ADVANCED MATERIALS

Production and Application of Rapidly Quenched Materials

Soft Magnetic Materials
Intermetallics
Brazing Alloys

By Hans Warlimont *

1. Introduction

The development of metallic glasses, i.e. amorphous metals produced by rapid quenching from the melt, has an impact on four areas of materials technology:
- substitution of existing materials
- innovation in applications
- instigation of competing material developments
- opening more widely the field of rapid solidification technology

In this overview both ribbon shaped soft magnetic materials and flake shaped hard magnetic materials are included, with emphasis on the former. It should be noted that other rapid solidification processes and products such as rapidly solidified powders, e.g. of aluminum alloys, and the formation of bulk materials by melt-spraying are also being developed and introduced commercially.

Table 1. Commercial applications of cooling wheel based RST.

	Single Roll		Double Roll	Centrifugal Water Cooling Wheel
Form of Product	strip	powder	strip	wire
Materials	amorphous magnetic alloys brazing alloys crystalline brazing alloys	$Fe_{14}Nd_2B$ Al alloys high speed steels hard facing alloys various steels (fibers)	Fe – Si	amorphous
Producers	Allied Signal Metglas Products Hitachi Metals Toshiba TDK VAC SISR I Shanghai CISRI, BMRI Beijing	Delco Remy Allied Signal Metglas Products Marko Materials Fibretech/Ribtec	Kawasaki Steel	Unitika

Table 1 shows a (possibly incomplete) compilation of the major materials, producers and forms of product of rapid solidification technology (RST). Table 2 shows an assessment of the products and applications of RST for 1988 indicating the uncertainty in quantitative data but giving some probable ranges. It should be noted that there are many more pilot productions in operation other than by those companies named in Table 1 and that thin strip casting is being developed on a much larger scale and for a much wider range of products than those comprised in Table 2. In most cases, however, product thickness is larger and cooling rates are lower, and therefore productivity rather than rapid solidification effects are sought.

Table 2. Rapid solidification technology – products and applications 1988.

Products	Applications	Quantities [tons]
amorphous ribbons Fe based	distribution transformers and large chokes	$10^2 \ldots < 10^3$
amorphous ribbons Fe and Co based	inductive components, sensors	$< 10^2$
microcrystalline $Fe_{14}Nd_2B$ powders	bonded permanent magnets	$> 10^2$
amorphous brazing alloys	aerospace	?
microcrystalline Al based powders	aerospace	?
microcrystalline steels	tools, reinforcement	?

2. Power Applications of Amorphous Metals

For this and the following section on the magnetic applications of metallic glasses, recent reviews [1, 2] and publications of conference proceedings [3, 4] should be consulted for details.

Figure 1 shows a comparison of different materials and operating conditions (peak induction $\hat{B}$) with regard to the

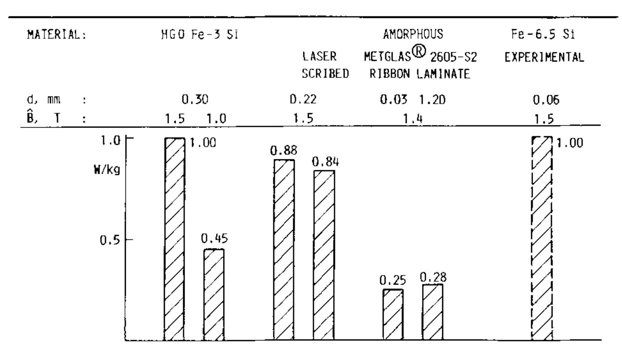

Fig. 1. 60 Hz power loss for typical Fe – Si and amorphous transformer materials.

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power loss p_{Fe} in transformers operating at a power grid frequency of $f = 60$ Hz. It is obvious that amorphous metals are substantially superior to the other materials but that progress has been made in the case of silicon steels and operating conditions are also yielding drastic differences. This indicates that economic aspects, such as investment and life cycle costs, will be decisive in the final use of transformer materials. The largest producer of amorphous core transformers in the USA, the General Electric Company, reports that their sales (over the last several years) total just 10000 amorphous core transformers (typically in the 30 kVA power range) but that they expect sales to double in each of the next few years. This should be compared with the total number of 1.2 million transformers sold in the USA annually. Jacksonville Electric Authority in Florida has so far bought 1600 amorphous-metal transformers which have cut power losses by 60%. The transformers are priced about 25% higher than conventional ones.[5]

