Damping behaviour and mechanical properties of rapidly solidified Al–Fe–Mo–Si/Al alloys

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In order to develop a new high damping aluminium alloy with strength and toughness for advanced aircraft structure application, rapidly solidified (RS) Al–Fe–Mo–Si/Al alloys were synthesized. The damping behaviour, mechanical properties and microstructures of the alloys were studied. Results showed that the damping capacities of RS Al–Fe–Mo–Si/10–15% Al alloys are stable between 7.0–10.0 $\times 10^{-3}$ at room temperature, which almost reach the high damping threshold, 10.0 $\times 10^{-3}$. At lower frequency (0.1–10 Hz) the damping capacity is decidely frequency and temperture dependent above 50 °C, with lowest frequency and highest temperature resulting in the highest less factor. It was noted that mechanical properties of the Al–Fe–Mo–Si/10–15% Al alloys are both excellent at room temperature ($\sigma_b = 536$–564 MPa, $\delta = 7.2$–11.4%) and at elevated temperature (250 °C: $\sigma_b = 295$–324 MPa). Analysis of microstructures reveal that the damping capacity arises from deformation of the pure Al areas, and strength at elevated temperature from the dispersion strengthening of intermetallic phase. © *1998 Chapman & Hall*

1. Introduction

It is very necessary for advanced aircraft structures to prevent large amplitudes of longitudinal vibration which often lead to fatigue failure. Conventional damping treatments do not effectively attenuate this kind of vibrations because the damping material is not in the path of these vibrations [1]. Fabrication from high damping materials would be productive but most structural materials, while having excellent stiffness and strength, possess poor damping properties [2]. Thus, the effort of reducing aircraft structure vibrations has increasingly focused on the search of high damping structure materials [1, 2, 3].

The primary objective of a research project funded by Chinese Aeronautics and Space Administration was to develop a new high damping aluminium alloy with high strength and toughness for advanced aircraft structure application. The first results about rapidly solidified Al–Fe–Mo–Si/Al alloys are presented in this paper.

2. Experimental

The damping aluminium alloys studied were manufactured by rapid solidification (RS)-powder metallurgy (P/M) process. The Al–8.0Fe–1.6Mo–1.4Si alloy powders (< 74 μm) produced by USGA technique were completely incorporated with 0.1, 0.15 and 0.2 vol fraction of pure aluminium powders (74–100 μm), respectively, in a high energy container under vacuum and then were vacuum-degassed at 400 °C/2 h, hot-pressed and extruded at 16:1 ratio, 490 °C into a 12.5 mm or 15 mm rod.

The damping capacity of the alloys studied were first measured at 28 Hz with a dynamic mechanical analyser (DuPont 1090 DMA) comparing with conventional wrought aluminium alloys while the temperature was varied from 20 to 200 °C. Further damping measurements, according to the national test standard QB/T 13665–92, were, respectively, by torsion pendulum method at a lower frequency (0.1–10 Hz) and flexural resonance method at sonic frequency (the resonant frequency is about 230 Hz) while the temperature was varied from 0 to 250 °C.

Microstructure analysis were completed in Jeol 2000FX scanning transmission electron microscope (STEM) equipped with a Link system 860 electron dispersive X-ray (EDX) spectrometer. Analysis by EDX were quantified using the Link system RTS-2/FLS computer program. The mechanical properties were examined using standard samples.

3. Results and discussion

3.1. Damping behaviour

Fig. 1 shows the damping capacity against temperature measured by DMA of RS Al–Fe–Mo–Si/Al alloys with various volume fraction of pure aluminium powders comparing with wrought 7075–T7351 and 2618–T6 alloys. At room temperature the loss factors of RS Al–Fe–Mo–Si/Al alloys almost reach the high damping threshold, 10×10^{-3}, is 3∼4 times size of that of 7075–T7351 and 2618–T6 alloys. The loss factor has little increase with increasing temperature at first, and when above 100 °C, is decidedly temperature dependent, which is also present in the data from the 7075–T7351 and 2618–T6 samples, but the loss factor of the 7075–T7351 and 2618–T6 alloys never exceeds the high damping threshold in the measured temperature range. The loss factor of

