Microstructure, fracture, and thermal stability of Ni–Fe–Cu–P–B two-phase amorphous composite produced from the double-chamber crucible

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ABSTRACT

The purpose of the work was investigation of the final microstructure and properties of the melt-spun Ni–Fe–Cu–P–B, Ni–Fe–B, and Ni–Cu–P alloys ejected as uniform liquid from the standard single-chamber crucible and from the double-chamber crucible as flux composed of the two Ni–Fe–B and Ni–Cu–P liquids cooled on a copper roller before formation of a uniform mixture. The methods applied in this study for microstructural investigations include scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), and Mössbauer spectroscopy. Thermal stability of the melt-spun alloys was tested using differential scanning calorimetry (DSC) and tensile test were performed. The results of the investigations are described and discussed in terms of the unique features of the two component melt spinning (TCMS) amorphous microstructure.

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1. Introduction

Metallic glasses as an engineering material present huge potential in the production of parts requiring excellent mechanical properties, special magnetic and electrical characteristics, etc. [1–4] However, the use of these materials is still very limited. Some solutions leading to the removal of limitations hindering the broader use of metallic glasses can be achieved through formation of amorphous–amorphous, amorphous-crystalline composites with controllable morphology, enhancing the ductility and use of cheaper precursors [5]. Amorphous/crystalline composites are produced using precursor species with positive heat of mixing between some of them [6–9]. There are works devoted to the production of two-phase amorphous composites using a miscibility gap in such systems as La–Zr–Al–Cu–Ni [10], Nd–Zr–Al–Co [11], and Ni–Nb–Y [12]. Unfortunately, in these cases [10–12] the production of the two-phase metallic glasses is restricted to alloys with special composition and the microstructure of these alloys is very heterogeneous with a large scatter of particle size. The new variation of melt-spinning with the double-chamber crucible proposed recently [13,14] does not have these limitations. This method enables the production of a composite with heterogeneous amorphous structure from the two melts of a relatively low glass forming ability and enables formation of a lamellar amorphous/amorphous composite microstructure. The aim of this work was to show interesting properties of the new two component melt spinning (TCMS) alloy produced from Ni$_{40}$Fe$_{40}$B$_{20}$ and Ni$_{70}$Cu$_{10}$P$_{20}$ melts.

