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Thermal Fatigue Behavior of 400 Series Ferritic Stainless Steels

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Abstract**—**In this study, thermal fatigue properties of 400 series ferritic 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. It has been revealed that load relaxation behavior at the temperatures of thermal cycle was closely related with the thermal fatigue property. Thermal fatigue resistance of 430J1L stainless steel is found to be superior to the other steels.

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

I. Introduction

EXHAUST manifolds are used in an environment that includes engine vibrations as well as heating and cooling cycles caused by the travel pattern. Therefore, among high-temperature characteristics, thermal fatigue resistance is an important one that affects the life span of an exhaust manifold. When the parts made of sheet steels suffer thermal fatigue, deflection and local strain concentration may cause buckling. In many cases, once bucking occurs, thermal strain may be concentrated at the point of buckling, resulting in fracture. Accordingly, it is important to restrict buckling for improvement of thermal fatigue resistance of steel sheets. Therefore, high proof strength at high temperature is required of such materials [1], [2]. Generally, 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 [3]. Especially, the operation temperature of the exhaust manifolds of hot end reaches up to 900°C and higher [4]. Increasing demands for weight reduction of automotive and high performance of engine systems give rise to employment of more advanced steels in automotive industry such as heat-resisting stainless steels [5]-[7].

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 [8]. 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 originated 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. Changes of the shapes of specimens have been observed as a result of thermal fatigue and internal constraints [9].

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 409, 429EM and 430J1L, 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 409, 429EM, and 430J1L.

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II. Experimental Procedures

The chemical compositions of STS 409, 429EM, and 430J1L are given in Table I, which were provided by POSCO in 12 mm thick plates. The plates were machined into rod-type specimens with gauge length of 15 mm and diameter of 6 mm 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
409	0.11	14	0.09	0.28	0.02	0.5	0.1	Bal.
429EM	0.13	11	0.07	0.27	0.01	1.5	0.1	Bal.
430J1L	0.15	19	0.02	0.27	0.05	0.3	0.5	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.

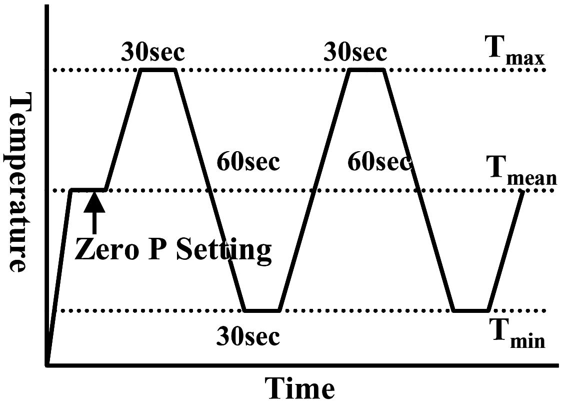

Fig. 1 Schematic illustration of the thermal cycle scheduled in this study

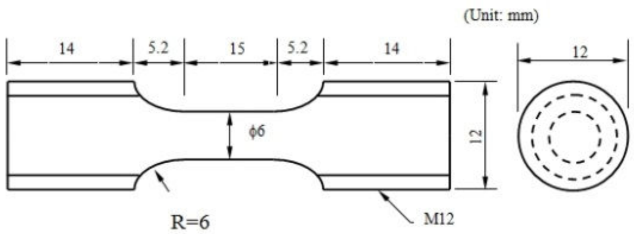

Fig. 2 Dimensions of specimen used in this study

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

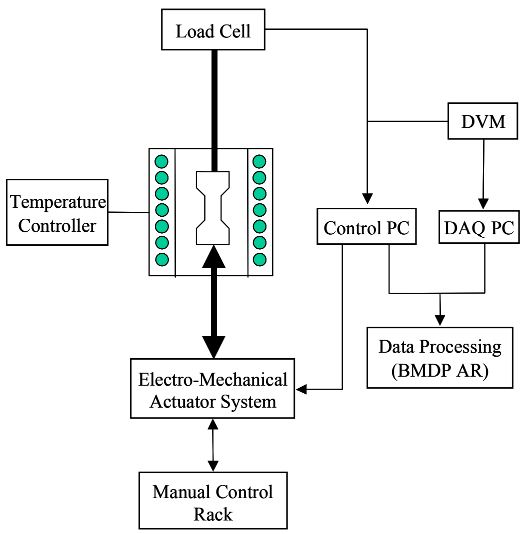

Fig. 3 Schematic illustration of load relaxation test employed in this study

Load relaxation tests were then carried out at the temperatures of 800°C and 900°C by using a computer controlled electro-mechanical testing machine (Instron 1361 model) attached with a furnace capable of maintaining the temperature fluctuation within ±1°C as schematically shown in Fig. 3. The variation of load with time was monitored through a DVM and stored in a personal computer for subsequent data analysis to determine the flow stress σ and inelastic strain rate $\dot{\varepsilon}$ following the usual procedure described in the literature. [10]

