पदार्थ विज्ञान प्रभाग, भाभा परमाणु अनुसंधान केंद्र में पदार्थ विकास गतिविधियाँ

1

Materials Development Activities at Materials Science Division in BARC

Raghvendra Tewari et al*
Materials Group, Bhabha Atomic Research Centre (BARC), Trombay, Mumbai 400085, INDIA

Materials being at the forefront of any societal advancement, Materials Science Division at BARC is actively engaged in the pursuit of development of materials with improved properties and performance for applications, spanning across in-core and out-of-core structural materials for nuclear reactors to materials to be used as magnets. This article presents a glimpse of this journey for three specific materials: (1) Bainitic steel for reactor pressure vessel (RPV) applications; (2) Ni-Cr-Mo alloy for molten salt breeder reactor (MSBR) applications; and (3) Fe-Co and Co–Zr based alloys for use as soft magnets and permanent magnets.

Development of Low-carbon Carbide-free Bulk Nanostructured Bainitic Steel

Carbide-free bainitic steels consisting of a fine network of bainitic ferrite platelets interspersed by thin retained austenite films could emerge as a material of choice for applications demanding high strength with satisfactory fracture toughness, like RPV. Achievement of uniformity of microstructure and properties across thick sections (~ 400-800 mm) is paramount for RPV. This poses challenges to fabrication routes relying on rapid heating/cooling to generate specific microstructural features. In view of this, Materials Science Division designed a low-carbon (0.23 wt.%) carbide-free bainitic steel composition, which would enable the development of a nanobainitic microstructure in bulk without resorting to faster heating/cooling cycles, together with exhibiting better microstructural uniformity, high strength and toughness, lower residual stresses, better fabricability, and good weldability. It was possible to demonstrate in the designed steel composition, following melting and forging, the evolution of a carbide-free bainitic microstructure through both isothermal holding (Fig.1) as well as via continuous cooling at very slow rates. The carbide-free fine bainitic microstructure displayed a tensile strength of ~ 1.5 GPa, tensile elongation of ~ 20% and fracture toughness of ~ 65 MPa.m$^{1/2}$.

Development of Ni-Cr-Mo Alloy

Ni-based alloys are suitable for MSBR applications due to their excellent molten salt corrosion resistance, high-temperature strength, and good weldability. To further improve these properties, the composition of the alloy was optimized based on thermodynamic calculations and laboratory scale melting (Table 1). Compression tests were carried out to develop processing map (Fig.2a), which identified 1150-1200^{0}C and 10^{-3}-10^{-2} s^{-1} as temperature and strain rate windows, respectively, to achieve dynamic recrystallization. The optimized processing conditions helped in successful forging of a large-scale ingots (~ 2 tons) without cracking. Heat treatment experiments revealed 1080 ^{0}C/30 mins as recrystallization parameters to generate strain-free grains (Fig.2b). In collaboration with NFC, several tubes were fabricated from the forged billets with properties superior to the design requirements. Aging treatments were performed up to 6500 h at 470 ^{0}C to study microstructural changes during operation. Fig.2c shows a high-resolution electron micrograph of the aged

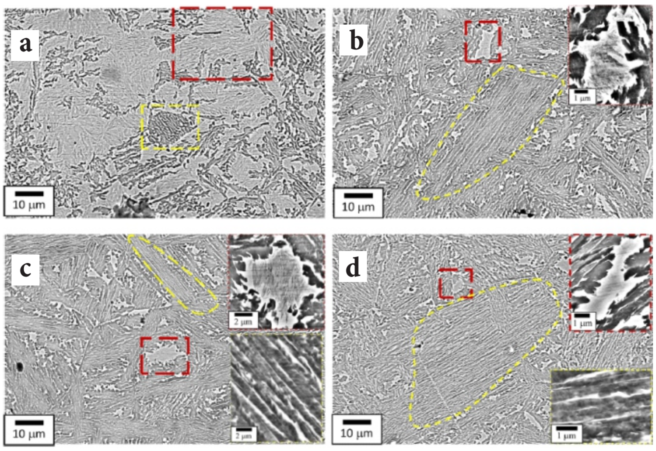

Fig.1: BSE-SEM micrographs of bainitic microstructure after isothermal treatment at (a) 450 ^{0}C, (b) 425 ^{0}C, 400 ^{0}C and (d) 375 ^{0}C. The regions marked in red and yellow, and their magnified insets, highlight martensite-austenite islands and film austenite, respectively.

