Effects of B upon glass forming ability of Al\textsubscript{87}Y\textsubscript{8}Ni\textsubscript{5} amorphous alloy

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\begin{abstract}
In this study, 15 at.% of boron is added to increase the thermal stability and amorphous forming ability of Al\textsubscript{87}Y\textsubscript{8}Ni\textsubscript{5} alloy ribbons by single roller melt-spinning process. Thermal properties including crystallization activation energy and the Avrami exponent of crystallization are investigated using non-isothermal and isothermal analyses. Only the (Al\textsubscript{84}Y\textsubscript{10}Ni\textsubscript{10})\textsubscript{85}B\textsubscript{15} amorphous alloy ribbon demonstrates a glass transition temperature (\(T_g\)) at 529 K, and its \(T_x = (T_g - T_r)\) value is 24.6 K. Crystallization kinetic study show that the 15 at.% of boron increases the activation energy for crystallization from 159 to 228 kJ/mol. The Avrami exponent \(n\) value of Al\textsubscript{85}Y\textsubscript{8}Ni\textsubscript{5} amorphous alloy is 1.5 \(\pm\) 2.1 indicating a decreasing nucleation rate with crystallization time, whereas the \(n\) value of (Al\textsubscript{84}Y\textsubscript{10}Ni\textsubscript{10})\textsubscript{85}B\textsubscript{15} amorphous alloy ribbon is 2.3 \(\pm\) 3.1 or the nucleation rate increases with time. The addition of boron could affect the crystal symmetry in atomic clusters and thus the phase separation behavior in the amorphous alloy. Boron is shown to delay the nucleation of boron-containing Al nano-crystals in crystallization. The maximum hardness is obtained for both non-boron and boron added alloys after crystallization at 592–596 K region due to formation of nano-crystallites. The highest hardness achieved is 575 and 595 Hv for Al\textsubscript{84}Y\textsubscript{10}Ni\textsubscript{10} and (Al\textsubscript{84}Y\textsubscript{10}Ni\textsubscript{10})\textsubscript{85}B\textsubscript{15} alloys, respectively. Both the Al nano-crystals and solute-rich amorphous phase formed by phase separation contribute to the hardness increase.
\end{abstract}

\section{1. Introduction}

Aluminum metallic glasses are of interest with combined high specific strength and good ductility. However, Al-metalloid and Al-transition metal (TM) alloys were found more difficult than other metallic alloys to obtain bulk metallic glass [1], because aluminum is reactive and difficult to achieve large supercooling [2–4]. Coexistent structure of amorphous and crystalline phase is usually formed in direct quench solidification of Al-based alloys. The first amorphous single phase Al-based alloys were found in 1981, including Al–Fe–B and Al–Co–B ternary alloys [5]. These amorphous alloys were rather brittle and did not attract much attention. The subsequent findings of amorphous Al–Fe–Si, Al–Fe–Ge and Al–Ge–Mn alloys [6,7] by melt-spin process were also found brittle, similar to the Al-(Fe or Co)-B amorphous alloys.

In 1987, an amorphous phase with good bending ductility was discovered by Inoue et al. [8] containing more than 80 at.\% Al in Al–Ni–Si and Al–Ni–Ge systems. Ductile Al-based amorphous alloys were subsequently found in a number of Al-early transition metal (EM)-late transition metal (LM) and Al-transition metal (TM)-rare earth metal (RE) [9,10] ternary alloys by melt spinning process. Among these, Al–TM–RE systems such as Al–Ni–Y [11], Al–Ni–Co–Y [12], Al–Ni–Gd [13] and Al–Ni–Fe–Gd [14] indeed demonstrated much better glass forming ability (GFA). In spite of numerous works on Al–TM–RE-based alloys, Al-based alloys have not been shown to form bulk metallic glass until the Al–Ni–Y–Co–La system reported by Yang et al. [15].