III. Results and Discussion

Fig. 4 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. 5.

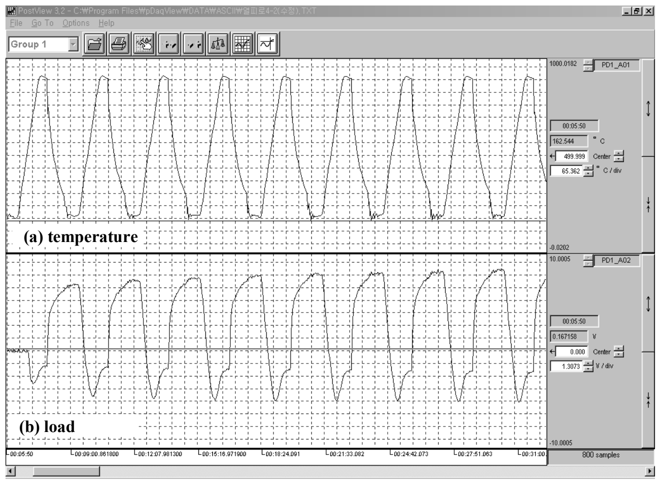

Fig. 4 An example of temperature control and load monitoring at the initial stage of thermal fatigue test conducted under 200-800°C temperature cycles

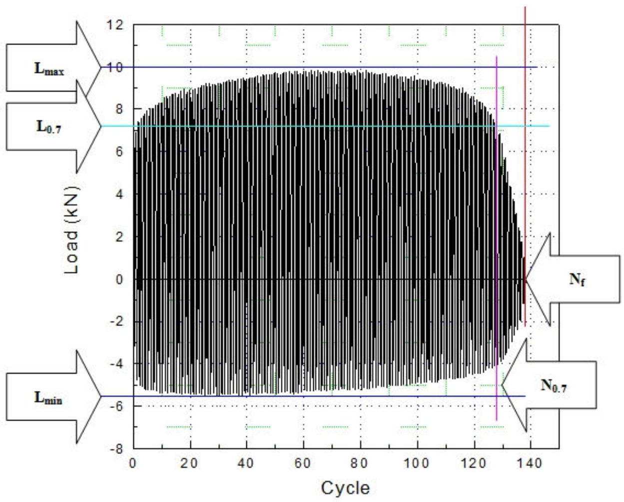

Fig. 5 Variations of load experienced by a specimen under 200-800°C temperature cycles and schematic illustrations of load and cycle of thermal fatigue

Fig. 6 shows thermal expansion coefficients of 400 series stainless steels used in this study at the temperatures ranging from room temperature to 1000oC. Thermal expansion coefficient of STS 429EM is somewhat higher than those of 409 and 360J1L in the temperature range over 700oC, which is caused by the fact that Cr content of STS 429EM is much lower than that of 409 and 360J1L steels. Thermal expansion coefficient curve of 400 series stainless steels has negative slope at the temperatures ranging from 600 to 700oC, which is presumably attributed to magnetic transition or phase transformation or precipitation. Interestingly, Thermal expansion coefficient curve of 400 series stainless steels showed very similar values at temperatures below the temperature of 700°C.