Table 1: Optimized composition of the Ni-Cr-Mo alloy

Elements	Ni	Cr	C	Mo	Ti
Composition (wt.%)	78.8	7.65	0.07	12.28	1.2

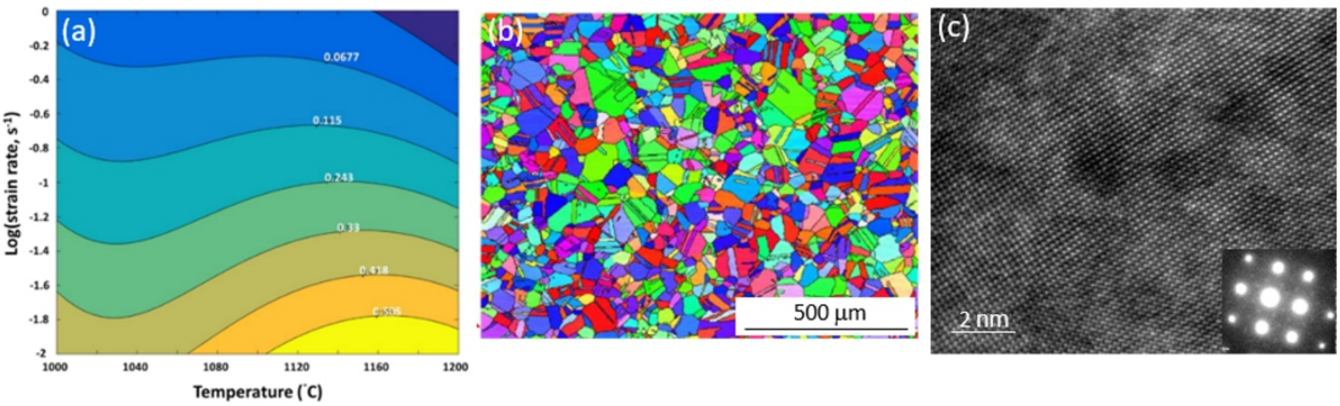

Fig.2: (a) processing map; (b) recrystallized microstructure; (c) high resolution electron micrograph (inset SAED pattern) of the aged Ni-Cr-Mo alloy.

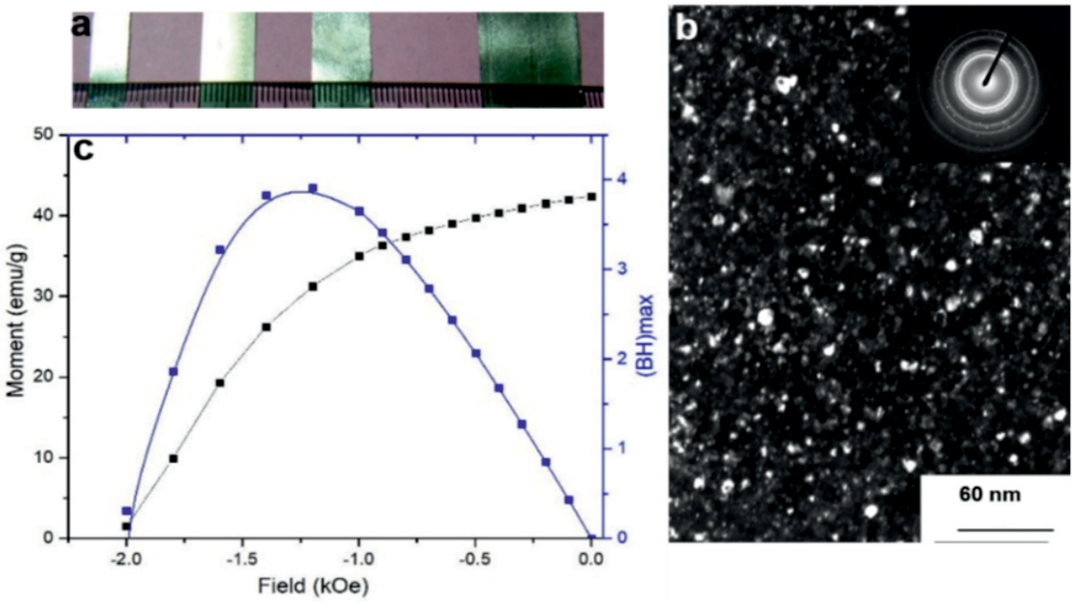

Fig.3: (a) Soft magnetic ribbons of varying width; (b) TEM micrograph showing a typical microstructure required for extremely soft magnets; (c) Magnetic moment and energy product of Zr-Co based metallic ribbon.

sample, revealing the formation of short-range ordered domains. The alloy exhibited weight loss comparable to that of commercial Hastelloy-N in molten salt corrosion experiments at 700 °C in FLiNaK salt. Welding trials using GTAW, electron beam welding, and laser welding were conducted. The weld joints satisfied ASME tensile and bend test requirements and exhibited better corrosion resistance than base material.

Development of Fe-Co and Co–Zr Based Alloys

Materials Science Division has developed the know-how for producing Fe- and Co- based soft magnetic metallic glasses in ribbon form, with widths ranging from 3 mm to 25 mm. Fig.3a shows soft magnetic ribbons of varying widths fabricated from the same alloy. These materials can exhibit magnetic inductions in the range of 1.6 – 2.1 Tesla, along with high permeability and elevated Curie temperatures. A minimum coercivity as low as 1 A/m can be achieved, and it can further be tuned to desired values through nanoscale microstructural tailoring. A representative microstructure corresponding to such optimized magnetic properties is shown in Fig. 3b.

In parallel, Materials Science Division is also engaged in the development of rare-earth-free permanent magnets with an energy product exceeding 10 MGOe. This goal is being pursued through nanoscale microstructural engineering to integrate soft and hard magnetic phases within nanocomposite materials. A Zr-Co based alloy has been identified as a promising candidate due to its high magnetic anisotropy and Curie temperature. The magnetic ribbon prepared from this alloy has demonstrated an energy product of 4 MGOe (Fig.3c).

***List of Co-Workers:** Donthula Harish, Vishal Singh, Naveen Kumar N., B. Vishwanadh, Nilabja K. Sarkar, Poulami Chakraborty, Sanjay Saini, A.P. Srivastava, S. Neogy & A. Biswas. All are affiliated to Materials Group, BARC.