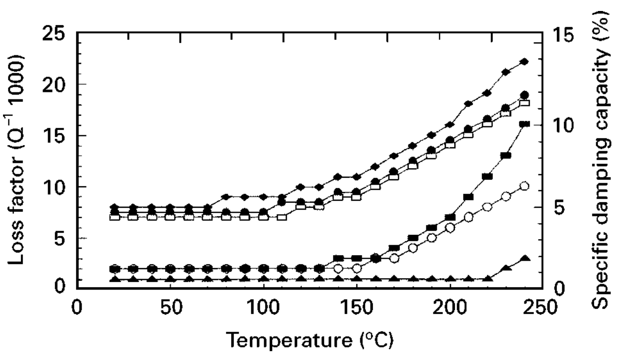

Figure 1 The effect of temperature and volume fraction of pure Al on the damping capacity of RS Al–Fe–Mo–Si/Al alloys. ○ 2618-T6; ■ 7075-T7351; ▲ Al–Fe–Mo–Si; ● Al–Fe–Mo–Si/10% Al; □ Al–Fe–Mo–Si/15% Al; ◆ Al–Fe–Mo–Si/20% Al.

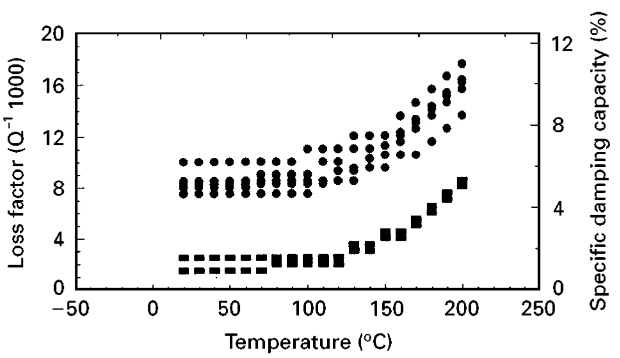

Figure 2 The repeated damping measurements of RS Al–Fe–Mo–Si/10–15% Al alloys. ● Damping alloy; ■ 7075-T6.

the RS Al–Fe–Mo–Si matrix alloy is 2.0×10^{-3}, approximating with 7075–T7351 alloys. With the addition of 10 v/o pure Al the loss factor increases greatly over room temperature to 200 °C. With the increase of addition of pure Al up to 20 v/o the loss factor has no distinct variation.

The repeated damping measurement over six batches of RS Al–Fe–Mo–Si/10–15% Al alloys were made using DMA. An example of the results is shown in Fig. 2. The loss factor stabilizes between $7.0 \sim 10 \times 10^{-3}$ at room temperature, and over 100 °C increases greatly with increasing temperature.

Fig. 3 shows the damping behaviour at lower frequency of the RS Al–Fe–Mo–Si/10–15% Al alloys

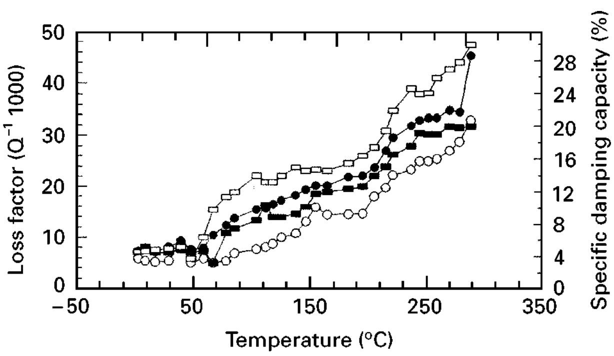

Figure 3 The effect of frequency on damping capacity of RS Al–Fe–Mo–Si/10–15% Al alloys measured at 0.1 (□), 0.32 (●), 1.0 (■) and 3.16 (○) Hz.