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2. Experimental

Nickel–iron–boron Ni_{40}Fe_{40}B_{20}, nickel–copper–phosphorus Ni_{70}Cu_{10}P_{20}, and nickel–iron–copper–phosphorus–boron Ni_{55}Fe_{20}Cu_{5}P_{10}B_{10} alloys were prepared starting from 99.95 wt% Ni, 99.95 wt% Fe, 99.95 wt% Cu, Ni–P, Cu–P, and Ni–B, Fe–B master alloys. The precursors were re-melted under an argon gettered protective atmosphere in an arc furnace. The alloys were then melt spun in a helium atmosphere. The linear velocity of the copper roller was 40 m/s and the ejection pressure 150 kPa. The crucible hole diameter was 1.2 mm. The four alloys were ejected on the roller. The first was obtained by two-component melt-spinning (TCMS). The ejection of alloys was preceded by heating and melting the Ni_{40}Fe_{40}B_{20} and Ni_{70}Cu_{10}P_{20} alloys in a double-chamber crucible separated with a partition barrier between the two melts (Fig. 1). However, three remaining ribbons, i.e., those produced from Ni_{40}Fe_{40}B_{20}, Ni_{70}Cu_{10}P_{20}, and Ni_{55}Fe_{20}Cu_{5}P_{10}B_{10} alloys were obtained by ejection after re-melting in a single-chamber crucible and then ejected into the copper roller. The tensile tests of the ribbons were performed. The specimens with a gauge length of 20 mm, a width of 2.4 mm, and a thickness of 23 μm ± 6 μm mm were prepared, and tested at room temperature at a crosshead speed of 1 mm/min. Following the tensile tests, the fractures of the Ni_{55}Fe_{20}Cu_{5}P_{10}B_{10} TCMS ribbon as well as the Ni_{40}Fe_{40}B_{20}, Ni_{70}Cu_{10}P_{20}, and Ni_{55}Fe_{20}Cu_{5}P_{10}B_{10} ribbons melt-spun from a single chamber crucible were observed by means of a scanning electron microscope with EDS JEOL 6610. The cross-section microstructure of the TCMS Ni_{55}Fe_{20}Cu_{5}P_{10}B_{10} ribbon was also studied under the SEM and analysed by EDS. Subsequently, after ion beam thinning, the ribbons were investigated by means of the JEOL 300 kV transmission electron microscope (TEM). X-ray diffraction was performed on a Rigaku Miniflex-2 diffractometer using CuKα radiation filtered by the LiF bent single crystal on the detector side. The scattering angle 2θ varied between 20° and 120° degrees. Scans were performed in the Θ-2Θ mode. X-ray high temperature studies of melt-spin ribbons as a function of temperature were then carried out using a Siemens D5005 (Bruker-AXS) diffractometer equipped with a Cu lamp with a 30 mA and 40 kV power supply. The radiation was monochromatized with a graphite monochromator. As-cast ribbons were stuck to a glass plate. The measurements were done at room temperature and at elevated temperatures, i.e., 553 K, 603 K, 663 K, and 753 K in an XRK-900 reaction chamber (Anton Paar). Diffraction patterns were registered in the range of 30°–60° (2θ) using 0–0 scan with 0.04°/1 s speed. Differential scanning calorimetry (NETZSCH DSC200 F3 MAIA) in an argon atmosphere was used for characterizing the crystallization sequences in all of the four amorphous ribbons with the heating rate of 40 K/min. Mössbauer transmission measurements were performed using the RENON MsAa-3 spectrometer equipped with a LND Kr-filled proportional detector and He–Ne laser based interferometer used to...
calibrate the velocity scale. A commercial $^{57}\text{Co}\text{(Rh)}$ source kept at room temperature was applied for 14.41-keV resonant transition in $^{57}\text{Fe}$. Mössbauer data were processed by means of Mosgraf-2009 software.

3. Results and discussion

The results of the X-ray diffraction are shown in Fig. 2. The studied ribbons show the presence of broad diffraction maxima located between $40^\circ$ and $50^\circ$ with the peak located at ca. $45^\circ$, which corresponds to $(d = 2.013 \text{ Å})$. Such patterns can be associated with the amorphous structure in these alloys. This value is close to the diffraction maxima obtained for amorphous Ni–P [15], i.e., $d = 2.02 \text{ Å}$ and amorphous Fe–P [16] close to $d = 1.97 \text{ Å}$.

The results of TEM observations are shown in Fig. 3. The TEM microstructure of the TCMS ribbon shows darker areas marked “A” and brighter areas marked “B” (Fig. 3a). The electron diffraction patterns (Fig. 3b) from both areas show broad diffusive rings typical to the amorphous alloys. Both of the strong diffusive rings are in a similar position and correspond to the range of $d$ values between $1.9 \text{ Å}$ and $2.3 \text{ Å}$. Due to the content of the species having different atomic number, one can expect that the “A” areas to be darker as they are enriched in Ni ($Z = 28$) and Cu ($Z = 29$) and “B” areas to be brighter as they are enriched in Ni ($Z = 28$) and Fe ($Z = 26$). Smooth transitions from one area to another without any traces of crystals between, may be due to the fact that the intermediate compositions between “A” and “B” are also amorphous.

The investigations performed using XRD and TEM confirm that all of the studied alloys are amorphous. TEM microstructure of the TCMS Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$ alloy has a lamellar wood-like morphology, consisting of brighter and darker stripes of the differentiated chemical composition that probably correspond to the amorphous Ni–Cu–P and Ni–Fe–B regions.

