A STUDY ON TENSILE STRENGTH DISTRIBUTION AND ITS TEMPERATURE DEPENDENCE FOR AMORPHOUS ALLOY RIBBONS

T. Sakai* and T. Ito**

Various kinds of amorphous alloys have been developed and applied to the electromagnetic and mechanical uses. Atomic packing feature of amorphous metals is almost random and crystalline grains are no longer formed anywhere in the material. A lot of works have been made on the electromagnetic properties, but their mechanical properties required to the mechanical design are still unsolved. From this point of view, tensile properties of Fe-base amorphous alloy ribbons together with their distribution characteristics were experimentally examined in a wide temperature range of room temperature to 500℃. Their distribution aspect was analysed by means of Weibull statistics. Based on the temperature dependence of the distribution parameters, the strength distribution at any temperature was quantitatively given as *P-S-T* characteristics.

INTRODUCTION

Atomic packing feature of amorphous metals is almost random and crystalline grains are no longer formed so that no grain boundary takes place in the material. Based on this significant microstructure, amorphous metals have some advantageous mechanical and electromagnetic properties. A lot of works have been made on the electromagnetic properties in respect to the processing conditions(1,2), but their mechanical properties required to the mechanical design are still unsolved at the present stage(3). It is supposed that the microstructure of any amorphous metal depends on the temperature and the mechanical properties also depend on the temperature. If the recrystallization takes place in the material, the mechanical properties would be degraded drastically.

From this point of view, tensile properties of the Fe-base amorphous alloy(Metglas: 2605S-2) were examined together with their distribution characteristics in a wide temperature range of room temperature to 500℃ in this study. Distribution characteristics of the tensile strength obtained at various temperatures were analysed by means of Weibull statistics. Based on the temperature dependence of the distribution parameters, Strength-Temperature relationship for any Probability of failure was analytically provided as *P-S-T* characteristics of the present material.

* Faculty of Science and Engineering, Ritsumeikan University
1-1-1 Nokihigashi, Kusatsu, Shiga, 525-8577 JAPAN
** Graduate School of Science and Engineering, Ritsumeikan University
1-1-1 Nokihigashi, Kusatsu, Shiga, 525-8577 JAPAN

SPECIMEN AND EXPERIMENTAL PROCEDURE

The material used in this study is amorphous alloy ribbon($Fe_{78}B_{13}Si_9$) produced through the rapid quenching by the Allied Metglas Products Co., and it is commercially supplied as Metglas 2605S-2. Thickness of this amorphous ribbon is 25 μm and its width is 50mm,

Table 1 Chemical composition of the material (mass %).

B	Si	C	Mn	Al	P	S	Cu	Fe
2.06	5.32	0.1>	0.1>	0.1>	0.1>	0.1>	0.1>	Bal.

Table 2 Typical properties of the material.

Young's modulus E(GPa)	Vickers hardness Hv(GPa)	Thermal expansion α (/℃)	Density ρ (g/cm^3)	Saturation induction (Tesla)
57	10.1	7.6x10^{-6}	7.18	1.56

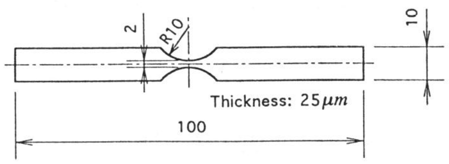


Fig.1 Configuration of tensile specimen.

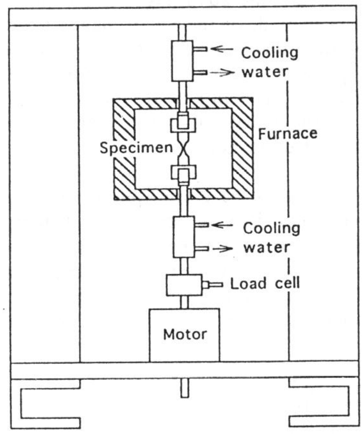


Fig.2 Schematics of tensile testing machine.