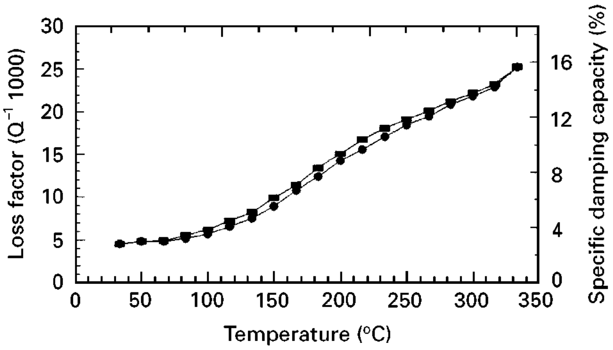

Figure 4 The effect of temperature on the damping capacity of RS Al–Fe–Mo–Si/10–15% Al alloys measured at the sonic frequency, 230 Hz. ● Heating; ■ cooling.

measured by torsion pendulum method. The damping capacity is decidedly frequency–dependent above 50 °C, with lowest frequency resulting in the highest loss factor. Variation of the loss factor with temperature at lower frequency is different to that at 28 Hz. The temperature at which the loss factor of the alloys begin to increase greatly with increasing temperature, decreases to 50 °C, at lower frequency, from 100 °C at 28 Hz. At room temperature the loss factor at lower frequency is approximately that at 28 Hz.

Fig. 4 shows the typical damping behaviour at sonic frequency of the RS Al–Fe–Mo–Si/10–15% Al alloys measured by flexural resonance method. There is no typical temperature at which the loss factor begin to

TABLE I The effect of volume fraction of pure Al on the strength and elongation in RS Al–Fe–Mo–Si/10–15% Al alloys

Sample	Testing temperature (°C)	Tensile properties σ_b (MPa)	$\sigma_{0.2}$ (MPa)	δ (%)
Al–Fe–Mo–Si/10% Al	RT	563	558	8.8
	150	414	–	5.4
	250	324	–	5.8
Al–Fe–Mo–Si/15% Al	RT	555	508	11.4
	150	388	–	7.2
	250	295	–	3.8
Al–Fe–Mo–Si/20% Al	RT	503	455	9.1
	150	351	–	6
	250	265	–	5.1
2618-T6	RT	411	324	9
	150	353	323	7
	250	245	225	11
7075-T7351	RT	505–530	435–470	7.8–11.4

increase greatly at sonic frequency. The loss factor gradually increases with increasing temperature although it increases slowly at first, and then increases rapidly. At room temperature the loss factor is slightly lower than that at lower frequencies. The temperature at which the alloys became high damping is about 150 °C, at this frequency.

3.2. Mechanical properties

Table I shows the tensile strengths and elongations of the RS Al–Fe–Mo–Si/10–15% Al alloys at room temperature and 150 and 250 °C. The results show that the tensile strengths and elongations of the alloys are both excellent. The elongation shows little change, while the volume fraction of pure Al powders varied from 0.1 to 0.2. There is also no distinct change for the tensile strengths, while the volume fraction of pure Al powders varied from 0.1 to 0.15. However, when the addition of pure Al powders came to 20 v/o, the tensile strength decreased conspicuously. The tensile strengths and elongations of RS Al–Fe–Mo–Si/10–15% Al alloys reach the level of 7075–T7351 at room temperature, and are greatly higher than that of 2618-T6 alloy at elevated temperature.

The test on the mechanical properties of the RS Al–Fe–Mo–Si/10–15% Al alloys was repeated. The results are shown in Tables II and III. The strengths and elongations of this alloy are relatively stable at room temperature and at elevated temperature. At room temperature, tensile strengths $\sigma_b = 536 \sim 564$ MPa and elongations $\delta = 7.2 \sim 11.4\%$, approximate to the target properties of 7075-T7351 alloy ($\sigma_b = 505 \sim 530$ MPa; $\delta = 7.8 \sim 11.4\%$). Tensile strengths, $\sigma_b = 388 \sim 420$ MPa at 150 °C and $\sigma_b = 295 \sim 324$ MPa at 250 °C, are greatly higher than that of 2618-T6 alloys (typical value: 150 °C, $\sigma_b = 353$ MPa; 250 °C, $\sigma_b = 245$ MPa).

