International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:8, No:5, 2014

Thermal Fatigue Behavior of Austenitic Stainless Steels

Jung-Ho Moon, Tae Kwon Ha

Abstract—Continually increasing working temperature and growing need for greater efficiency and reliability of automotive exhaust require systematic investigation into the thermal fatigue properties especially of high temperature stainless steels. In this study, thermal fatigue properties of 300 series austenitic stainless steels have been evaluated in the temperature ranges of 200-800°C and 200-900°C. Systematic methods for control of temperatures within the predetermined range and measurement of load applied to specimens as a function of temperature during thermal cycles have been established. Thermal fatigue tests were conducted under fully constrained condition, where both ends of specimens were completely fixed. Load relaxation behavior at the temperatures of thermal cycle was closely related with the thermal fatigue property.

Keywords—Austenitic stainless steel, automotive exhaust, thermal fatigue, microstructure, load relaxation.

I. Introduction

THERMAL fatigue is a process of damage origination and growth in machine parts and structural components due to changes in internal energy caused by multiple cycle or periodic changes of temperature [1]. As a result, a component may undergo a change in geometry, the physical properties of the material may change, or cracking may start. Thermal fatigue is produced basically by cyclic or periodic temperature changes and complete or partial restriction of thermal deformation. The restriction may be due to external or internal factors. It is the way in which thermal deformation is hampered that forms the basis for thermal fatigue to be divided into two classes [2]; (1) thermal fatigue with external constraints; (2) thermal fatigue with internal constraints. External constraints produce forces that act on a component that is alternately heated and cooled, whilst internal constraints may result from temperature gradients, structural anisotropy and different coefficients of expansion in adjacent grains or phases including the matrix and the reinforcement in composites. Changes of the shapes of specimens have been observed as a result of thermal fatigue and internal constraints [3].

Automotive exhaust system consists mainly of exhaust manifolds, front pipes, catalytic converter, pre-muffler, middle pipe, main muffler, and tail pipe. Parts from exhaust manifolds to catalytic converter operated at high temperatures above 600°C are called hot end, which has been produced by heat-resisting steels. Those from pre-muffler to tail pipe operated at relatively lower temperatures below 600°C are categorized into cold end, usually made from corrosion-resistant steels [4]. Especially, the operation temperature of the exhaust manifolds of hot end reaches up to 900°C and higher [5]. Increasing demands for weight reduction of automotives and high performance of engine systems give rise to employment of more advanced steels in automotive industry such as heat-resisting stainless steels [6]-[8].

In the present work, it was attempted to provide systematic methods for control of temperatures within the predetermined range and measurement of load applied to specimens as a function of temperature during a thermal cycle. Thermal fatigue tests were conducted for typical heat-resisting stainless steels, i.e. STS 304, 310S and XM15J1, in the temperature ranges of 200-800°C and 200-900°C. Load relaxation behavior of the stainless steels at the temperatures of thermal cycle was measured for the purpose of explaining the difference of thermal fatigue property between STS 304,310S and XM15J1.

II. Experimental Procedures

The chemical compositions of STS 304, 310S and XM15J1 are given in Table I, which were provided by POSCO in 12mm thick plates. The plates were machined into rod-type specimens with gauge length of 15mm and diameter of 6mm for thermal fatigue test.

TABLE I
Chemical Compositions of the Alloys Used in This Study (wt.%)

Alloys	Ni	Cr	C	Mn	Mo	Si	Cu	Fe
304	8.25	18	0.05	1.1	0.1	0.5	0.2	Bal.
310S	19.5	25	0.04	1.3	0.01	0.5	0.1	Bal.
XM15J1	13.5	20	3.62	0.6	-	3.6	-	Bal.

Thermal cycle scheduled in this study is schematically illustrated in Fig. 1. Full constraint condition was applied, in which the both ends of the specimens were completely fixed during the tests. The minimum temperature (T_{min}) was 200°C in all cases and the maximum temperature (T_{max}) was taken as 800 and 900°C. The specimens were set to show zero-load at the mean temperature (T_{mean}) using a universal testing machine (Instron 8501 Plus). Specimens were heated up by induction method and cooled down by directly blowing air. The temperature of specimen during thermal cycles was measured through a thermocouple spot-welded on the surface of specimen. The load of specimen during thermal cycles was recorded using a load-cell attached to the universal testing machine. Fig. 2 shows an example of thermal fatigue test conducted in this study.