A crystallization temperature, \(T_x\), is commonly observed in the amorphous alloy systems. However, according to Perepezko and Hebert [16], not all amorphous Al alloys demonstrates glass transition phenomenon. Only some of the Al–Y–Ni and Al–Ce–Ni alloys give rise to both \(T_g\) and \(T_x\) in heating [17]. For both alloys, it is found that the glass transition phenomenon is present for Al–Y–Ni containing \(\sim 10\) at.\% of Y and for Al–Ce–Ni with 4–6\% of Ce. The presence of \(T_g\) appears to be dominated by the amount of RE metals and is less dependent of Ni content. Meanwhile, both \(T_g\) and \(T_x\) increases with Ni concentration. The highest \(T_g\) and \(T_x\) are shown in AlY\textsubscript{10}Ni\textsubscript{10} at 582 and 604 K, respectively. The difference of \(T_g\) and \(T_x\) temperatures or the supercooled liquid region, \(\Delta T_x\), achieves \(22\) K which is also an important index of thermal stability for amorphous phase. A large \(\Delta T_x\) or wide supercooled liquid region could lead to superplasticity [18] and improved ductility. These amorphous alloys showing \(T_g\) therefore demonstrate relatively better ductility than those without \(T_g\).
Jun et al. [19] found that, when 2 at.% of Be is added to Al87Ni7–Y8, both Tg and Ea increased. It indicated that the thermal stability of the amorphous Al85Ni7–Y8 alloy is enhanced by the addition of 2% Be, mainly due to the small atom size of Be. Be addition gives rise to higher packing density and thus increases thermal stability of the (Al85Ni7–Y8)98Be2 amorphous phase, although the bonding forces between Be and the constituent elements are weak. Unfortunately, the increased thermal stability by 2% Be addition did not lead to a glass transition temperature. It implies that the chemical interaction between Al and the alloying elements still play an essential role in the practical GFA for Al-based alloys [19].

Boron is another small atom that brings specialty properties to amorphous alloy systems. The addition of B to ferrous alloys has been shown very effective in increasing GFA for Fe–Si alloys [20,21]. The soft magnetic properties of Fe–Si–B amorphous alloys also received great attention since 1970s [22,23]. It is of interest to investigate how boron affects the thermal stability and GFA of Al85–Ni7–Y8 alloy, because the atomic radius of Al (1.43 Å) is even larger than Fe (1.26 Å). The small boron atom (radius = 0.98 Å) could also bring interesting effects upon then Al–TM–RE alloy systems. In addition to the great difference of boron in atomic radius with those of Al (1.43 Å), Ni (1.24 Å), and Y (1.78 Å), boron also has negatively large enthalpy of mixture with Ni (–4 kJ/mol) and Y (–32 kJ/mol). These could increase the tendency of keeping all atoms in one amorphous phase [24] and might be more effective than Be addition to bring practical GFA to the Al–Y–Ni–B system. It is thus the goal of this study to look into the glass formation ability and crystallization kinetics of (Al87Y8Ni7)85B15 alloy by adding 15 at.% boron to Al87Y8–Ni7 alloy.