TABLE II The results of repeated tests of tensile properties at RT on RS Al–Fe–Mo–Si/10–15% Al alloys

Repeated batch	No.	σ_b (MPa)	$\sigma_{0.2}$ (MPa)	δ (%)
1	1	563	561	9.6
	2	564	551	10.8
	3	563	561	11.6
	4	563	558	8.8
	5	561	558	9.2
2	6	563	558	8.4
	7	562	558	8.8
	8	560	550	8.4
	9	557	548	10.4
	10	559	554	8.0
	11	554	549	10.0
	12	564	561	8.0
	13	564	558	7.2
	14	569	559	8.0
3	15	539	535	12.8
	16	540	534	8.8
	17	536	/	8.8
	18	558	512	10.8
	19	555	508	11.4
	20	557	508	9.3

TABLE III The results of repeated test of tensile properties at elevated temperature on RS Al–Fe–Mo–Si/10–15% Al alloys

Repeated batch	No.	Temperature (°C)	σ_b (MPa)	δ (%)
1	1	150	420	5.6
	2		417	5.4
	3		416	5.5
	4	250	320	5.4
	5		326	5.0
	6		326	6.0
2	7	150	416	5.2
	8		414	5.4
	9		416	5.2
	10	250	321	6.6
	11		324	5.8
	12		321	5.7
3	13	150	388	7.2
	14		396	5.4
	15		391	6.6
	16	250	295	3.8
	17		299	–
	18		300	5.2

3.3. Microstructure

Fig. 5 shows the typical TEM microstructures of the damping RS Al–Fe–Mo–Si/10–15% Al alloys. It

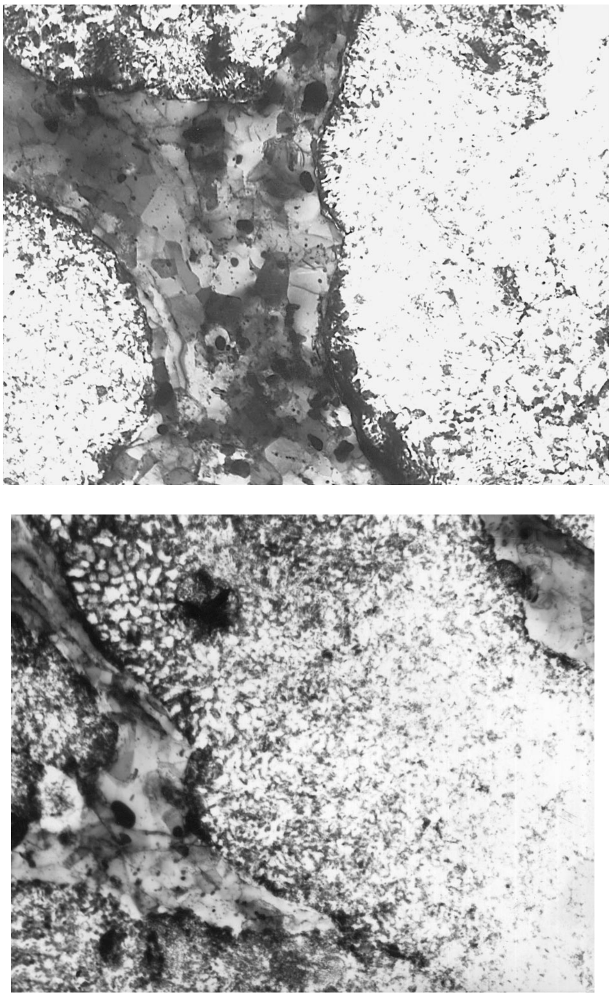

Figure 5 Typical TEM microstructures of the damping RS Al–Fe–Mo–Si/10–15% Al alloys.