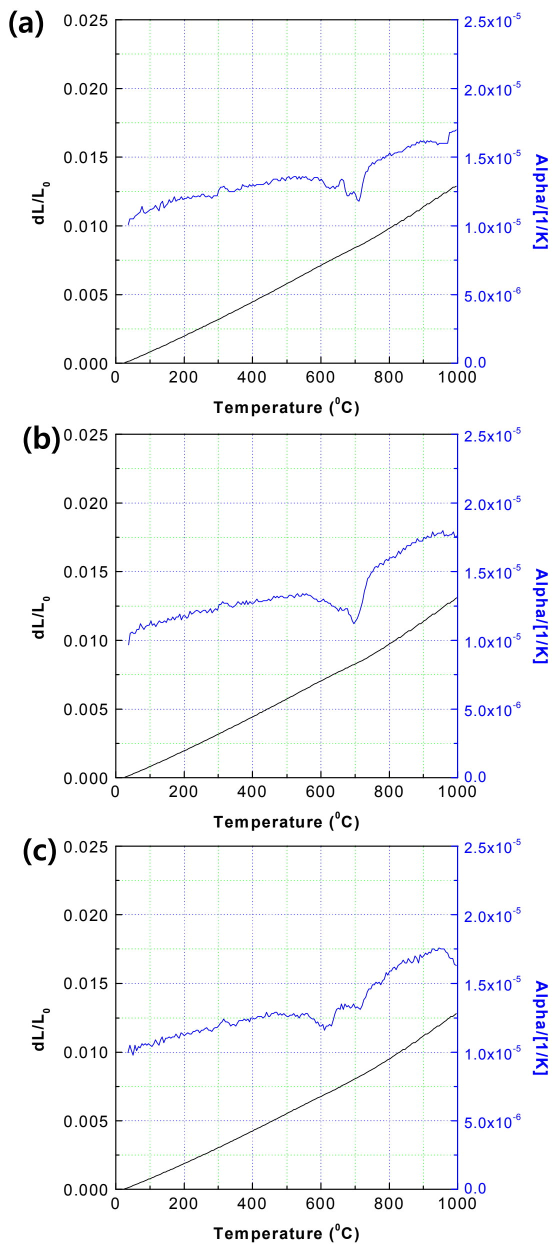

Fig. 7 Thermal expansion coefficients of STS 409 (a), 429EM (b), and 430J1L (c), respectively, obtained at temperature range from 20 to 1000°C

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)
409	82	68	182	-119
429EM	100	91	249	-100
430J1L	102	93	276	-110
200-900°C	N_f	$N_{0.7}$	L_{max}(MPa)	L_{min}(MPa)
409	66	54	182	-122
429EM	81	72	253	-100
430J1L	77	63	268	-106

In Table II, results of thermal fatigue tests were summarized. It is interesting to note that the load of STS 430J1L is much higher than those of 409 and 429EM steels. Thermal fatigue lives of 429EM stainless steels were also superior to 409 and 430J1L steels. In Fig. 5, 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 $N_{0.7}$.

It is interesting to note that the failure of specimen occurred by barreling in the center part and necking at the edge part of heating zone as shown in Fig. 8. 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. 8 shows the microstructure of 409 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°C thermal cycles, similar results were obtained as illustrated in Fig. 9.

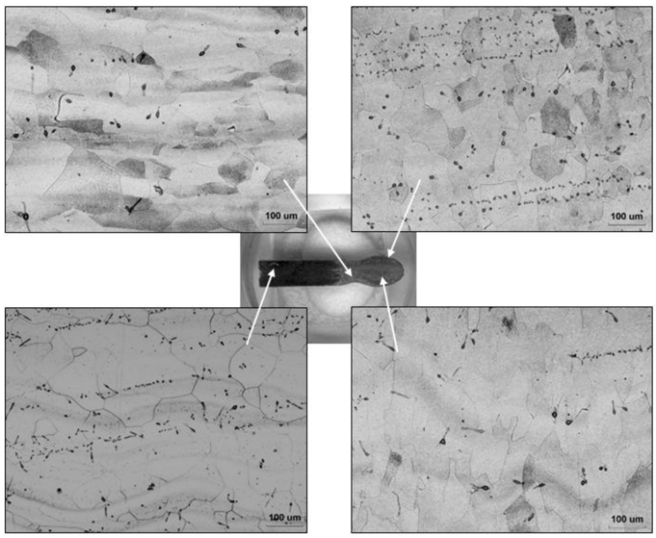

Fig. 8 Microstructure of STS 429EM specimen tested under 200-800°C thermal cycles