J. Moon is with the Department of Electronics Engineering, Gangneung-Wonju National University, 120 Gangneung-daehangno, Gangneung, Gangwon 210-702, South Korea.
T. K. Hais with the Department of Advanced Metal and Materials Engineering, Gangneung-Wonju National University, 120 Gangneung-daehangno, Gangneung, Gangwon 210-702, South Korea (phone: 82-10-2367-1989; e-mail: tkha@gwnu.ac.kr).

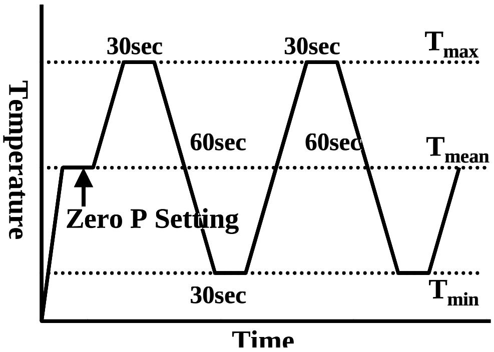

Fig. 1 Schematic illustration of the thermal cycle scheduled in this study

Fig. 2 Experimental apparatus for thermal fatigue test used in this study

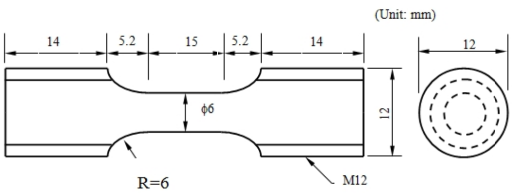

Fig. 3 Dimensions of specimen used in this study

Thermal expansion coefficients of the stainless steels were measured at temperatures from 20 to 1000°Cwith heating rate of 2°C/min, using NETZSCH DIL402C.

III. Results and Discussion

Fig. 3 shows an example of temperature control and load variation of a specimen at the initial stage of thermal fatigue test. It is apparent that the temperature of specimen was successfully controlled between 200 and 800°C. Variations of load experienced by specimens during thermal fatigue test of 200-800°C temperature cycles are given in Fig. 4.

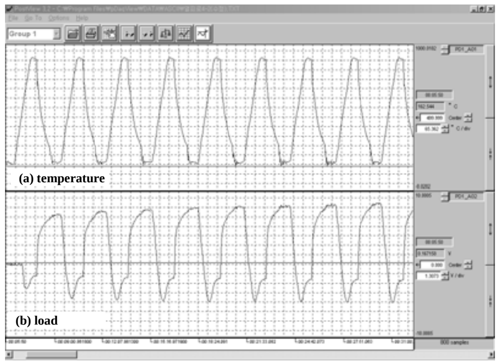

Fig. 3 An example of temperature control and load monitoring at the initial stage of thermal fatigue test conducted under 200-800°C temperature cycles

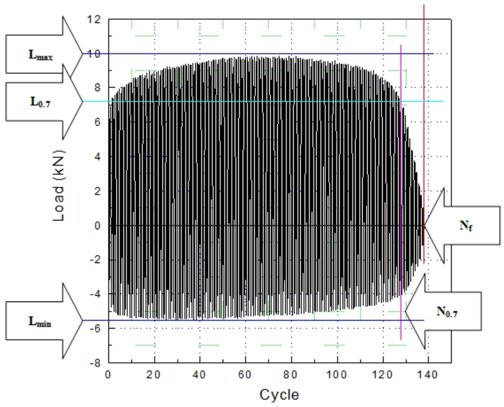

Fig. 4 Variations of load experienced by aspecimen under 200-800°C temperature cycles and schematic illustrations of load and cycle of thermal fatigue

Fig. 5 shows thermal expansion coefficients of 300 series stainless steels used in this study at the temperatures ranging from room temperature to 1000°C. Thermal expansion coefficient of STS304 is somewhat higher than those of 310S and XM15J1 in all temperature range, which is caused by the fact that Ni content of STS 304 is much lower than that of 310S and XM15J1 steels. Thermal expansion coefficient curve of XM15J1 has negative slope at the temperatures ranging from 550 to 650°C, which is presumably attributed to phase transformation or precipitation.