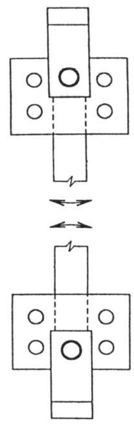


Fig.3 Chucking device.

respectively. The chemical composition and typical properties of the present material are shown in Tables 1 and 2, respectively. Configuration of the tensile specimen is shown in Fig.1, where the longitudinal direction of the specimen is adjusted to agree with that of the amorphous ribbon supplied.

Schematics of tensile testing machine originally developed in this study is shown in Fig.2. Specimen is mounted between top and bottom chucks and surrounded by an electric furnace. Loading lods are cooled by circulation of water as shown by arrows in Fig.2. The bottom lod is pulled down by a motor. Thus the tensile load is applied and the load is picked up by means of a load cell. Chucking devices is designated not to cause any moment to the specimen as indicated in Fig.3.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Tensile Strength Distributions

Tensile tests were repeatedly performed by using thirty specimens at each temperature of room temperature(RT), 100℃, 200℃, 300℃, 400℃ and 500℃, respectively. Weibull plots of tensile strength distributions obtained at the respective temperatures are indicated in Fig.4, in which the cumulative probability of i'th weakest strength $F(\sigma_i)$ is calculated by $F(\sigma_i)=(i-0.5)/n$, where n is the total number of specimens assigned to each testing temperature(4). Solid curves passing through the respective experimental results indicate the distribution functions of 3-parameter Weibull distribution fitted by correlation coefficient method proposed by one of the authors(4). Distribution function of Weibull type is represented as follows(5);

$$F(\sigma)=1-\exp\left\{-\left(\frac{\sigma-C}{B}\right)^{A}\right\}, \quad \text{------------------------ (1)}$$

where A, B and C are shape, scale and location parameters, respectively.

Weibull parameters obtained at the respective temperatures are listed in Table 3. Experimental results in the range of RT-300℃ yield within a common band, but the result at T=400℃ gives a distinct scatter. The scatter becomes small again in the

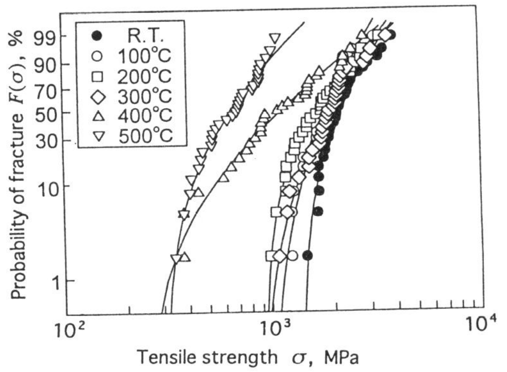


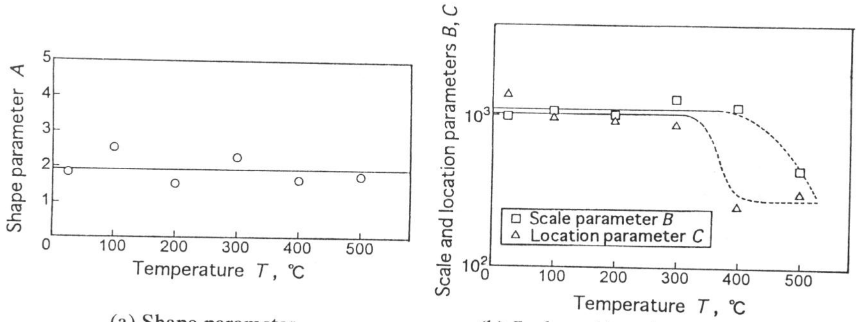
Fig. 4 Tensile strength distributions.

Table 3 List of Weibull parameters.

T(℃)	A	B	C
RT	1.839	9.873×10^2	1.378×10^3
100	2.538	1.084×10^3	9.616×10^2
200	1.532	1.014×10^3	9.150×10^2
300	2.274	1.300×10^3	8.618×10^2
400	1.632	1.142×10^3	2.466×10^2
500	1.742	4.340×10^2	2.999×10^2
RT-300	2.193	1.274×10^3	8.795×10^2

case of T=500℃, although the strength tends to decrease distinctly. It is noted that the upper bound of the result at T=400℃ is almost same as that of the results in RT-300 ℃, whereas the lower bound is close to that of the result at T=500℃.