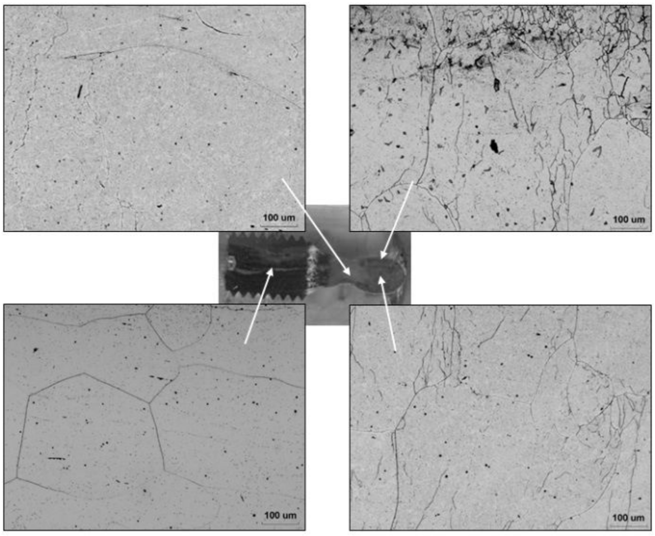

Fig. 9 Microstructure of STS 430J1L specimen tested under 200-900°C thermal cycles

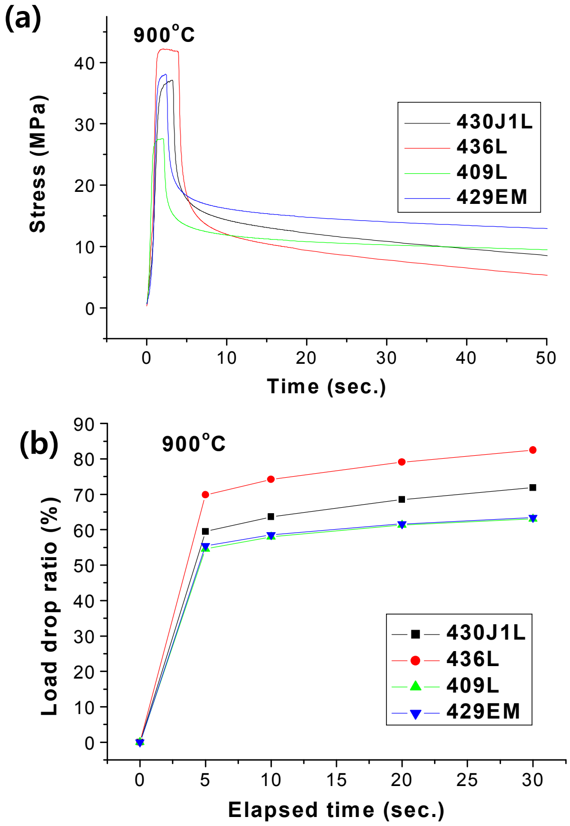

Fig. 10 Load relaxation curves (a) and load drop rate (b) of 400 series stainless steels obtained at temperature of 900°C

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. Generally, austenitic stainless steels have higher strength than ferritic stainless steels at high temperature. However, thermal fatigue resistance of ferritic stainless steel is higher than that of austenitic stainless steels due to the lower thermal expansion coefficient.

Fig. 10 shows the load relaxation test results, in which drop ratio was displayed as a function of elapsed time obtained at 900°C together with 436L. Apparently, the load drop rate of STS 436J1L is much higher than the other stainless steels, which indicates that STS 436J1L is deformed faster during thermal cycles and reaches earlier failure. In other words, faster deformation during thermal cycles seems to expedite necking and lower strength causes earlier failure.

In fact, in the present study, the thermal expansion coefficient of STS 429EM (ranging from 1.0×10-5 at 20oC to 1.8×10-5 at 1000oC) was found to be somewhat higher than the other steels. It is reported that thermal conductivity of 400 series stainless steel is comparable to one another [11]. Considering the fact that the fatigue strength σf is generally dependent on the tensile strength, the σf of STS 430J1L is expected somewhat higher than that of the other steels. Assuming Young's modulus of austenitic stainless steels is comparable to one another, the value of the parameter σf k/Eα for STS 430J1L is higher than those of the other steels. Although, this parameter alone is not enough to successfully explain the result given in Table I and, a large number of systematic and accurate measurements of σ_f, k, E, and α should be performed.

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 409, 429EM, and 430J1L stainless steels have been evaluated in the temperature ranges of 200-800°C and 200-900°C. Thermal fatigue property of 430J1L was superior to that of the other 400 series stainless steels. Load relaxation behavior was found to be closely related with thermal fatigue properties of 400 series stainless steels.

Acknowledgment

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