2. Experimental procedures

Al87Y8Ni5 and (Al87Y8Ni5)85B15 master alloys were prepared by arc melting appropriate proportions of 99.99% purity Al, 99.9% purity Ni, 99.7% purity Y, and 99.6% purity B under argon atmosphere using pure Ti as oxygen getter. Amorphous ribbons about 30 µm thickness and 2 mm wide were manufactured by the roller melt-spinning technique at a velocity of 42 m/s under argon. Over 10°C/s of cooling rate could be achieved [25]. The crystallization behaviors of amorphous ribbons were investigated by a Perkin–Elmer Diamond Differential Scanning Calorimetry (DSC) using a combination of continuous heating and isothermal heating. The activation energy of crystallization was obtained using Kissinger plots by heating the ribbons at different rates. Specimens of amorphous ribbon were also annealed under argon atmosphere at different transformation temperatures identified by the DSC analysis to calculate the Avrami exponents at different stages of crystallization. Master alloy, as-spun and annealed specimens were characterized using X-ray Diffractometer (XRD) and Scanning Electron Microscopy (SEM) to verify the formation of different phases. Both surfaces of the ribbons are smooth. No surface features could be observed at over 10,000 x magnification under SEM. The surface roughness should be well below 10 nm. Vickers hardness was measured using a 15 g load on the mounted ribbons to observe the change of hardness with formation of different phases. The 15 g loading would mark a 500 Hv object with an indentation of 7.46 µm diagonal and 1.5 µm depth. The 1.5 µm depth indentation is fairly small (5%) in comparison with ribbon thickness of 30 µm and is much larger than the roughness of ribbon surface. Therefore, the substrate effect of Vickers hardness testing on the ribbons is minimal.

3. Results and discussion

3.1. Phase identification

Fig. 1 shows the XRD spectra of Al87Y8Ni5 and (Al87Y8Ni5)85B15 master alloys. Al, Y, AlNi, NiY, and Al phases are present with Al phase as the matrix phase. The boron addition in (Al87Y8Ni5)85B15 alloy also leads to the formation of B2.5Ni2Y indicating that B has a negatively large enthalpy of mixture with Ni and Y. The peaks of Al phase in Fig. 1 for both alloys are essentially at the same 2θ angles as those in pure aluminum in spite of large amount of alloying elements. Several different stoichiometric NiY phases are formed in both of the master alloys. It suggests that the local chemical homogeneity is hardly achieved on rapid solidification due to formation of many small NiY precipitates in the melts. The enthalpy of mixing for Y and Ni must be fairly low to form different stoichiometric Ni–Y intermetallic compounds from the melt as also shown by its phase diagram [26].

Fig. 2 shows comparably larger and more precipitate phases in the Al87Y8Ni5 alloy than (Al87Y8Ni5)85B15 alloy. The morphology of precipitates turns from large plate-shape into rod and needle-like shapes with boron addition. The plate-shaped Al1Y phase appears to form with the preferred (220) aluminum plane parallel to the ribbon surfaces according to XRD spectra of Al87Y8Ni5 in comparison with that of (Al87Y8Ni5)85B15 alloy. The XRD spectra of as melt-spun Al87Y8Ni5 and (Al87Y8Ni5)85B15 ribbons are shown in Fig. 3. Both alloy ribbons bear one wide and

![Fig. 1. XRD spectra of Al87Y8Ni5 and (Al87Y8Ni5)85B15 master alloy ingots.](Author's personal copy)
3.2. Thermal stability of Al–Y–Ni–B and Al–Y–Ni

The Al<sub>87</sub>Y<sub>8</sub>Ni<sub>5</sub> and (Al<sub>87</sub>Y<sub>8</sub>Ni<sub>5</sub>)<sub>85</sub>B<sub>15</sub> ribbons were analyzed using DSC at a heating rate of 0.66 K/s. It can be seen that, in (Al<sub>87</sub>Y<sub>8</sub>Ni<sub>5</sub>)<sub>85</sub>B<sub>15</sub> alloy, an endothermic peak appears at 529 K (Fig. 4). This peak is in contrast to all other exothermic peaks in either Al<sub>87</sub>Y<sub>8</sub>Ni<sub>5</sub> and (Al<sub>87</sub>Y<sub>8</sub>Ni<sub>5</sub>)<sub>85</sub>B<sub>15</sub> ribbons during heating. The 529 K peak in boron-bearing alloy clearly represents a glass transition temperature \(T_g\) occurring prior 553 K crystallization \(T_x\). The existence of \(T_g\) for this alloy system is critical in demonstrating possible ductility of the amorphous alloys [12,27], because the viscosity of these alloys decreases and allows the alloy to deform between \(T_g\) and \(T_x\) as a supercooled liquid [28]. The supercooling area of \(T_x - T_g\) is as high as 24.6 K for boron-bearing (Al<sub>87</sub>Y<sub>8</sub>Ni<sub>5</sub>)<sub>85</sub>B<sub>15</sub> ribbons. Such value is comparable to those in (Al<sub>85</sub>Ni<sub>10</sub>Ce<sub>x</sub>)<sub>100</sub>-xB<sub>x</sub> (x = 1–10) systems as reported by Sobu et al. [29].

