**TeNSILE AND LOW-CYCLE FATIGUE PROPERTIES OF Fe–15Mn–4Si–10Cr–8Ni ALLOY for FATIGUE-RESISTANT SEISMIC DAMPERS**

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**ABSTRACT**

Steel seismic dampers have a large load capacity, high stiffness, and outstanding cost-to-performance ratio, making them indispensable for economical vibration-control structures. As a new problem, long-period ground motion is likely to cause high-rise buildings to resonate, thereby inducing large-amplitude cyclic deformation of seismic dampers. In earthquake-prone countries, it is difficult to overcome this problem with conventional steel dampers because their fatigue resistance is insufficient. A Fe–15Mn–4Si–10Cr–8Ni alloy with enhanced low-cycle fatigue resistance has been developed to provide a new steel seismic damper with superior fatigue-resistance against large-amplitude cyclic deformations. This study aims to confirm the tensile and low-cycle fatigue properties of this alloy under conditions that are relevant to seismic dampers. The results of tensile-strength tests of this alloy show that it has a small yield–tensile ratio, a large elongation, and undergoes stable deformation. The results of symmetric tensile–compressive low-cycle fatigue tests of this alloy show that it has an outstanding fatigue life in comparison with the steels that are used for conventional steel dampers under broad conditions. The aforementioned results confirm that the tensile and low-cycle fatigue properties of this alloy make it suitable for use in seismic dampers.

*Keywords: Fe*–*Mn*–*Si-based alloy; Long-period ground motion; Tensile strength; Low-cycle fatigue property*

**1. INTRODUCTION**

Structures for seismic isolation and vibration control to protect buildings from being damaged by earthquakes have become widespread in earthquake-prone countries. Steel seismic dampers have large load capacity, high stiffness, and outstanding cost-to-performance ratio, making such dampers widely used and indispensable in economical vibration-control structures.

In recent years, long-period ground motion has emerged as a new problem in that long-period earthquake waves are likely to resonate with the natural period of high-rise buildings, causing them to vibrate for a long time and with large amplitude. In this situation, large-amplitude cyclic deformation occurs in the seismic dampers that are installed in high-rise buildings. It is difficult to overcome this problem with conventional steel dampers because their fatigue resistance is insufficient. Consequently, to withstand these large-amplitude cyclic deformations, the durability of seismic dampers must be increased appreciably.

Against this background, we focus on the Fe–15Mn–4Si–10Cr–8Ni alloy to develop a new steel seismic damper with superior fatigue resistance. This alloy was developed based on Fe–Mn–Si-based shape-memory alloys. This study aims to confirm the tensile and low-cycle fatigue properties of this alloy regarding its use in seismic dampers. We conducted uniaxial static tensile-strength test and low-cycle fatigue tests on this alloy, and the results show that its tensile properties and low-cycle fatigue characteristics make it suitable for use in seismic dampers against large-amplitude cyclic deformation caused by long-period persistent earthquake motion.

**2. FATIGUE RESISTANT FE–MN–SI-BASED ALLOY**

We focused on fatigue-resistant Fe–Mn–Si-based alloys to provide a new steel seismic damper with superior fatigue resistance against large-amplitude cyclic deformations. Fe–Mn–Si-based alloys are low-cost ferrous shape-memory alloys that are applicable to large structural components. Their shape memory is associated with the deformation-induced → martensitic transformation and its reversion on subsequent heating. Additionally, this transformation in Fe–Mn–Si-based alloy has been reported to lead to the reverse transformation via counter-directional deformation (Sawaguchi et al. 2006). Recently, reversible two-way martensitic transformation under cyclic tensile–compressive loading has also been shown to improve low-cycle fatigue life (Sawaguchi et al. 2015).

Based on these findings, a Fe–15Mn–4Si–10Cr–8Ni alloy was developed for use in steel seismic dampers with superior fatigue resistance (Sawaguchi et al. 2015). The development was carried out in consideration of mass production for use in large-scale structural members for buildings. The manganese concentration of the developed alloy was kept at 15 % mass by weight, thereby allowing for mass production in electric arc furnaces.