Weibull parameters are plotted as functions of the testing temperature in Fig.5. Shape parameter is almost constant in the entire range of the temperature. Scale and location parameters also keep almost constant in T<350℃, but they tend to decrease sharply around 350℃-400℃. Temperature dependence of each Weibull parameter is represented by each curve in Fig.5, and one can obtain the parameter values at any temperature through the respective curves.



(a) Shape parameter. (b) Scale and location parameters.

Fig.5 Temperature dependence of Weibull parameters.

P-S-T Characteristics

Since Weibull parameters at any temperature are given through the respective curves in Fig.5, one can calculate the relationship between tensile strength and temperature under a definite probability of failure. *P-S-T* curves thus obtained for failure propbabilities of F=1%, 10%, 50%, 90% and 99% are indicated in Fig.6, in which the dashed curve provides the relationship between location parameter and temperature and this curve gives the lower bound of the strength distribution. *P-S-T* characteristics thus analysed are in good agreement with the overall trend of the experimental results in a wide range of the testing temperature.

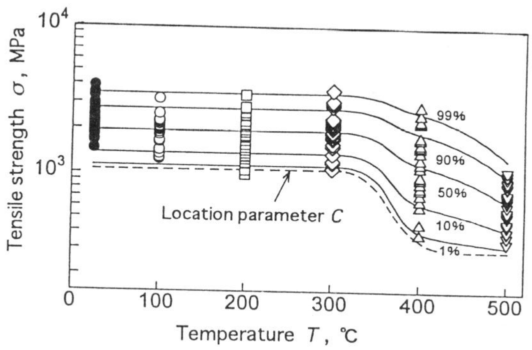


Fig. 6 *P-S-T* characteristics of the present material.

X-ray analysis of the material

Distribution characteristics of the tensile strength were distinctly changed around the temperature of 350℃-400℃ as explained in the previous section. Such a drastic change of the strength distribution would be attributed to the recrystallization of the material. In order to confirm the occurrence of the recrystallization, X-ray diffraction patterns were examined on specimens fractured at the respective temperatures. Fig.7 indicates some examples of the X-ray diffraction profiles obtained on the specimens tested at RT, 300℃ and 400℃, respectively. In a temperature range of RT-300℃, the profile is almost flat as shown in Fig.7(a) and (b). But, a sharp peek and some other slight peeks appears in the case of T=400℃ as seen in Fig.7(c). This peek tends to be a little more distinct in the case of T=500℃.

Based on these results, it was found that the recrystallization took place in the temperature range of $T \geq 400$℃ and the drastic change of the strength distribution in above came from the recrystallization of this material. Thus one can suppose that the experimental results at RT-300℃ provide those of amorphous state whereas the result at T=500℃ gives that of crystalline state of the present material. It is also noted that the results at T=400℃ include those for both states of amorphous and crystal. From this point of view, the results at RT-300℃ were pooled altogether as common data in the amorphous state and Weibull parameters obtained for the pooled data were given at the bottom line in Table 3.

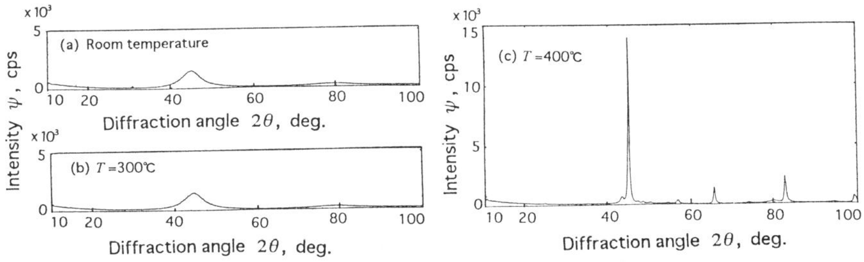


Fig.7 Some examples of X-ray diffraction profiles.