\(T_g\) affirms that boron has a positive effect on the thermal stability of (Al<sub>87</sub>Y<sub>8</sub>Ni<sub>5</sub>)<sub>85</sub>B<sub>15</sub> amorphous alloy. (Al<sub>87</sub>Y<sub>8</sub>Ni<sub>5</sub>)<sub>85</sub>B<sub>15</sub> also demonstrates higher \(T_x\) temperature than non-boron Al<sub>87</sub>Y<sub>8</sub>Ni<sub>5</sub> alloy. In Fig. 4, the outstanding exothermic peak at 722–762 K in the DSC curve of (Al<sub>87</sub>Y<sub>8</sub>Ni<sub>5</sub>)<sub>85</sub>B<sub>15</sub> confirms that boron addition also increases the difficulty for crystallization. According to Chiriac [30], small boron atoms increase the stacking density in liquid structure of the alloy by reducing free volume, therefore atoms in the alloy require higher energy to move and to crystallize which increases the thermal stability of amorphous alloys.

In a recent study on molecular dynamics simulations of amorphous Al [2], it is shown that Al metal glass bears a large amount of deformed-bcc short-range and medium-range orders. This is in contrast to the usual icosahedral short-range and medium-range orders as found in other excellent glass forming alloys [31]. The similarity of deformed-bcc and fcc Al in crystal symmetry could explain the poor glass formation ability of Al-based alloys. Along this consideration, the existence of 15 at.% B might enhance the fivefold symmetry component in the current Al alloy system similar to the case of Ni<sub>81</sub>B<sub>19</sub> [31]. That is, boron could have an effect on modifying the short-range and medium-range orders of amorphous aluminum clusters leading to the increase of their thermal stability.

Fig. 5 shows the DSC curves of two ribbons at temperatures over 850 K. Two observations should be noted. The first, the boron-containing ribbon has higher transformation temperatures. The second, extended exothermic tails appears in the region of 890–910 K for Al<sub>87</sub>Y<sub>8</sub>Ni<sub>5</sub> ribbon, and the extended exothermic tail is similar to that of Al nano-crystals in Al<sub>85</sub>Ni<sub>5</sub>Ce<sub>x</sub> [32]. In contrast, the boron containing (Al<sub>87</sub>Y<sub>8</sub>Ni<sub>5</sub>)<sub>85</sub>B<sub>15</sub> alloy demonstrates a sharp exothermic peak indicating the characteristics of glass transition similar to that in the Al<sub>85</sub>Ni<sub>5</sub>Y<sub>8</sub>Ce<sub>2</sub> [12] system. These again confirm the improved thermal stability of the (Al<sub>87</sub>Y<sub>8</sub>Ni<sub>5</sub>)<sub>85</sub>B<sub>15</sub> amorphous alloy through boron addition.

3.3. The crystallization kinetics of Al–Y–Ni–B and Al–Y–Ni

Li et al. [2] employed molecular dynamics to simulate the atomic-scale structural evolution of aluminum alloys from liquids to glasses transition. It is demonstrated that the liquid–crystal transitions both in the cooling and heating processes are first-order phase transition. Kissinger analyses of crystallization kinetics [33] during continuous heating can be applied to interpret the crystallization behaviors of Al metallic glasses.

