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DEVELOPMENT OF HIGH STRENGTH AND STRONGLY CUBE TEXTURED Ni-5% W / Ni-10% W COMPOSITE SUBSTRATE TAPES FOR COATED CONDUCTOR APPLICATION

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ABSTRACT

The development of thin, mechanically strong and highly cube textured substrates is of great technological importance for increasing the engineering current density of the YBCO coated conductors. Nickel is a suitable substrate for this in view of its ability to form the strong cube texture after heavy cold rolling and annealing and for its excellent oxidation resistance. However, nickel is very soft (yield strength ~ 40 MPa) and this limits the processing to thin tapes. The ferromagnetism of Ni is also undesirable for application of coated conductors in magnetic fields. The present paper reports the development of Ni-5 at. % W / Ni-10 at. % W composite substrates of 80 μm thickness with strong cube texture, high yield strength (> 200 MPa) and reduced magnetisation losses.

1. INTRODUCTION

The Rolling Assisted Biaxially Textured Substrates (RABiTS™) method of Ni and Ni-based alloys (NiCu, NiFe, NiV, NiCr, NiW) is a very promising approach for the profitable production of long lengths of high temperature superconducting (HTS) $YBa_2Cu_3O_{7-8}$ (YBCO) tapes capable of carrying high currents in magnetic fields at 77 K [1-28]. In this method, the desired strong biaxial texture in the superconducting YBCO film is achieved by epitaxial growth of a buffer and YBCO film on a highly textured substrate. Initially, it has been shown [1-3] that Ni is ideally suited as a substrate material due to its ability to form a strong cube texture after heavy cold rolling and recrystallisation. In addition, its oxidation resistance and the small lattice mismatch allow epitaxial growth of buffer (for e.g. CeO_2 + yttria stabilized zirconia (YSZ)) and YBCO films. In YBCO films on Ni substrates, current densities exceeding 10^6 Acm^{-2} have been achieved [1-3]. To achieve a high engineering current density (i.e., the current in the HTS film divided by the cross section of the whole tape) very thin tapes are desirable. But the low tensile strength of Ni limits the possibility of producing very thin HTS tapes by a continuous reel-to-reel deposition process. For this reason, the strengthening of Ni substrate material is important. The need for a strong cube texture limits the possibilities of strengthening the substrate. Further, the ferromagnetism of Ni leads to hysteresis losses in coated conductors in alternating current (AC) applications [20], but it is not of great importance for direct current (DC) applications. There are two known metallurgical routes of strengthening the recrystallised substrate material i.e., solid solution and precipitation strengthening. It was shown that the substrate strength could be increased by factor 3 with substantial additions of Cr, V or W (≥ 5 at. %, compositions are given in at. % throughout the paper) without losing the strong cube texture [8-11]. The additions (> 10 %) of Cr and V also suppress the Curie temperature to below 77 K, thus reducing the magnetization losses in the coated conductors [8,20]. However, the ease of Cr/V oxide formation on the surface at the buffer and YBCO deposition temperatures (these are prepared in oxidizing atmospheres) makes the epitaxial growth difficult. Higher strength levels can also be achieved by precipitation of Al_2O_3 particles through controlled internal oxidation of a Ni-1% Al alloy [29-30]. However, the formation of Al_2O_3 particles on the surface degrades its quality rendering it unsuitable for further epitaxial deposition. These surface oxidation problem can be overcome by the design of a composite substrate [30-32]. The critical issues in the design of the composite tapes are discussed in recent publications [30-32]. It is important to have the outer sleeve and the inner core materials with similar recrystallisation temperatures. It was recently shown that the presence of non-cube texture forming alloy in the core of the composite has no detrimental effect on the growth of cube grains on the surface during recrystallisation even in thin 40 μm substrate [32]. The strength difference between the outer sleeve and the inner core is important during the rolling of the composite. Too strong differences could result in inhomogeneous deformation leading to defects like surface cracks in the tapes. This issue is the focus of the current investigation. It was reported that tungsten (W) is a good choice for solid solution strengthening without the problems of oxidation. Ni-W-alloys form a strong cube texture up to 5 % W [11,21,28,33]. This is proved by a critical current density of 1.2 $MAcm^{-2}$ achieved on an YBCO film deposited on such a substrate [11-12,28]. To investigate the effect of strength difference on the texture development, Ni-5%W and Ni-10% W alloys were chosen as the outer sleeve and core materials of the composite. It may be noted that the Ni-10% W (core) alloy does not form cube texture following heavy rolling and recrystallisation[33]. In the present paper, we report on the development of strongly cube textured and high strength Ni-5% W (outer sleeve) / Ni-10% W composite substrate and the magnetisation behaviour of the composite tape at 77 K.