TABLE II
Characteristics of Thermal Fatigue of Alloys Used in This Study

200-800°C	N_f	$N_{0.7}$	L_{max}(MPa)	L_{min}(MPa)
304	140	143	370	-215
310S	133	137	417	-223
XM15J1	138	130	355	-210
200-900°C	N_f	$N_{0.7}$	L_{max}(MPa)	L_{min}(MPa)
304	83	76	340	-194
310S	60	58	381	-182
XM15J1	64	59	328	-188

In Table II, results of thermal fatigue tests were summarized. It is interesting to note that the load of STS 304 is much higher than those of 310S and XM15J1 steels. Thermal fatigue lives of

304 stainless steels were also superior to 310S and XM15J1 steels. In Fig. 4, the number of thermal cycles until failure is defined as N_f, fatigue life, and the number of cycles till the load drops to 70% of peak value as $N_{0.7}$.

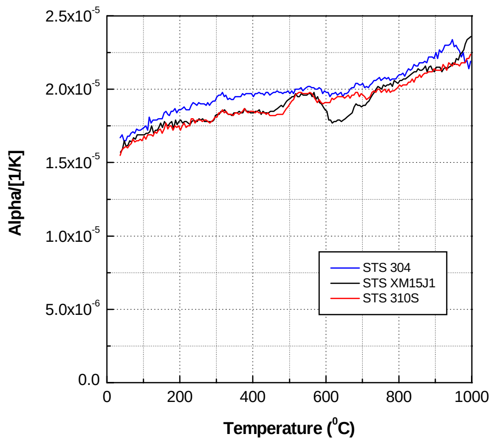

Fig. 5 Thermal expansion coefficients of 300 series stainless steels used in this study

It is interesting to note that the failure occurred by barreling in the center part and necking at the edge part of heating zone as shown in Fig. 6. This peculiar shape change is attributed to the full constraint condition employed in this study, in which the thermal stress can only be removed by plastic deformation of specimen. The complete blocking of thermal expansion and contraction is closely related with load relaxation behavior of testing materials especially at T_{max}.

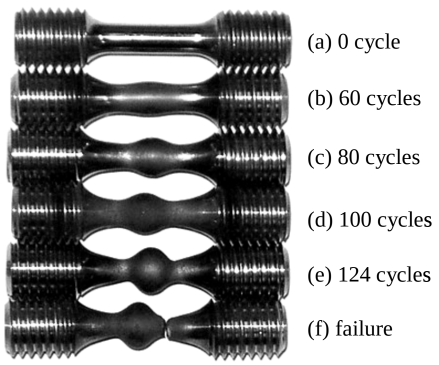

Fig. 6 Appearances of STS 304 specimen tested under 200-800°C thermal cycles

It is well known that the tendency of thermal fatigue failure is related to the parameter σ_f k/Eα, where σ_f is the fatigue strength at the mean temperature, k the thermal conductivity, E the Young's modulus, and α the thermal expansion coefficient, respectively [9]. A high value of this parameter indicates good resistance to thermal fatigue. Austenitic stainless steel has been known to be particularly sensitive to thermal fatigue because of its low thermal conductivity and high thermal expansion.

In fact, in the present study, the thermal expansion coefficient of STS 304 (ranging from 1.6×10^{-5} at 20°C to 2.2×10^{-5} at 1000°C) was found to be similar to the other steels. It is reported that thermal conductivity of STS 304 stainless steel is higher than that of the other steels [10]. Considering the fact that the fatigue strength σ_f is generally dependent on the tensile strength, the σ_f of STS 304 is expected somewhat higher than that of the other steels. Assuming Young's modulus of austenitic stainless steelsis comparable to one another, the value of the parameter σ_f k/Eα for STS 304 is higher than those of the other steels. Although, this parameter alone is not enough to successfully explain the result given in Table 1 and, a large number of systematic and accurate measurements of σ_f, k, E, and α should be performed.