SEM image and EDS line scan done at the cross-section of the TCMS Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$ ribbon (Fig. 4) show the presence of bands with differentiated chemical composition. Brighter and darker bands are arranged along the longitudinal direction of the ribbon. The EDS line scan indicates that the brighter bands are enriched in Ni, Cu, and P, while the darker bands are enriched in Fe. Boron was not detected in the analysis, although it is expected that the regions also contain B. Obviously, the streams of both Ni–Fe–B and Ni–Cu–P liquids were partially mixed during the passing through the orifice in the crucible, but the rapid cooling during the melt-spinning process did not allow for the extensive diffusion of the species in the liquid state and complete homogenization of the alloy.

The results of the tensile tests (Fig. 5) show that the highest tensile strength and Young modulus are obtained for the Ni$_{40}$Fe$_{40}$B$_{20}$ alloy, i.e.: $R_m = 2055 \text{ MPa}$, $E = 152 \text{ GPa}$, respectively. Substantially lower $R_m$ and values are obtained for the remaining ribbons melt-spun from the single-chamber crucible, i.e.: Ni$_{70}$Cu$_{10}$P$_{20}$ – $R_m = 592 \text{ MPa}$, $E = 54 \text{ GPa}$, and Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$ $R_m = 634 \text{ MPa}$, $E = 78 \text{ GPa}$. For all of the above mentioned alloys $\sigma$–$\varepsilon$ linear relationships without apparent plastic deformation are observed. However, the TCMS Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$ $\sigma$–$\varepsilon$ plot does not constitute a straight line. Tensile strength of the alloy is $R_m = 985 \text{ MPa}$, and Young modulus (the slope) varies from $E = 95 \text{ GPa}$ at the beginning of the test to $E = 143 \text{ GPa}$ for the interval between $\varepsilon = 0.4\%$ and $\varepsilon = 0.75\%$. Above $\varepsilon = 0.75\%$ a plastic deformation is observed at $R_e = 361 \text{ MPa}$.

Fractures of the Ni$_{40}$Fe$_{40}$B$_{20}$, Ni$_{70}$Cu$_{10}$P$_{20}$, and Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$ ribbons melt spun after ejection from the single-chamber crucible are shown in Fig. 6a–c, respectively. These fractures present smooth and brittle glassy appearances typically found in amorphous alloys due to the result of intense localization of plastic flow.
The observation is consistent with the findings of Spaepen [17] that the deformation behaviour of glassy materials at low temperatures and high stresses is extremely inhomogeneous and plastic flow is highly localized in thin shear bands.

However, the fracture surface in the TCMS Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$ (Fig. 6d and e) is more developed than in the case of the Ni$_{40}$Fe$_{40}$B$_{20}$, Ni$_{70}$Cu$_{10}$P$_{20}$, and Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$ amorphous alloys obtained by ejection from the single-chamber crucible (Fig. 6a–c). The appearance of the fracture surface is ductile with the presence of a vein-like pattern. The SEM microphotographs and EDS maps show that there are strip-like regions of the differentiated chemical composition on the fracture parallel to its edge (Fig. 6f). It is characteristic that the location of some segments of this vein-like pattern is coincidental with the boundaries of the Ni–Fe–B and Ni–Cu–P areas. These boundary Ni–Fe–B/Ni–Cu–P regions are marked with dotted lines and white arrows on Fig. 6e and f (SEM micrograph and Fe map). Therefore, it is obvious, that this differentiation of the chemical composition influenced the fracture formation in the TCMS Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$ amorphous alloy. This is in agreement with findings of Concustell et al. [18], where the formation of the Ni–Nb–Y amorphous/amorphous double phase composite led to formation of multiple shear bands. The improvement of ductility is attributed to the fact that the precipitation of a second phase in the amorphous matrix may affect the course of the shear band [18,19]. Therefore, the appearance of the ductile fracture in this TCMS alloy is probably due to the disruption of the shear bands. The TCMS Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$ metallic glass is

![Fig. 5. Stress-strain σ–ε curves of homogeneous Ni$_{40}$Fe$_{40}$B$_{20}$, Ni$_{70}$Cu$_{10}$P$_{20}$, Ni$_{55}$Fe$_{20}$-Cu$_{5}$P$_{10}$B$_{10}$ alloys and Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$ TCMS amorphous/amorphous composite alloy.](image)