2. EXPERIMENTAL

Ni-5 % W and Ni-10 % W alloys were prepared by melting the elements having a purity of 99.98% in an induction furnace and casting them in a cylindrical mould of 32 mm diameter. The Ni-5 % W alloy was hot rolled at 1373 K to a square 22×22 mm^2 rod. The Ni-10% W alloy was hot forged at 1373 K to 8 mm diameter and inserted into the Ni-5% W rod [30]. This pre-form was hot and cold rolled to 80 μm thickness with the final cold deformation being > 95 %. The hot rolling serves two purposes, 1) to achieve good bonding between the outer and inner layers and, 2) to recrystallise the outer layer and the inner core. Samples cut from the long tape were recrystallised by a two step recrystallisation annealing procedure in which the samples were initially heated to 973 K held for 30 min. following which they were further heated to 1373 K at 100 K/h and held for 30 min. [32-33]. The microtextures and misorientation distributions were investigated by Electron Back Scattered Diffraction (EBSD) technique in the scanning electron microscope (JEOL JSM 6400) with Channel (HKL Technology, Denmark) software. The X-ray pole figures (with $2° \times 2°$ grid), Phi (ϕ) and Omega (ω) scans were performed in a Philips texture goniometer with Cu-Kα radiation. The yield and tensile strengths of the tapes were measured with an INSTRON 8500 testing machine with 25 mm extensometer on samples of 10 cm length. The loading direction was along the [100] crystallographic direction of the biaxially textured substrates. Magnetisation measurements were made at 77 K in a Quantum Design PPMS ACMS magnetometer.

3. RESULTS AND DISCUSSION

3.1 Microstructure and texture

The microstructure after the intermediate hot rolling shows a completely recrystallised outer sleeve and core of the composite (Fig. 1). Microhardness measurements at this stage revealed that the core is $\sim$ 40% stronger than the sleeve (Fig. 1). This composite was further cold rolled to 80 μm thickness and the total reduction was $> 95\%$, which is a necessary condition for achieving the strong recrystallisation cube texture. It was recently shown that recrystallisation at high temperature/long times resulted in abnormal grain growth leading to a destruction of the cube texture in the Ni-4.5%W / Ni-15%Cr composite [32]. This problem was overcome by using a two step recrystallisation annealing (TSA)

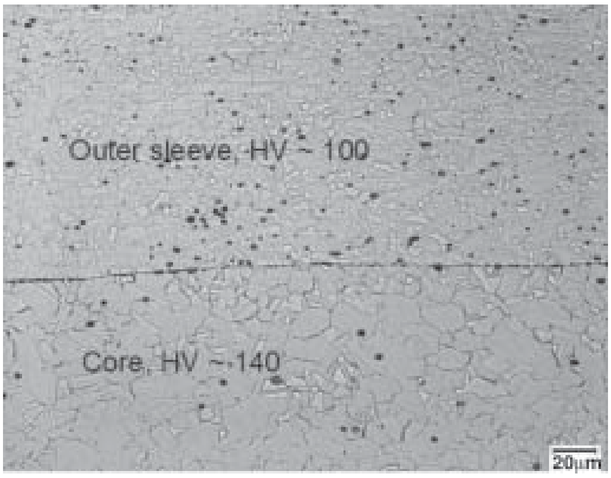

Fig. 1 : Microstructure of the Ni-5% W/Ni-10% W composite after the intermediate hot rolling.