With increasing heating rate from 40 to 80 K/min, the exothermic crystallization peaks shift toward higher temperatures and become broader (Fig. 6). The variation of observed peak temperatures with heating rates is analyzed using Kissinger equation to obtain the activation energy of crystallization (Eq. (1)):
\[
\ln \frac{T_p^2}{\Phi} = \frac{Q}{RT_p} + B
\]  
\(1\)

where \(\Phi\) is heating rate, \(T_p\) is the temperature of exothermic peak, \(Q\) is the activation energy of crystallization, \(R\) is the gas constant, and \(B\) is a constant.

The Kissinger plot of both \((\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5})_{85}\text{B}_{15}\) and \(\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5}\) ribbons are shown in Fig. 7. The linear fits in Fig. 7 gives \(R^2\) values of over 0.98 indicating that the crystallization of these ribbons are well fit with Kissinger analyses. Furthermore, single slope for each ribbon means that, in the range of heating rates employed, no apparent change occurs in the mechanism of crystallization. The activation energies for crystallization of \((\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5})_{85}\text{B}_{15}\) and \(\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5}\) ribbons are 228 and 159 kJ/mole, respectively (Table 1). 15 at.% of boron addition increases the activation energy by as much as 43%.

Fig. 8 shows the DSC curves of both \(\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5}\) and \((\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5})_{85}\text{B}_{15}\) amorphous ribbons by isothermal annealing at 503–513 K and 533–543 K, respectively. The kinetics of crystallization are expressed by Johnson–Mehl–Avrami equation (Eq. (2)):

\[
X = 1 - \exp\left(-Kt^n\right)
\]  
\(2\)

Fig. 4. DSC curves of \(\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5}\) and \((\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5})_{85}\text{B}_{15}\) alloy ribbons at 0.66 K/s heating rate.

Fig. 5. DSC curves of \(\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5}\) and \((\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5})_{85}\text{B}_{15}\) alloy ribbons at temperatures up to the melting point using 0.66 K/s heating rate.

(a)

(b)

Fig. 6. Changes of transformation points with variation of heating rate in the DSC curves of (a) \(\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5}\) and (b) \((\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5})_{85}\text{B}_{15}\) alloy ribbons.
where $X$ is the fraction of crystallization after isothermally annealing for a period of $t$, $n$ is the Avrami exponent which depends on the mechanism of crystallization, and $K$ is an Arrhenius-type crystallization constant.

Fig. 9 plots $\ln(-\ln(1-X))$ versus $\ln(t)$ for Al$_{87}$Y$_8$Ni$_5$ and (Al$_{87}$Y$_8$Ni$_5$)$_{38}$B$_{15}$ ribbons with $t$ measured starting at the onset of crystallization. The Avrami exponents are fitted to have $n = 1.5$–2.1 for Al$_{87}$Y$_8$Ni$_5$ and $n = 2.3$–3.1 for (Al$_{87}$Y$_8$Ni$_5$)$_{38}$B$_{15}$ ribbons. The Avrami exponent of 1.5–2.1 indicates that the crystallization takes place with nucleation rate decreasing in the case of Al$_{87}$Y$_8$Ni$_5$. It is possible that some nano-size nuclei form in quench solidification, and therefore the number of nucleation reduces with annealing time. According to Kelton et al. [34], an alternative explanation is that phase separation is formed to bear Al-rich and solute-rich regions in the amorphous structures which accelerates the nucleation in crystallization. The $n = 2.3$–3.1 Avrami exponent for (Al$_{87}$Y$_8$Ni$_5$)$_{38}$B$_{15}$ ribbon indicates that its crystallization is representative of continuous nucleation and three dimensional diffusion-controlled parabolic growth. The boron addition increases the difficulty for atom migration and thus is harder to nucleate in rapid solidification. Fig. 9 also shows that the boron-containing ribbon requires both higher temperatures and longer time to complete crystallization in each isothermal treatment indicating its comparably better thermal stability as amorphous phase.