We have developed shear-panel-type fatigue-resistant Fe–15Mn–4Si–10Cr–8Ni alloy seismic dampers as shear panels to counteract long-period ground motion (Sawaguchi et al. 2016). In 2014, 16 seismic dampers made of this alloy were installed in a 196-m-tall high-rise building in Nagoya, Japan. In that project, Fe–15Mn–4Si–10Cr–8Ni alloy rolled plates were produced for industrial use by an electric arc furnace with an authorized capacity of 10 tons. Figure 1 shows the appearance of a Fe–15Mn–4Si–10Cr–8N alloy rolled plate produced by the electric arc furnace and having a thickness of 18.5 mm, a width of 1,260 mm, and a length of 3,550 mm.

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Figure 1. Fe–15Mn–4Si–10Cr–8Ni alloy rolled plate produced in an electric arc furnace

Recently, it has become possible to produce these alloy rolled plates by using continuous casting, a general industrial method for producing rolled plates made of stainless steel. This progress regarding mass production has resulted in large rolled plates with low cost and excellent dimensional accuracy.

Figure 2 shows the appearance of a Fe–15Mn–4Si–10Cr–8Ni rolled plate produced by continuous casting using a melting furnace with an authorized capacity of 60 tons. These plates are 23 mm thick, 1,300 mm wide, and 10,000 mm long, and their dimensional accuracy and surface condition are good. Moreover, these plates satisfy the same quality-control standards as do structural steels for use in buildings. The specimens used in the present study were taken from Fe–15Mn–4Si–10Cr–8Ni alloy rolled plates produced using continuous casting process.

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Figure 2. Fe–15Mn–4Si–10Cr–8Ni alloy rolled plate produced by continuous casting

**3. TENSILE AND LOW-CYCLE FATIGUE TESTS**

***3.1 Tensile-strength tests***

We conducted an uniaxial static tensile-strength test on the Fe–15Mn–4Si–10Cr–8Ni alloy to assess its essential mechanical properties. For use in brace-type seismic dampers, the specimens were cut from the alloy rolled plates in the longitudinal direction. Figure 3 shows the dimensions of a specimen.

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Figure 3. Dimensions of a specimen used in this tensile strength test

Figure 4 shows the results of the static tensile-strength test conducted on this alloy. The engineering strain was measured using strain gauges, and continuous yielding behavior was observed in the stress–strain curves of this alloy. Consequently, a proof stress of 0.2% was used to determine its yield strength. Table 1 gives the mechanical properties of the alloy as obtained from this test. These results indicate that this alloy has a small yield–tensile ratio, large elongation, and undergoes stable deformation, making it suitable for use in seismic dampers.

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Figure 4. (a) Stress–strain curve and (b) stress–displacement curve obtained from the tensile-strength test

Table 1. Mechanical properties

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| **0.2 % proof stress**  **(N/mm2)** | **Tensile strength**  **(N/mm2)** | **Yield-point ratio**  **(%)** | **Elongation**  **(%)** |
| 285 | 661 | 43.1 | 54 |

***3.2 Low-cycle fatigue tests***

Low-cycle fatigue tests of the Fe–15Mn–4Si–10Cr–8Ni alloy were conducted by applying a symmetric tensile–compressive loading over total strain amplitudes in the range 0.01–0.04. Figure 5 shows the specimen dimensions.

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Figure 5. Dimensions of specimens used in low-cycle fatigue tests.

Figure 6 shows the low-cycle fatigue behavior of this alloy, which under broad amplitude conditions, has an outstanding fatigue lifetime compared with the low-yield-point steel (LY225) used in conventional steel dampers. Additionally, we have confirmed that this alloy produced by continuous casting has a fatigue lifetime similar to that of this alloy produced in an electric furnace in previous work (Sawaguchi et al. 2016). Furthermore, a recent report has also confirmed the superior fatigue lifetime of this alloy when subjected to extremely high strain amplitudes (Nikulin et al. 2018). For example, this alloy exhibits a fatigue lifetime of 112 cycles at a total strain amplitude of 0.08, at which steel is reported to fail in fewer than 10 cycles.