treatment [32-33]. Figures 2(a) and 2(b) show the EBSD map and misorientation distribution of the composite tape following the TSA treatment. It is clear that the two-step annealing procedure was successful in obtaining a very strong cube texture with a very negligible fraction of twin and other misoriented grains (Fig. 2). This can also be seen from the background corrected logarithmic scale {111} X-ray pole figure (Fig. 3). From the X-ray pole figure and the EBSD data, the volume fraction of the cube texture component (defined as with in 15° from the ideal cube orientation {001}<100>) was calculated to be ~ 97.8 % and 99.1 % respectively. It is important to note the reasonably good agreement between the macrotexture and microtexture measurements, which indicates the homogeneity of the cube texture throughout the sample. The X-ray ϕ and ω scans of the composite are shown in Fig. 4a and b respectively. From these scans, the FWHM for the in plane texture and out of plane texture were estimated (by Gaussian fit) to be 6.3° and 5° respectively. These results indicate that the substrate texture quality is excellent and recent reports show that the texture is significantly sharpened in subsequent buffer layers deposited on the substrate (by 1-2° in comparison to the substrate) [32-34]. This results in an outstanding template for growing quasi-single crystal like YBCO films with high current densities. Figure 5 shows the sectional view micrograph of the composite. The thickness of the core (Ni-10%W) was found to be ~ 20 μm and the core contained many annealing twins (Fig. 5) some of which grew across the Ni-10%W / Ni-5%W

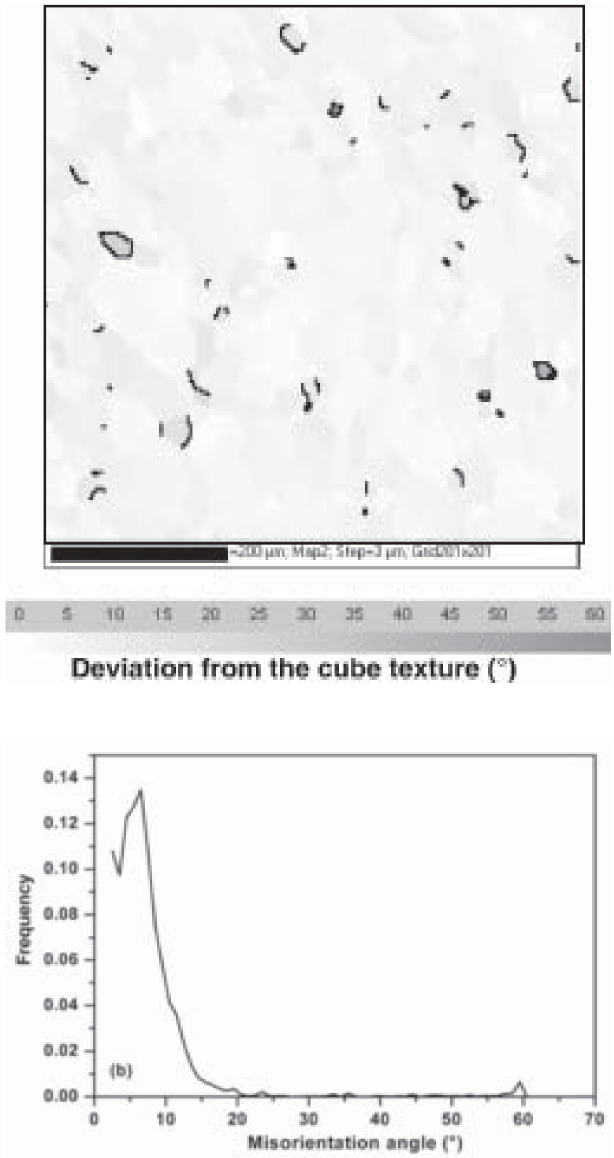

Fig. 2 : a) EBSD map and, b) grain boundary misorientation distribution in the Ni-5%W / Ni-10% W composite tapes following two step recrystallisation annealing. (Grain boundaries above 10° are marked by black lines in the EBSD map)

interface and into the outer layer (Ni-5%W). The above results show that the strength difference (~ 40 % in hardness observed at the intermediate stage) has no detrimental influence on the recrystallisation cube texture on the outer sleeve and it gives scope for further optimization in mechanical and magnetic properties (see below).