3. Speciality Magnetic Applications of Amorphous Metals

The drastic reduction of iron loss in amorphous vs. crystalline soft magnetic materials is a major reason for their applications in power transformers. Their low coercivity H_c reduces their hysteresis losses, but their low ribbon thickness $d \lesssim 0.030$ mm and their high electrical resistivity $\rho \gtrsim 130$ μΩcm are still more effective in reducing the eddy current losses, which are proportional to d^2/ρ. This leads to the competitive situation between amorphous metal ribbons and ferrites shown in Figure 2. The ferrites have been improved in the sequence N27, N67, H_{7c4} (commercial designations) but the Co based amorphous ribbons are superior at all frequencies if their ribbon thickness is reduced to $d \simeq$ 15 μm which is technically and economically feasible. Apart from lower losses another favorable property of amorphous metal cores with a Z type loop is their high squareness.

Table 3 is a compilation of speciality applications of soft magnetic amorphous metals. They have reached different degrees of importance. The use of amorphous cores in current compensated chokes may be pointed out as a special case. The effectiveness of these chokes in suppressing common mode interference is expressed by the insertion loss as a function of the frequency of the noise spectrum. Figure 3 shows the superiority of amorphous core chokes compared to permalloy and ferrite core chokes which exhibit lower insertion losses and pronounced minima at certain frequencies due to resonance effects.

Table 3. Magnetic speciality applications of amorphous metals.

Field of Application	Specific Application
power supplies	switched mode power supplies: – inverter transformers – chokes for magnetic amplifiers – storage chokes – RF current compensated chokes high repetition rate pulse compressors: – step-up transformers – saturable reactors
other HF circuits	– transformers – chokes
magnetic heads	– audio – data storage
magnetic shielding	– flexible shields
sensors	– magnetic field – position, displacement – force, torque – identification and anti-theft markers

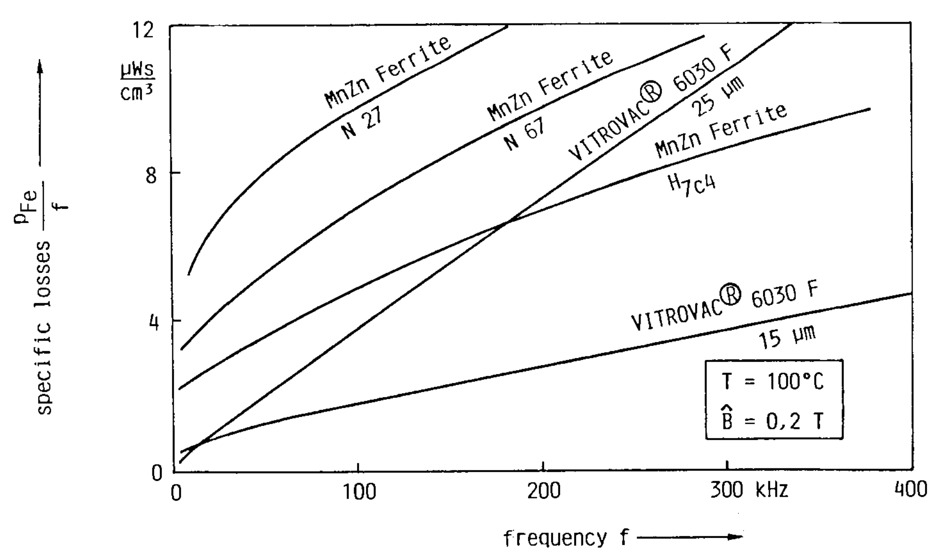

Fig. 2. Power losses per cycle for medium frequency materials.

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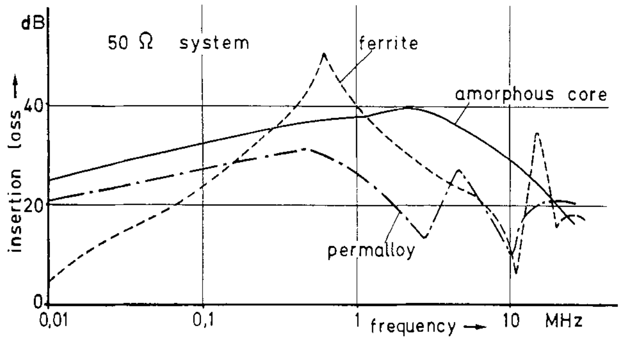

Fig. 3. Insertion loss of common mode interference in current compensated chokes.