### 3.4. Crystallization phases of Al–Y–Ni–B and Al–Y–Ni ribbons

Fig. 10 shows the XRD spectra of Al$_{87}$Y$_8$Ni$_5$ ribbon by annealing for 600 s at different peak temperatures chosen based on Table 2 and Fig. 4. Al, Al$_3$Y, and Ni$_x$Y$_y$ phases are formed in sequence with increasing annealing temperatures from 506 K to 746 K. For boron-containing (Al$_{87}$Y$_8$Ni$_5$)$_{38}$B$_{15}$ ribbon, Al, B$_{2.5}$Ni$_2$Y, Al$_3$Y, and Ni$_x$Y$_y$ phases are formed sequentially with annealing temperatures increasing from 553 K to 762 K. It is also observed that the aluminum peaks in Fig. 10 all shift somewhat to the left and are wider when compared to those shown in Fig. 1 of the master alloys. The starting aluminum precipitates are apparently nano-sized and should contain higher alloying element contents. Annealing process allows the Al precipitates to achieve more thermally equilibrium composition by diffusion. Higher alloying element contents of the large-size Y atoms and interstitial B atoms in the Al precipitates both could lead to the increase of lattice sizes and shifts the X-ray peaks leftward.

The Al$_3$Y and Ni$_x$Y$_y$ phases are precipitated due to the large negative enthalpy of mixing between these atoms which are also reported in the case of Al$_{85}$Y$_{1.1}$Ni$_{14}$ [35] and Al$_{85}$Y$_3$Ni$_{19}$ [36] alloys. The precipitation of B$_{2.5}$Ni$_2$Y phase prior Al$_3$Y and Ni$_x$Y$_y$ phases indicates that the affinity of B, Ni, and Y is even stronger or more negative in the enthalpy of mixture than the affinity between Al, Y, and Ni. The smaller size of boron atom could also play a part in easier diffusion and benefits the precipitation of B$_{2.5}$Ni$_2$Y phase. As AlB$_2$ is not observed as it should be according to the Al–B phase diagram.

### Table 1

Thermal properties of Al$_{87}$Y$_8$Ni$_5$ and (Al$_{87}$Y$_8$Ni$_5$)$_{38}$B$_{15}$ ribbons.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>$T_g$ (K)</th>
<th>$\Delta T_s$ ($T_s - T_a$) (K)</th>
<th>$T_x$ (K)</th>
<th>$T_m$ (K)</th>
<th>$T_m/T_g$</th>
<th>$E_a$ (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_{87}$Y$_8$Ni$_5$</td>
<td>–</td>
<td>–</td>
<td>506</td>
<td>908</td>
<td>–</td>
<td>159</td>
</tr>
<tr>
<td>(Al$_{87}$Y$<em>8$Ni$<em>5$)$</em>{38}$B$</em>{15}$</td>
<td>529</td>
<td>24.6</td>
<td>553.6</td>
<td>909</td>
<td>0.402</td>
<td>228</td>
</tr>
</tbody>
</table>
Table 3 summarizes the microhardness of ribbons after annealing at different temperatures. The as melt-spun ribbons bear 363 and 380 Hv for non-boron and boron-containing alloys which are similar to those reported in $(\text{Al}_{84}\text{Ni}_{10}\text{Ce}_{6})_{100-x}\text{B}_x$ and $(\text{Al}_{84}\text{Ni}_{5}\text{Y}_{9}\text{Co}_{2})_{100-x}\text{B}_x$ systems [29]. As high as 595 Hv is achieved by annealing the $(\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5})_{85}\text{B}_{15}$ ribbon at 596 K for 600 s. The hardness of boron-containing alloy ribbon is higher than the highest 575 Hv achieved by non-boron ribbon. Other than the interstitial effects given by the small boron atoms, boron also forms $\text{B}_{2.5}\text{Ni}_2\text{Y}$ precipitates. It is seen that the first crystallization temperature gives rise to the largest hardness increase. The main increases of hardness appear to be provided by the precipitation of nano-size Al phase.