The success of TSA treatment in obtaining strong cube texture is qualitatively explained as follows. The origin of recrystallisation cube texture in FCC

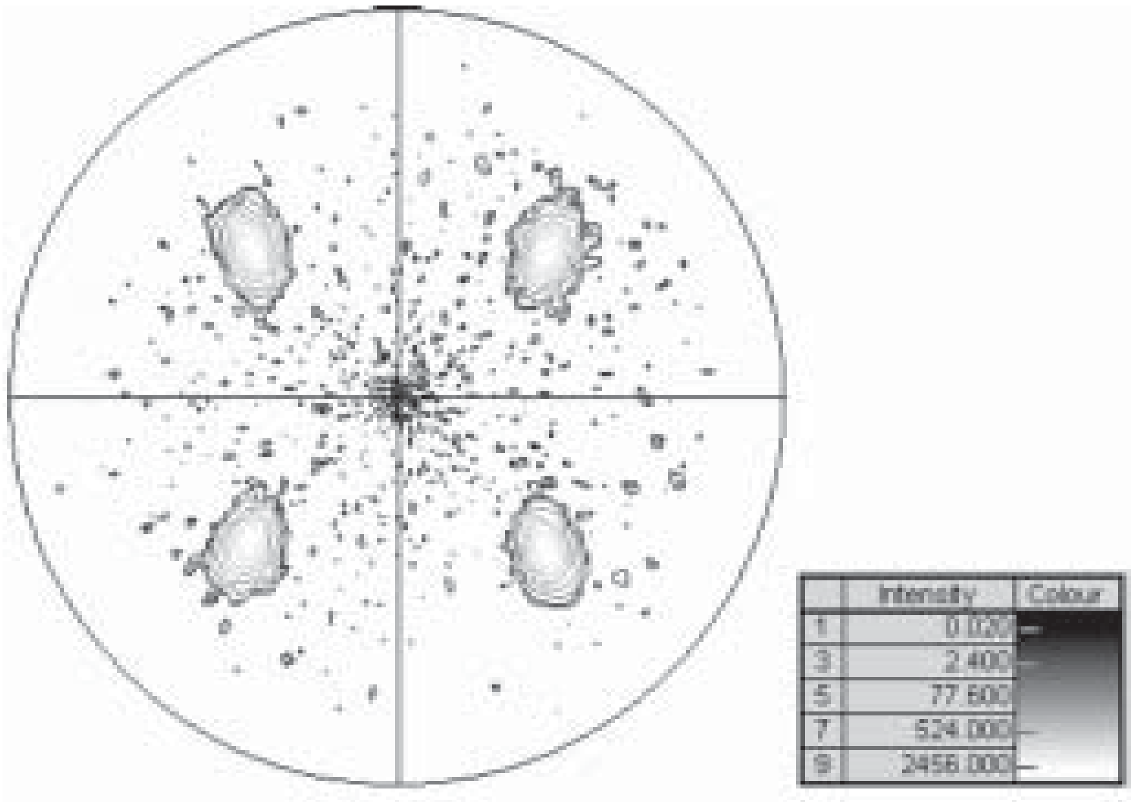

Fig. 3 : Background corrected X-ray {111} pole figure of the Ni-5% W / Ni-10% W composite tape of 80 μm following two step annealing.