4. Rapidly Quenched $Fe_{14}Nd_2B$

The hard magnetic compound $Fe_{14}Nd_2B$ is becoming important among the rare earth bearing permanent magnetic materials because of its high ratio of performance vs. cost. It is produced both by conventional powder metallurgical processing and by RST. To utilize the magnetic material to the full, anisotropic magnets are produced using powder metallurgy. Rapid solidification yields a higher coercivity and a somewhat lower temperature coefficient of the remanence B_r which is useful in some applications, and it allows the production of bonded magnets which are formed more easily yielding in certain cases an economic advantage. Since the material is produced by ribbon formation in the amorphous state, followed by disintegration into flakes and crystallization of the intermetallic compound, the magnetic easy axis is oriented randomly yielding isotropic properties. However, it has been found that uniaxial hot pressing of the flakes induces oriented selective grain growth such that anisotropic properties result. Table 4 gives properties of powders which

Table 4. Properties of rapidly quenched $Fe_{14}Nd_2B$ powders [a].

Type	Remanence B_r [T]	Coercivity $_iH_c$ [kA/cm]	$(dB_r/dT)/B_r$ [%/K (25...100 °C]
A. isotropic	0.75	12	−0.13
B. isotropic	0.80	7	−0.11
C. anisotropic	0.95	9	−0.12
E. anisotropic	0.86	10	−0.17

[a] Magnequench by Delco Remy.

are commercially available. In the present state of evaluation it is to be expected that sintered and rapidly quenched $Fe_{14}Nd_2B$ hard magnetic materials will be supplementing rather than competing with each other.

5. Further Materials Developments and Perspectives

Apart from the soft magnetic amorphous materials and the microcrystalline hard magnetic $Fe_{14}Nd_2B$ compound, other RST materials are beginning to assume commercial importance such as brazing alloys, nanocrystalline soft magnetic alloys and others (Table 2).

Rapid solidification of brazing alloys has yielded two advantageous aspects: a) amorphous and microcrystalline structures impart favorable mechanical properties to brazing alloys; b) supersaturation effects and favorable brazing behavior permit the design of active brazing alloys with technical and economic advantages. Active brazing involves an alloy containing an oxygen getter which eliminates the use of flux media for metal brazing and the need to metallize ceramic parts to be brazed. The resulting simplification of the brazing process is indicated in Figure 4. A typical alloy which was developed for this application is Ag−Cu−Ti.[6]

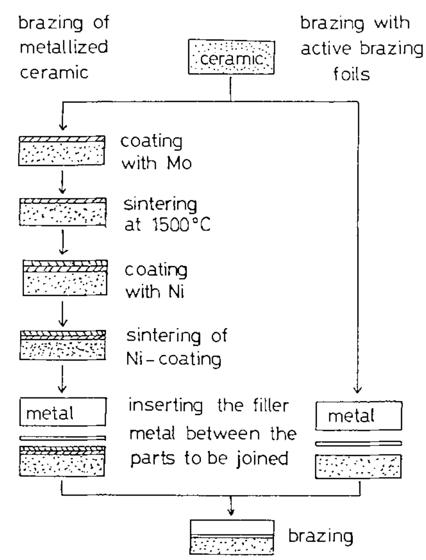

Fig. 4. Comparison of brazing processes for metal-ceramic joints.

A recent development by Hitachi Metals Ltd.[7] has yielded a rapidly solidified soft magnetic material with an extremely low grain size in the nm range. A typical composition

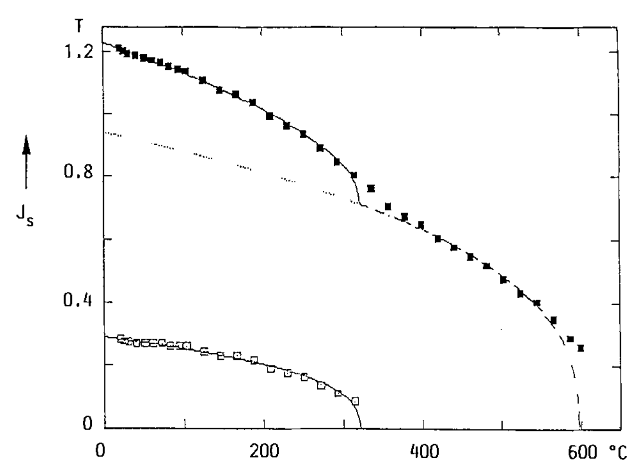

Fig. 5. Magnetization vs. Temperature of rapidly quenched $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ annealed 1 h at 520 °C.

