Advanced high-strength and ductile Fe-Cr-Mo-Ga-Si alloys

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Outline

✓ Introduction
✓ Design of alloys
✓ Results & Discussion
✓ Conclusions
✓ The next steps

Goals of the work
Experimental procedure
Relationship between applied preparation conditions, microstructure and resulting mechanical properties of studied alloys
What makes these materials so special?

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Among glass-forming alloy systems reported so far, Fe-based BMGs play special role.

Why?

Because of their unusual combination of engineering properties.

However

The wider application of Fe-based bulk glassy alloys as structural materials is strongly limited due to their little macroscopic plasticity.

Aim of the work

Improvement of ductility of Fe-based bulk glassy alloys by:

Formation of BMG composite materials

1Akihisa Inoue - Institute for Materials Research, Tohoku University, Japan
Materials and Experiments

- A multicomponent alloy with a tendency to form a glassy phase was chosen as the starting material.

Advantages
- Very good soft magnetic properties
- Excellent mechanical strength $\sigma_f$ compression $\approx 2.8$ GPa

Disadvantage
- Almost no plasticity upon compression deformation
  - $\varepsilon_{pl}$ compression $\approx 0.15 \%$
  - $\varepsilon_f$ compression $\approx 1.9 \%$

Preparation methods
- Arc-melting (master alloy ingots)
- Centrifugal casting (rod-shaped samples with a length of 70 mm and a diameter of 3 mm)

Derived compositions:
- $\text{Fe}_{65.5}\text{Cr}_4\text{Mo}_4\text{Ga}_4\text{P}_{12}\text{C}_5\text{B}_{5.5}$
- $3.2$ at.% Si
- $6.4$ at.% Si

The glass-forming ability of studied alloys is not sufficient to obtain a glassy phase as a result of casting process.

- Applied investigation methods:
  - Structural characterization:
    - X-ray diffraction
    - Optical microscopy
    - Scanning electron microscopy
    - Transmission electron microscopy
  - Mechanical properties:
    - Room temperature compression tests
    - Vickers hardness

Different crucible material used:
- Al$_2$O$_3$
- Glass carbon

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Interaction among: processing route → microstructure

- X-ray diffraction patterns for as-cast rod samples
  Co-Kα radiation
  \( \lambda = 0.17889 \text{ nm} \)

- SEM micrographs taken from the middle part of the rods

Additional measurements:
- EDX
- WDX

**Chemical compositions:**
- \( \text{Fe}_{81.1}\text{Cr}_{5.2}\text{Mo}_{5.2}\text{Ga}_{5.2}\text{Si}_{3.2} \)
- \( \text{Fe}_{78.0}\text{Cr}_{5.2}\text{Mo}_{5.2}\text{Ga}_{5.2}\text{Si}_{6.4} \)

**Phase identifications:**
- Martensite
- \( \text{Cr}_3\text{Si} \)
- Unidentified phase(s)
- \( \text{f.c.c.} \) \( \gamma \)-Fe
- \( \text{b.c.c.} \) \( \alpha \)-Fe
- \( \text{Mo}_2\text{C} \) or \( \text{MoSi}_2 \)

**Microstructure features:**
- Glass carbon
- Glass
- Ga-rich phase
- Homogeneous single-phase structure
- Composite structure
- Single-phase structure
- Cr- and Mo-rich matrix
Interaction among:
 microstructure

- TEM bright-field images of as-cast alloys

Fe$_{78.0}$Cr$_{5.2}$Mo$_{5.2}$Ga$_{5.2}$Si$_{6.4}$

The detailed insight into the microstructure of the investigated samples has revealed certain differences regarding the shape and morphology of precipitated phases.
The appearance of the specific complex microstructure leads to a material with very high fracture strength and good ductility, while the formation of the single-phase structure results in extremely high plasticity of examined alloys.
**Mechanical properties**

**Vickers hardness measurements**

Properties of phases $\approx$ microhardness

$\text{HV}_{\text{Ga-rich precipitates}} = 4.2 \text{ GPa}$

$\text{HV}_{\text{Cr- and Mo-rich matrix}} = 6.28 \text{ GPa}$

Investigated composites essentially consist of soft Ga-enriched precipitates embedded in a hard Cr- and Mo-enriched matrix.

$\text{HV}_{\text{monolithic Fe-based BMG}} = 8.68 \text{ GPa}$

Because of the coexistence of the ductile precipitates with a high-strength matrix the excellent mechanical properties are observed.
**Mechanical properties**

- **Fracture behavior**

  Fe$_{81.1}$Cr$_{5.2}$Mo$_{5.2}$Ga$_{5.2}$Si$_{3.2}$

  Fe$_{78.0}$Cr$_{5.2}$Mo$_{5.2}$Ga$_{5.2}$Si$_{6.4}$

- SEM micrographs showing the fracture surface features of the compressed alloys

- Free of cracks dendritic phase

For both alloys the fracture surface appears to consist of a number of cracks as well as void-like "black dimples" (marked by yellow and blue arrows).

The soft Ga-rich dendrites act as obstacles for dislocations and crack propagation, and, therefore, cause pronounced strain-hardening.
Processing route \rightarrow \text{Centifugal casting method} \rightarrow \text{Crucible material used} \rightarrow \text{Microstructure} \rightarrow \text{Mechanical properties} \rightarrow \text{Compression tests results} \rightarrow \text{Alloy with an amazing capacity for compression deformation.}

\begin{itemize}
  \item Diffusion of the carbon into the melt.
  \item Ga-rich soft dendrites
  \item Cr- and Mo-rich hard matrix
  \item Complex structure
  \item Single-phase structure
\end{itemize}

Cooling rate $10^3$-$10^2$ Ks$^{-1}$
Conclusions

✓ Novel multi-component Fe-based alloys were prepared by copper mold casting technique.
✓ The strong relationship between processing route, structure and resulting mechanical properties was observed.
✓ Formation of the composite microstructure consisting of soft Ga-rich precipitates embedded in a hard Cr- and Mo-rich matrix phase leads to material with unique mechanical properties:

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\begin{align*}
\text{Fe}_{81.1}\text{Cr}_{5.2}\text{Mo}_{5.2}\text{Ga}_{5.2}\text{Si}_{3.2} & \quad \sigma_{\text{f comp.}} \approx 2.9 \text{ GPa} \\
\text{Fe}_{78.0}\text{Cr}_{5.2}\text{Mo}_{5.2}\text{Ga}_{5.2}\text{Si}_{6.4} & \quad \sigma_{\text{f comp.}} \approx 3.3 \text{ GPa}
\end{align*}
\]

\[
\begin{align*}
\varepsilon_{\text{f comp.}} & \approx 13 \% \\
\varepsilon_{\text{f comp.}} & \approx 6 \%
\end{align*}
\]

✓ Such excellent mechanical characteristics have never been observed before for any crystalline as well as glassy Fe-based alloy.

Further work

„...Compressive „ductility“ is not necessarily valid or even very interesting without corresponding measurements in tension...“.

In order to confirm following conclusion, tensile tests must be performed.

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