Analysis by Mixed Mode Weibull Distribution

Based on the discussion in the previous section Weibull parameters of the strength distributions for amorphous and crystalline states of the material are given as follows; A_a=2.193, B_a=1.274x10^3, C_a=8.795x10^2 for amorphous, and A_c=1.742, B_c=4.340x10^2, C_c=2.999x10^2 for crystal. Of course, it is supposed that experimental results in both states are mixedly included in the data tested at T=400℃. If the number of specimens in amorphous state is denoted by n_a and that in crystalline state by n_c, then the occurrence probabilities of the respective states are provided as follows;

$$P_a = \frac{n_a}{n} \text{ and } P_c = \frac{n_c}{n}, \qquad (2)$$

where n is the total number of specimens tested at T=400℃. and, therefore, we have $n = n_a + n_c$ in this concept. The lower bound of the results at T=400℃ coincides with that of the results at T=500℃ whereas the upper bound coincides with that of the common results at RT-300℃. Accordingly, we put P_a=0.5 and P_c=0.5 for the sake of convenience. Distribution function in mixed-mode Weibull distribution is given by the following equation(6);

$$F(\sigma) = P_a F_a(\sigma) + P_c F_c(\sigma), \qquad (3)$$

where $F_a(\sigma)$ and $F_c(\sigma)$ indicate distribution functions for amorphous state and crystalline state specimens. They have the common type of distribution function given by Eq.(1).

All the experimental data in Fig.4 are replotted in Fig.8, in which distribution functions of amorphous and crystalline states are plotted by dashed lines passing through the corresponding data points. Solid curve indicates the theoretical distribution function of the tensile strength at T=400℃ calculated by Eq.(3) and this curve yields along the experimental results at this temperature. Thus it is found that the present analysis is reasonable as an attempt to interpret the statistical fluctuation of the tensile strength. However, in order to clarify the detailed aspect of the strength distribution around the recrystallization temperature, more experimental results should be accumulated systematically to obtain the temperature dependence of the occurrence probabilities of P_a and P_c.

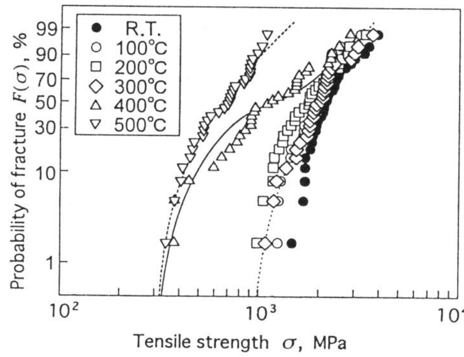


Fig.8 Experimental and analytical tensile strength distributions.

CONCLUSIONS

Main conclusions obtained in this study are summarized as follows; (1)Distribution characteristics of the tensile strength of the present material in the temperature range of RT-300℃ were well represented by a common distribution function in conventional Weibull type. This fact indicates that the strength distribution is independent of the temperature in this temperature range and it gives the distribution function for the amorphous state specimens. (2) Recrystallization of the material was completed at T=500℃ and the strength distribution was also represented by a conventional Weibull distribution having different values of distribution parameters. This was thought of the distribution function for the crystalline state specimens. (3)Characteristic strength distribution at T=400℃ was successfully explained by means of the mixed-mode Weibull distribution, which was composed of distribution functions for amorphous and crystalline states specimens.

REFERENCES

(1) Datta, A., DeCristofaro, N. J. and Davis, L. A., Proc. 4th Int. Conf. on Rapidly Quenched Metals, Vol.2, 1981, pp.1007-1010.
(2) Wakamiya, M., J. Soc. Mater. Sci., Japan, Vol.42, 1993, pp.771-779.
(3) Kimura, H. and Masumoto, T., Acta Metallurgica, Vol.31, 1983, pp.231-240.
(4) Sakai, T. and Tanaka, T., Proc. Int. Conf. Fatigue'84, Vol.2, 1984, pp.1125-1137.
(5) Weibull, W., J. Appl. Mech., Vol.18, 1951, pp.293-297.
(6) Sakai, T., Ramulu, M. and Suzuki, M., Int. J. Fatigue, Vol.13, 1991, pp.117-125.