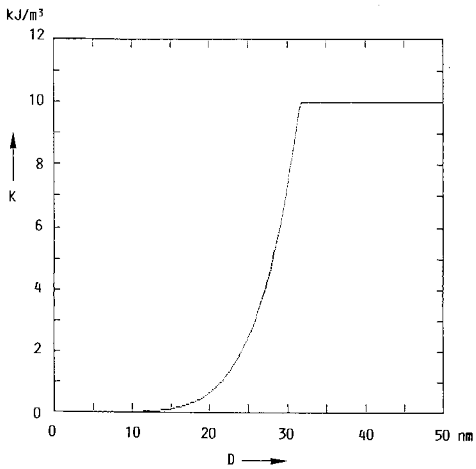

Fig. 6. Computed magnetocrystalline anisotropy K vs. grain diameter D.

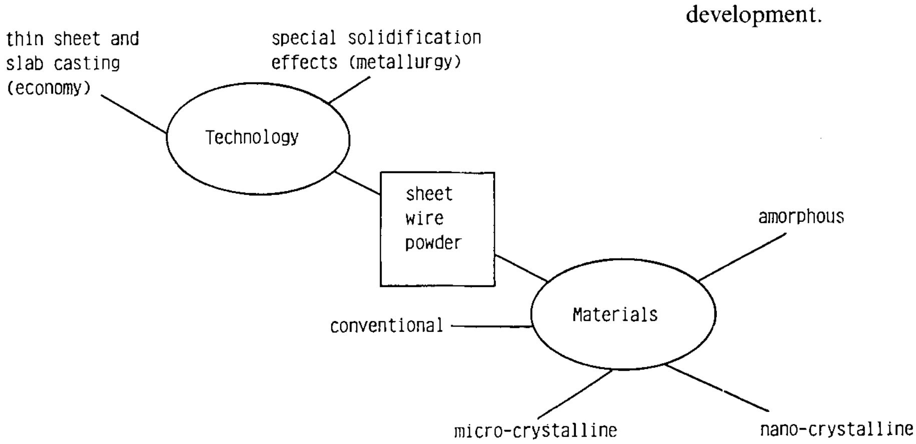

Fig. 7. Perspectives of rapid Solidification technology.

is $Fe_{73.4}Cu_1Nb_{3.1}Si_{13.4}B_{9.1}$. At variance to normal behavior where the coercivity H_c is expected to vary as the inverse of the grain diameter D, this material has a very low coercivity in the same range as that of the best amorphous materials. The explanation was found[8] by first determining the temperature dependence of the saturation polarization shown in Figure 5. It indicates clearly the presence of two ferromagnetic phases with different Curie temperatures which are due to a crystalline Fe–Si rich phase (high-T_c) and probably an amorphous phase (lower-T_c) forming a grain boundary layer. In a second step the magnetocrystalline anisotropy of such a microstructure was computed as a function of grain diameter D, Figure 6. It can be seen that magnetic isotropy prevails up to $D \lesssim 15$ nm. This is one of the essential prerequisites of a low magnitude of H_c. Combined with further favorable magnetic properties such as high B_r and low magnetostriction λ_S and losses p_{Fe} this material is quite promising for a number of applications.

Brazing alloys and nm-range crystalline soft magnetic alloys are just two examples of the versatility and the range of potential developments of rapid solidification technology. In Figure 7 a schematic view of the field is given. One important feature is the technology which allows on one hand for the design of special structural and microstructural effects and on the other, the economy of a one-step process from the melt to the final (or a near-final) product. The second aspect of the application of this technology is the different materials which can be produced possessing a variety of properties. It is obvious that this field has a great potential for further development.

Received March 14, 1989

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