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Figure 6. Low-cycle fatigue characteristics of Fe–15Mn–4Si–10Cr–8Ni alloy

Figure 7 shows the stress–strain hysteresis loops at various strain amplitudes. Each stress–strain curve shown in Figure 7 was plotted over roughly half the fatigue lifetime (*Nf*/2) in each test. The alloy exhibited stable hysteresis loops across a range of strain form small to large. As a comparison, Figure 8 shows the stress–strain hysteresis loops of LY225. As Figure 7 and 8 show, the stress–strain hysteresis loops of this alloy are different in shape from those of LY225. Because of strain hardening, the hysteresis loops of the alloy are characterized by a larger rise in stress in the plastic region compared to that for LY225.

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Figure 7. Stress–strain hysteresis loops of Fe–15Mn–4Si–10Cr–8Ni alloy during low-cycle fatigue tests

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Figure 8. Stress–strain hysteresis loops of low-yield-point steel (LY225) during low-cycle fatigue tests

Figure 9 shows the evolution of the tensile and compressive peak stress with the number of cycles for each low-cycle fatigue test. As Figure 9 shows, the peak stress increased because of strain hardening in approximately 1–10 cycles. This confirms that the peak stress was stable until just before failure.

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Figure 9. Peak stress during low-cycle fatigue tests

***3.3 Studies of analysis models***

As mentioned in Section 3.2, the stress–strain hysteresis loops of the Fe–15Mn–4Si–10Cr–8Ni alloy differ in shape from those of the LY225 steel. To evaluate the hysteresis loops and the characteristic values of the alloy analytically, we must consider a new appropriate analytical model. Herein, we approximate the hysteresis characteristic of this alloy using the Ramberg–Osgood (RO) function model (Ramberg and Osgood, 1943). The RO model describes the nonlinear relationship between stress and strain and is applied to metals that harden by plastic deformation, thereby exhibiting a smooth elastic–plastic transition. Figure 10 shows the RO model schematically.

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Figure 10. Schematic of Ramberg–Osgood (RO) function model

This model comprises a skeleton curve [Equation 1] and a hysteresis curve [Equation 2].

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where , and ** and ** are form factors. We calculated the stress–strain hysteresis curves of the Fe–15Mn–4Si–10Cr–8Ni alloy by substituting the following values into Equation 1 and 2.

Figure 11 shows the stress–strain curves calculated using the RO model and those obtained from the low-cycle fatigue tests. The hysteresis curves according to this model clearly match well with the experimental results. Consequently, we confirmed that the hysteresis curves of this alloy obtained using the RO model accurately reproduce the experimental hysteresis curves at each strain amplitude.

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Figure 11. Stress–strain curves calculated using the RO model (blue) and from experiments (black)

**4. Conclusions**

In this study, we confirmed that the tensile properties and low-cycle fatigue characteristics of Fe–15Mn–4Si–10Cr–8Ni alloy make it suitable for use in fatigue-resistant seismic dampers against large-amplitude cyclic deformations. Additionally, we confirmed that the hysteresis curves of this alloy obtained using the RO function model accurately reproduce the experimental value at each strain amplitude.

**5. Acknowledgments**

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**6. References**

Sawaguchi T., Sahu P., Kikuchi T., Ogawa K., Kajiwara S., Kushibe A., Higashino M. and Ogawa T. (2006) Vibration mitigation by the reversible fcc/hcp martensitic transformation during cyclic tension-compression loading of an Fe–Mn–Si-based shape memory alloy, Scripta Materialia, **54**(11):1885-1890.

Sawaguchi T., Nikulin I., Ogawa K., Sekido S., Takamori T., Maruyama T., Chiba Y., Kushibe A., Inoue Y. and Tsuzaki K. (2015) Designing Fe–Mn–Si alloys with improved low-cycle fatigue lives, Scripta Materialia, **99**: 49-52.

Sawaguchi T., Maruyama T., Otsuka H., Kushibe A., Inoue Y., Tsuzaki K. (2016) Design concept and applications of Fe–Mn–Si-based alloys –from shape-memory to seismic response control-, Materials Transactions, **57**(3):283-293.

Nikulin I., Nagashima N., Yoshioka F., Sawaguchi T. (2018) Superior fatigue life of Fe–15Mn–10Cr–8Ni–4Si seismic damping alloy subjected to extremely high strain amplitudes, Materials Letters, **230**:257-260.

Ramberg, W., & Osgood, W. R. (1943). Description of stress–strain curves by three parameters. *Technical Note No. 902*, National Advisory Committee for Aeronautics, Washington DC.

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