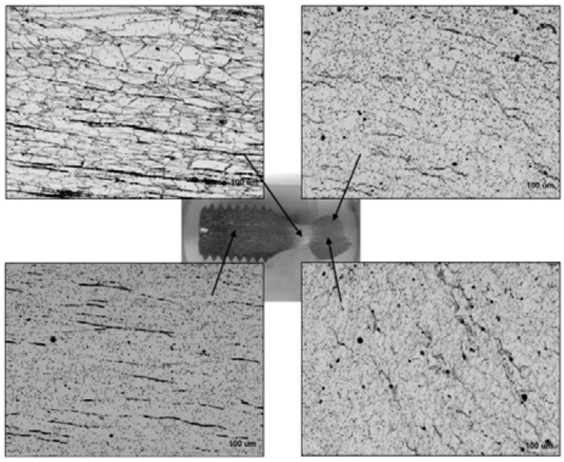

Fig. 7 Microstructure of STS 304 specimen tested under 200-800°C thermal cycles

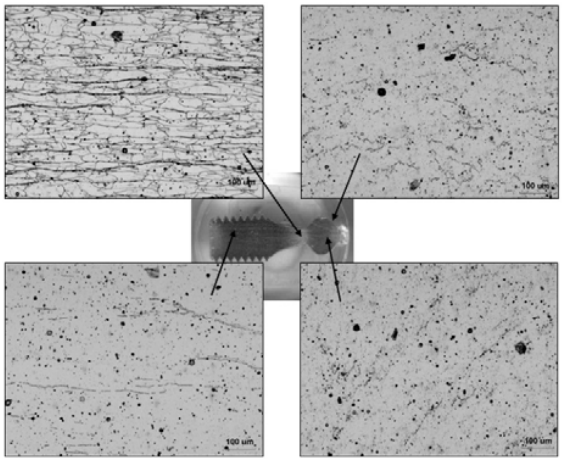

Fig. 8 Microstructure of STS 304 specimen tested under 200-900°C thermal cycles

Fig. 7 shows the microstructure of 304 stainless steel observed after thermal fatigue test conducted under thermal cycles of 200-800°C. Recrystallization has occurred during thermal cycles at the necking region, while other regions showed no trace of plastic deformation. In the case of 200-900^{o}C thermal cycles, similar results were obtained as illustrated in Fig. 8.

IV. Conclusions

Systematic methods for control of temperatures within the predetermined range and measurement of load applied to specimens as a function of temperature during a thermal cycle have been established. Thermal fatigue properties of 304, 310S, and Xm15J1 stainless steels have been evaluated in the temperature ranges of 200-800^{o}C and 200-900^{o}C. Thermal fatigue property of STS 304 was superior to that of the other 300 series stainless steels.

Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation (NRF) funded by the Ministry of Education, Science and Technology. (No. 2011-0013839).

References

[1] R. Zuchowski, PraceNaukowe Inst. Mater. I Mech. Tech. Pol. Wrocl., vol. 43, 1989.
[2] D. A. Spera, "*Thermal fatigue of materials and components*," ASTM STP 612, p. 69, 1976.
[3] F. D. Fisher, F. G. Rammersdorfer, F. J. Bauer, Metall. Trans. A, vol. 21, p. 935, 1990.
[4] N. Matsuura, 2nd Annual Conference of the International Stainless Steel Forum, Market Development Committee, p. 1, 1998.
[5] J. W. Kwon, Y. H. Kim, and Y. D. Lee,The 7th Steel Symposium on "*Development of Automotive Materials and Parts for Weight Reduction*", Eds. by O. Kwon, Y. S. Jin, S. J. Kim, and W. P. Lee, KIM, Korea,p. 285, 2000.
[6] Y. D. Lee, and S. H. Park,Bull. of the Koeran Inst. of Met. &Mater.,vol. 6, p. 41, 1993.
[7] J. W. Kwon, Y. Y. Lee, and Y. D. Lee,Materials at High Temperature, vol. 17, p. 319, 2000.
[8] M. Barteri, M. G. Mecozzi, and S. Fortunati, International Congress Stainless Steel '99, vol. 3, p. 75, 1999.
[9] N. Fujita, N. Ohmura, E. Sato, and A. Yamamoto, Nippon Technical Report, No. 71, p. 25, 1996.
[10] F. Cverna, "*Thermal Properties of Metals*," ASM International, Materials Park, Ohio, 2002.