![Fig. 6. SEM images of the fractures after tensile breaking of amorphous alloys: a) Ni$_{40}$Fe$_{40}$B$_{20}$; b) Ni$_{70}$Cu$_{10}$P$_{20}$; c) Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$; d) and e) TCMS Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$; f) EDS maps showing the distribution of Ni, Fe, Cu, and P for the SEM image from Fig. 5e; dashed lines and white arrows indicate the coincidence between the vein-like pattern (Fig. 5e) and the boundaries of the Ni–Fe–B and Ni–Cu–P areas (Fig. 5f).](image)
composed of the two amorphous phases of different chemical compositions. Therefore, the ductile fracture is induced by this differentiated phase composition.

Comparison of the tensile fractures in the ribbons traditionally melt spun and the TCMS Ni_{55}Fe_{20}Cu_{5}P_{10}B_{10} ribbon, suggests that the special lamellar wood-like microstructure of the latter alloy influences formation of more complex fractures. This in turn derives from the presence of more than one amorphous phase in the sample.

Mössbauer spectra obtained at room temperature are shown in Fig. 7, while essential parameters are listed in Table 1. The uppermost spectrum belongs to the amorphous Ni_{40}Fe_{40}B_{20} homogeneous alloy. This indicates the definite magnetic order of the iron magnetic moments at room temperature and the average hyperfine field is larger than in the analogous Ni_{40}Fe_{40}P_{20} alloy [14]. On the other hand, the isomer shift is smaller, indicating higher electron density on iron nuclei in Ni_{40}Fe_{40}B_{20} than in Ni_{40}Fe_{40}P_{20}. The replacement of phosphorus by boron preserves the amorphous state and increases the magnetic ordering temperature. The same effect was observed comparing the homogeneous amorphous Ni_{55}Fe_{20}Cu_{5}P_{10}B_{10} alloy (lowest spectrum of Fig. 7) with the analogous Ni_{55}Fe_{20}Cu_{5}P_{20} alloy [14]. Replacement of phosphorus by boron lifts the magnetic ordering temperature from below to above room temperature. Some traces (2%) of iron phosphide are observed. The central spectrum of Fig. 7 belongs to the amorphous alloy obtained by the TCMS method from two alloys Ni–Fe–B and Ni–Fe–Cu–P–B–Ni.
Ni–Cu–P. The spectrum is composed of two components. The dominant component (89%) is similar to the spectrum of Ni$_{40}$Fe$_{40}$B$_{20}$. Slight reduction of the hyperfine field and increase of the isomer shift is an indication of the transfer of some elements from Ni–Cu–P – presumably phosphorus. The minor non-magnetic component (11%) is similar to the spectrum of iron phosphides. Hence, one can conclude that some amount of iron migrated from Ni–Fe–B to Ni–Cu–P. Hence, a composite alloy is generally obtained as only about 11% of elements exchange phases.

DSC traces performed for the TCMS Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ and single-channel crucible melt-spun Ni$_{40}$Fe$_{40}$B$_{20}$ and Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ ribbons are presented in Fig. 8. The temperatures of the crystallization onset as well as peak temperatures are shown in Table 2. The highest onset temperature is found in the Ni$_{40}$Fe$_{40}$B$_{20}$ (B) alloy where $T_{on}$ was 708 K; it also has only one crystallization peak at $T_1B = 719$ K. On the other hand, the Ni$_{70}$Cu$_{10}$P$_{20}$ alloy has a substantially lower thermal stability with onset at $T_{on} = 589$ K. It is worth noting that the TCMS Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ alloy starts crystallization at $T_{on} = 587$ K, which is a similar value to the one found in the Ni$_{70}$Cu$_{10}$P$_{20}$ alloy. However, the Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ ejected from the single-channel crucible, in spite of the similar average composition, starts crystallization at a substantially higher temperature, i.e., $T_{on} = 636$ K.