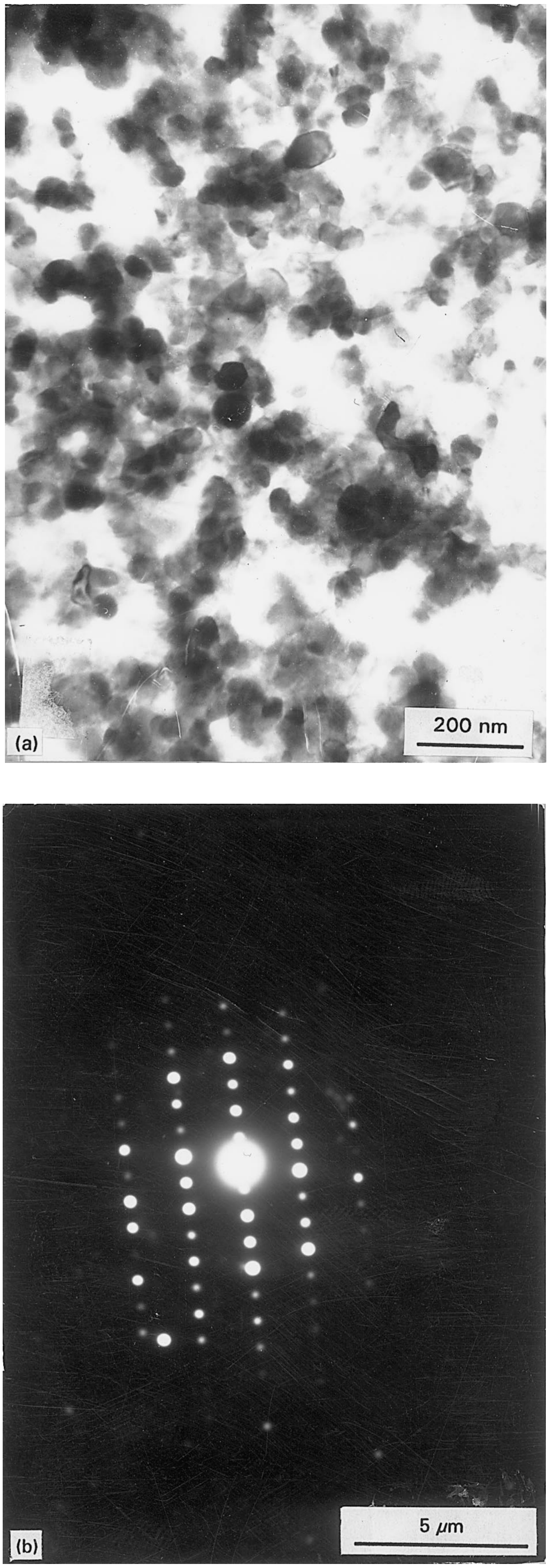

Figure 6 Typical particulate microstructure in the area of the Al–Fe–Mo–Si alloy. (a) BF; (b) EPD, ZA = [1 3 3].