According to [38–40], nano-size aluminum particles could be strained with low defect content and thus have higher strength. These particles disperse in the amorphous matrix and barricade the shear flow of the amorphous phase in deformation. On a separate note, the phase separation observed in as-quenched Al-TM-RE (such as Al$_{85}$Y$_9$Ni$_6$) metallic glasses [34] demonstrates that the formation of solute-rich amorphous phase could also play a role on the increase of hardness. With increasing crystallization temperatures, both the growth of nano-particles and formation of more defects causes the hardness to drop.

4. Conclusion

Boron has an effect of increasing the starting crystallization temperature of $\text{Al}_{87}\text{Y}_{8}\text{Ni}_{5}$ ribbon from 506 K to 553 K. There is no
Table 2
Transformation temperatures of Al87Y8Ni5 and (Al87Y8Ni5)85B15 ribbons obtained from Fig. 4.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Tx1 (K)</th>
<th>Tx2 (K)</th>
<th>Tx3 (K)</th>
<th>Tx4 (K)</th>
<th>Tx4 end (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al87Y8Ni5</td>
<td>506</td>
<td>592</td>
<td>650</td>
<td>712</td>
<td>746</td>
</tr>
<tr>
<td>(Al87Y8Ni5)85B15</td>
<td>553</td>
<td>596</td>
<td>645</td>
<td>722</td>
<td>762</td>
</tr>
</tbody>
</table>

Table 3
Microhardness of the ribbons after annealing at different temperatures.

<table>
<thead>
<tr>
<th>Annealing temperature</th>
<th>Al87Y8Ni5 hardness (HV)</th>
<th>(Al87Y8Ni5)85B15 hardness (HV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>as melt-spun</td>
<td>363</td>
<td>380</td>
</tr>
<tr>
<td>Tx1</td>
<td>448</td>
<td>514</td>
</tr>
<tr>
<td>Tx2</td>
<td>575</td>
<td>595</td>
</tr>
<tr>
<td>Tx3</td>
<td>393</td>
<td>464</td>
</tr>
<tr>
<td>Tx4</td>
<td>341</td>
<td>389</td>
</tr>
</tbody>
</table>
glass transition temperature present in the case of Al$_{87}$Y$_8$Ni$_5$ ribbon, whereas a $T_x$ at 529 K occurs in the boron-bearing (Al$_{87}$Y$_8$Ni$_{15}$)$_{85}$B$_{15}$ ribbon. The supercooling liquid range, $\Delta T_m$, is as high as 24.6 K. The presence of $T_x$ and large $\Delta T_m$ indicates that boron addition has a positive effect on increasing glass formation ability of Al$_{87}$Y$_8$Ni$_5$. 

During isothermal crystallization of Al$_{87}$Y$_8$Ni$_5$ ribbon, aluminum nuclei possibly pre-exist in the quenched ribbons and reduces nucleation rate. Lower Avrami exponents of $n = 1.5$–$2.1$ are obtained. Phase separation prior devitrification could assist the nucleation. While in the case of boron-containing ribbon, the nucleation rate during crystallization increases with time indicating that boron atoms increase the energy needed to nucleate by atomic migration. Larger Avrami exponents of $n = 2.3$–$3.1$ are demonstrated. The activation energy for crystallization of (Al$_{87}$Y$_8$Ni$_{15}$)$_{85}$B$_{15}$ ribbon is as high as 228 kJ/mole in contrast to the 159 kJ/mole activation energy for crystallization of Al$_{87}$Y$_8$Ni$_5$. This again confirms that the amorphous phase in the boron-containing alloy achieves higher hardness than the non-boron opponent besides the formation of B$_{2.5}$Ni$_2$Y phase.

References