Another special feature of the TCMS Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ alloy is that there is a coincidence between peak temperatures found on the DSC trace of this alloy and the traces of alloys of Ni$_{70}$Cu$_{10}$P$_{20}$ (A) and Ni$_{40}$Fe$_{40}$B$_{20}$ (B) (see Table 2). The first crystallization peak for the TCMS Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ alloy is at $T_{1A} = 607$ K and its maximum is at the same temperature as the first peak for Ni$_{70}$Cu$_{10}$P$_{20}$ (A) – $T_{1A} = 607$ K. The second peak for the TCMS alloy $T_{2A} = 662$ K corresponds to second peak found in alloy A, i.e., $T_{2A} = 658$ K. The third peak for the TCMS alloy found on the DSC trace at $T_{3A} = 724$ K can be associated with the first and the only crystallization peak for the DSC trace of the B alloy, i.e., $T_{3B} = 719$ K.

The fourth DSC peak of the TCMS alloy located at $T_{3A} = 743$ K is close to the position of the third peak for the A alloy – $T_{3A} = 744$ K. However, in the latter case, the value of $T_{2C} = 739$ K found for the Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ (C) alloy ejected from the single-channel crucible should also be considered, due to the fact that some small boundary regions (between A and B) of the TCMS alloy may have a composition very close to Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ (C).

Generally, the DSC study confirms that the unique feature of the TCMS Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ alloy is that the temperatures of the exothermic effects occurring in the alloy are similar to both amorphous alloys, i.e., for Ni$_{70}$Cu$_{10}$P$_{20}$ (A) and Ni$_{40}$Fe$_{40}$B$_{20}$ (B). Therefore, the TCMS alloy enabled inheritance of the transformations. This was not observed in the traditionally melt-spun Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ (C) alloy with uniform chemical composition. The presence of the peak at $T_{3A} = 743$ K on the DSC trace of the TCMS Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ alloy confirms the presence of the transition regions between Ni–Fe–B and Ni–Cu–P regions, where it is possible that a range of intermediate chemical compositions occur. In probability, these boundary compositions are close to the composition of Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ (C). This is in accordance with the Mössbauer study.

The X-ray diffraction patterns performed in situ at elevated temperatures are presented in Fig. 9. Table 3 indicates the presence of a given phase at a given temperature, which is represented by a solid dot. The initially amorphous sample (Fig. 2) remains glassy even at 553 K (Fig. 9), where diffraction still has a broad peak between 40° and 50°. The first diffraction peaks confirming the appearance of the crystalline phases are recorded at 603 K. At this temperature, the peaks can be attributed to three phases. The first one is isomorphic with Ni fcc solid solution (space group Fm-3m, $a = 3.5238$ Å, PDF no 00-004-0850), the second corresponds to the tetragonal Ni$_3$P phosphide (space group: I4, $a$: 8.956 Å, c: 4.388 Å, PDF no 00-005-5615), and the third one can be attributed to the CuNi solid solution (space group: Fm-3m, $a$: 5.3636(5) Å, PDF no 01-071-7832). The same phases also seem to be present at 663 K. However, at a temperature of 753 K, a new series of diffraction peaks are present, which can be identified as the patterns from the next three phases, i.e., the phase isomorphic with FeNi fcc solid solution (space group: Fm-3m, $a$: 3.575 Å, PDF no 01-071-8322), the orthorhombic FeNi$_{1.5}$Ni$_{1.5}$B compound (a: 5.34 Å, b: 6.637 Å, c: 4.437 Å, PDF 04-001-9092), and the fcc FeNi$_3$ phase (space group: Fm-3m, $a$: 3.556 Å, PDF no 01-071-8324). It is clear from Table 1 that crystallization of the amorphous TCMS Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ alloy starts with the formation of the solid solutions and compounds containing Ni, Cu, and P, although it did not occur until 753 K crystallization of the phases containing Fe and B.

On the basis of the comparison of the XRD and DSC investigations, it can be concluded that the DSC peaks observed at $T_{1A} = 607$ K and $T_{2A} = 662$ K are associated with crystallization of the Ni–Cu–P regions, although at higher temperature crystallization of the Fe–Ni–B regions proceeds. There are also traces of crystallization of amorphous regions containing all the species, i.e., Ni, Fe, Cu, P, and B. The latter is associated with devitrification of the transition regions between frozen streams of Ni–Cu–P and Ni–Fe–B.