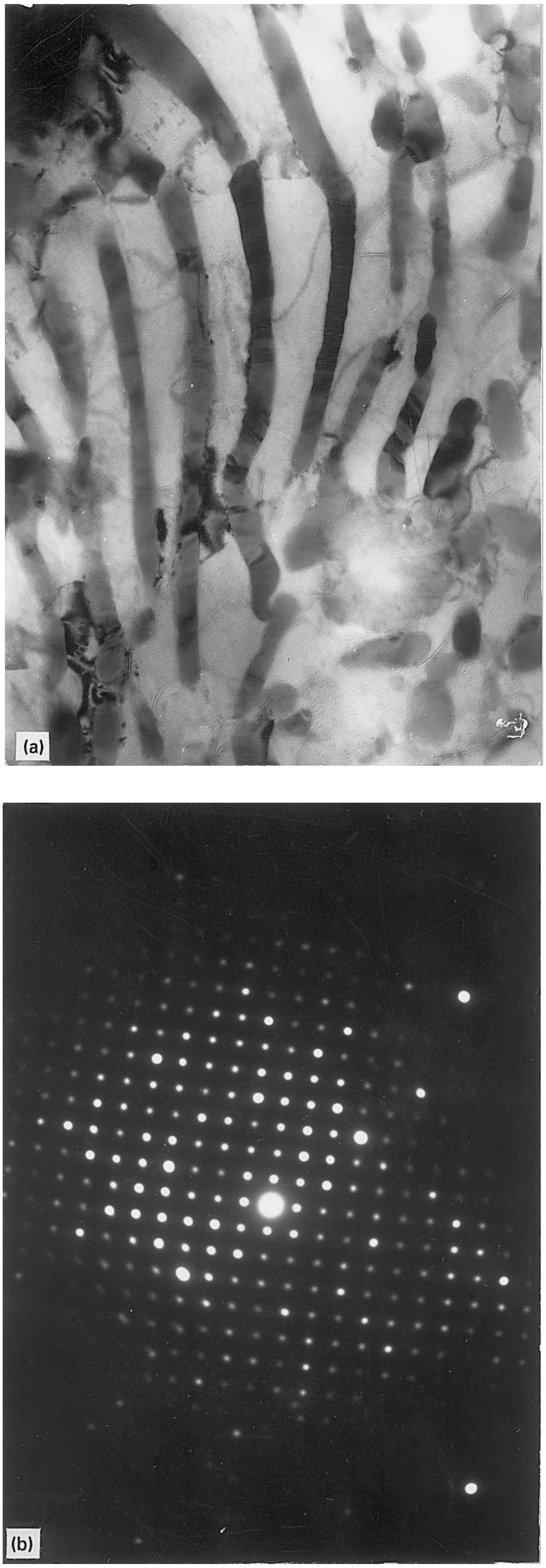

Figure 7 Typical particulate microstructure in the area of the Al–Fe–Mo–Si alloy. (a) BF; (b) EPD, ZA = [1 0 0].

consists, of an area of RS Al–Fe–Mo–Si alloy and an area of RS pure Al. The pure Al area is distributed like a river over the area of matrix Al–Fe–Mo–Si alloy, and cuts up the matrix microstructure into many separated fine areas. Two kinds of microstructure exist in the area of Al–Fe–Mo–Si alloy: particulate microstructure and flaky microstructure (typical microstructures shown in Figs 6 and 7). The

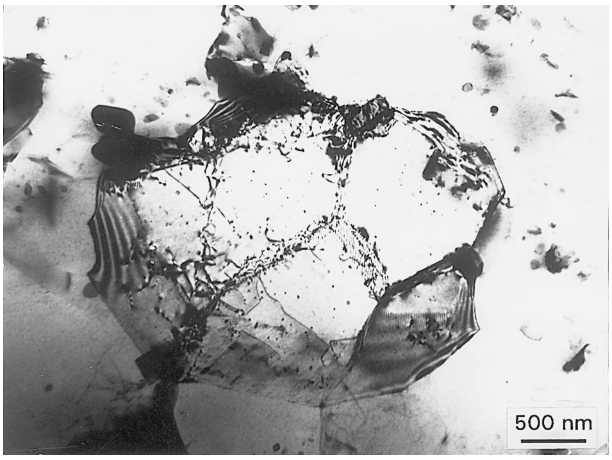

Figure 8 Typical microstructures of the pure Al area.

particulate and flaky phases were identified to be b.c.c. $Al_{12}(Fe, Mo)_3Si$(Im3, $a = 1.26$ nm) by TEM, CBED and EDX.

Careful observations on the area of pure Al found that it consists of many fine grains. Many small angle boundaries exist in these fine grains – a typical microstructure shown in Fig. 8. Through the studies of microstructure, it is obvious that the damping capacity comes from deformation of the pure Al areas, and strength at elevated temperature from the dispersion strengthening of the $Al_{12}(Fe, Mo)_3Si$ phase.

4. Conclusions

1. The damping capacities of RS Al–Fe–Mo–Si/10–15% Al alloys are stable between $7.0–10.0 \times 10^{-3}$ at RT, which is three to four times the size of that of 7075-T7351 and 2618-T6 alloys. With the increase of addition of pure Al from 10 v/o to 20 v/o, the loss factor of the damping alloys has no distinct variation.

2. At lower frequency (0.1–10 Hz, torsion pendulum method) the damping capacity is decidedly frequency and temperature dependent above 50 °C, with lowest frequency and highest temperature resulting in the highest loss factor. It is also decidedly temperature dependent above 100 °C at the frequency 28 Hz (DMA method) and above RT at the frequency 230 Hz (flexural resonance method).

3. For the RS Al–Fe–Mo–Si/10–15% Al alloys, $\sigma_b = 536–564$ MPa, $\delta = 7.2–11.4\%$ which are the target properties of 7075-T7351 alloy at RT; $\sigma_b = 388–420$ MPa at 150 °C, $\sigma_b = 295–324$ MPa at 250 °C, being greatly higher than that of 2618-T6 alloy.

4. The damping capacity comes from deformation of the pure Al areas, and strength at elevated temperature from the dispersion strengthening of the $Al_{12}(Fe, Mo)_3Si$ phase.

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