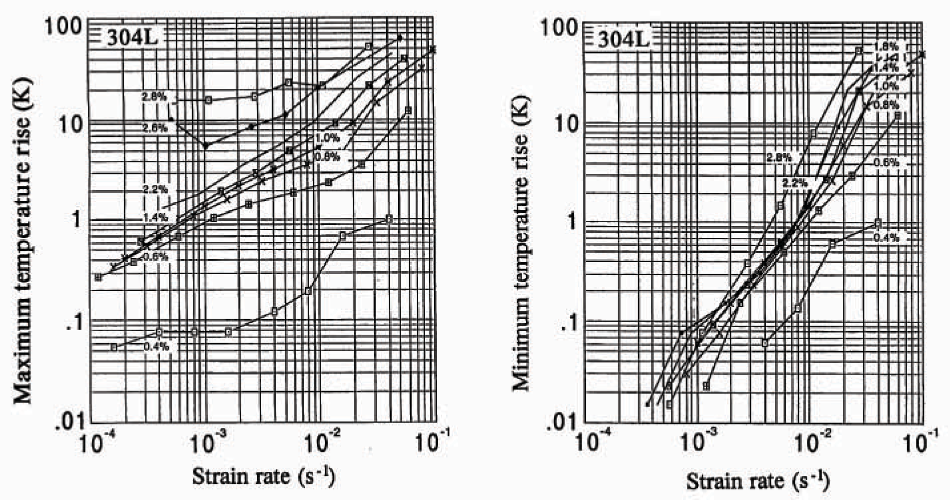


Fig. Temperature rise of specimen for SUS304L steels as a function of strain rate and strain range.

strain-controlled fatigue tests

310S-HighData 310S-LowData

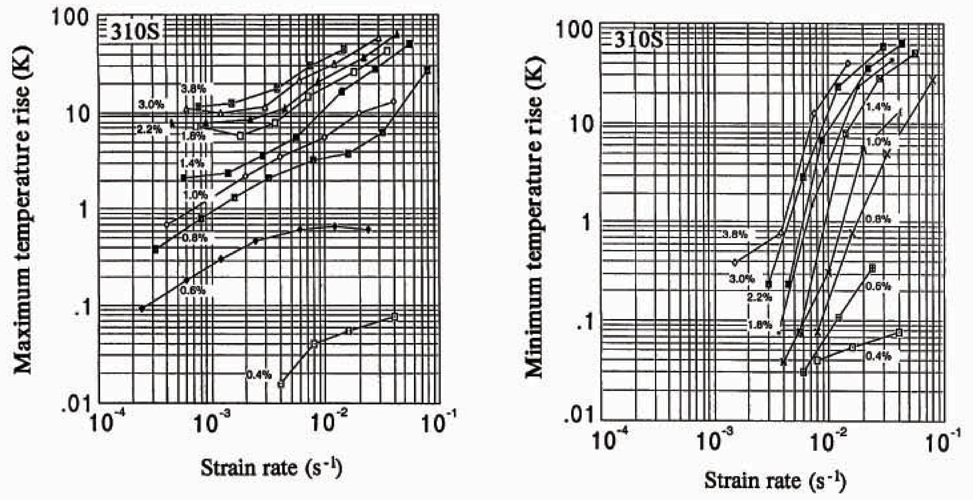


Fig. Temperature rise of specimen for SUS310S steels as a function of strain rate and strain range.

316LN-HighData 316LN-LowData

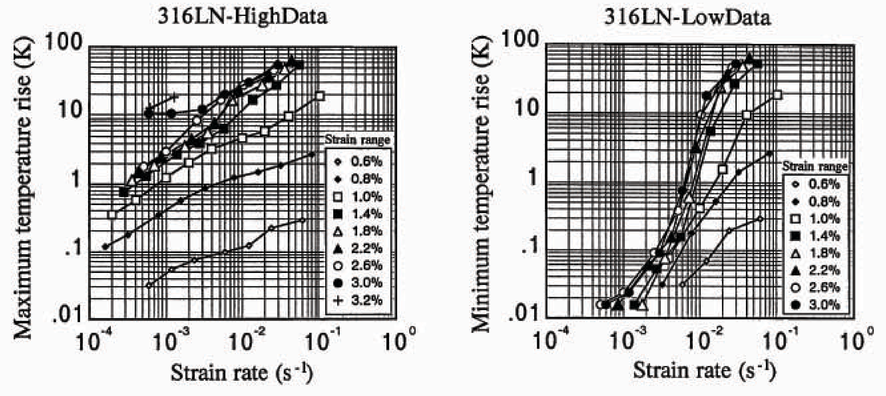


Fig. Temperature rise of specimen for SUS316LN steels as a function of strain rate and strain range.

CONCLUSION

1. Specimen temperature rises with an increase of plastic deformation, and return to liquid helium temperature in the region of elastic deformation.
2. Specimen temperature rises constantly at higher testing frequency.
3. Specimen temperature rises at least 1 K at the strain rate of more than 4 x 10^{-3} s^{-1} in strain-controlled fatigue tests for stainless steels.
4. A practical temperature rise occurs in the condition that the ratio of plastic deformation is high even at lower strain rate.