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**Table 2**

Values of crystallization onset and peak temperatures obtained from the DSC curves of the amorphous Ni$_{70}$Cu$_{10}$P$_{20}$, Ni$_{40}$Fe$_{40}$P$_{20}$, TCMS Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$, and Ni$_{55}$Fe$_{20}$Cu$_{10}$P$_{10}$B$_{10}$ alloys.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Temperature of effects [K]</th>
<th>$T_{on}$</th>
<th>$T_{1A}$</th>
<th>$T_{1C}$</th>
<th>$T_{2A}$</th>
<th>$T_{AB}$</th>
<th>$T_{IB}$</th>
<th>$T_{3A}$</th>
<th>$T_{3C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni$<em>{70}$Cu$</em>{10}$P$_{20}$ (A)</td>
<td>589</td>
<td>607</td>
<td>-</td>
<td>-</td>
<td>658</td>
<td>-</td>
<td>744</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Ni$<em>{40}$Fe$</em>{40}$P$_{20}$ (B)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>708</td>
<td>719</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>TCMS Ni–Fe–Cu–P–B</td>
<td>587</td>
<td>607</td>
<td>-</td>
<td>-</td>
<td>662</td>
<td>706</td>
<td>724</td>
<td>743</td>
<td></td>
</tr>
<tr>
<td>Ni$<em>{55}$Fe$</em>{20}$Cu$<em>{10}$P$</em>{10}$B$_{10}$ (C)</td>
<td>-</td>
<td>636</td>
<td>651</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>739</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3**

Phases identified on XRD as a function of scan temperature.

<table>
<thead>
<tr>
<th>Scan temperature [K]</th>
<th>Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>Ni$_3$P</td>
</tr>
<tr>
<td>553</td>
<td></td>
</tr>
<tr>
<td>603</td>
<td></td>
</tr>
<tr>
<td>663</td>
<td></td>
</tr>
<tr>
<td>753</td>
<td>⬤</td>
</tr>
</tbody>
</table>

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![Fig. 9. X-ray diffraction patterns registered at different temperatures.](image-url)
4. Conclusions

1. The results of the X-ray diffraction and TEM observations prove that the microstructure all of the investigated alloys is amorphous, although the TCMS alloy presents a microstructure composed of the stripes of differentiated chemical composition.

2. The microscopic observations of the TCMS alloy confirm that the microstructure of the alloy consists of $\text{Ni}–\text{Cu}–\text{P}$ and $\text{Ni}–\text{Fe}–\text{B}$ stripes forming wood-like morphology. This favours the ductile fracture related with the arrangement of the amorphous stripes of the differentiated chemical composition.

3. The special feature of the TCMS Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$ alloy is a coincidence between the peak temperatures found on the DSC trace of this alloy and the DSC traces of the Ni$_{70}$Cu$_{10}$P$_{20}$ and Ni$_{40}$Fe$_{40}$B$_{20}$ alloys. It can be assumed that the TCMS alloy inherited the transformations from the precursor alloys in their amorphous state.

4. The Mössbauer study confirms the composite structure of the TCMS alloy, where 89% of the iron sites are similar as in the Ni$_{40}$Fe$_{40}$B$_{20}$ alloy, and 11% of iron sites can be attributed to the regions that probably formed due to mixing of the two fluxes, forming the non-magnetic constituent of the alloy consisting of all the alloying species, i.e., Ni, Fe, Cu, P, and B.

5. The DSC study also confirms the presence of transformations of the transition intermediate regions between $\text{Ni}–\text{Fe}–\text{B}$ and $\text{Ni}–\text{Cu}–\text{P}$. The position of the peaks from these transformations suggests that the composition of the intermediate regions are close to the average Ni$_{55}$Fe$_{20}$Cu$_{5}$P$_{10}$B$_{10}$ composition.

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