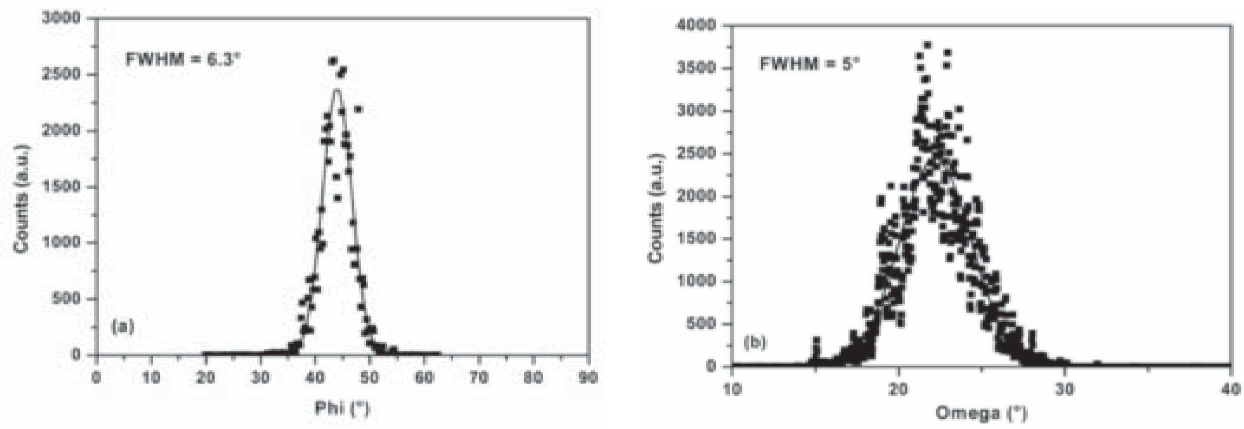

Fig. 4 : a) X-ray ϕ scan and, b) ω scan of the Ni-5% W / Ni-10% W composite substrate after two step annealing.

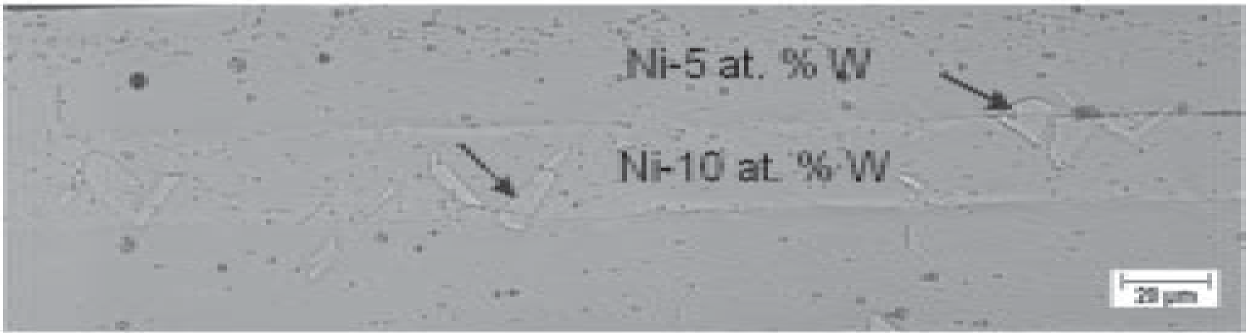

Fig. 5 : Cross sectional microstructure of the Ni-5%W / Ni-10% W composite. Few twinned grains are marked with arrows.

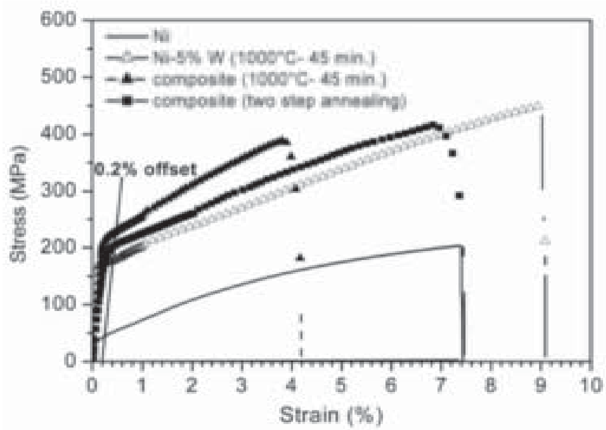

Fig. 6 : Room temperature tensile properties of the Ni-5% W/Ni-10% W composite, Ni-5% W and Ni.

metals and alloys with high and medium stacking fault energy lies in the deformation texture where the pure metal type Cu {112}<111> and S {123}<634> orientations are predominant. During annealing, it was reported that the cube orientation recovers quickly at low temperatures giving rise to significant size advantage over other orientations [35]. It was also shown that the activation energy for sub-grain growth is lower (about 40 kJ/mol) at low temperatures, which is also beneficial for the growth of cube orientation [36]. Therefore, at low temperatures nearly only cube orientation is nucleated. With increase of annealing temperature, the nuclei are more randomly oriented. On the other hand, high temperatures favour the growth of cube grains. This is explained on the basis of 40° <111> orientation relationship between the recrystallised cube grains and the deformed matrix [37]. It was also experimentally shown that for Ni-0.1 at. % W alloy a sharper cube texture was obtained after annealing at 673 K to

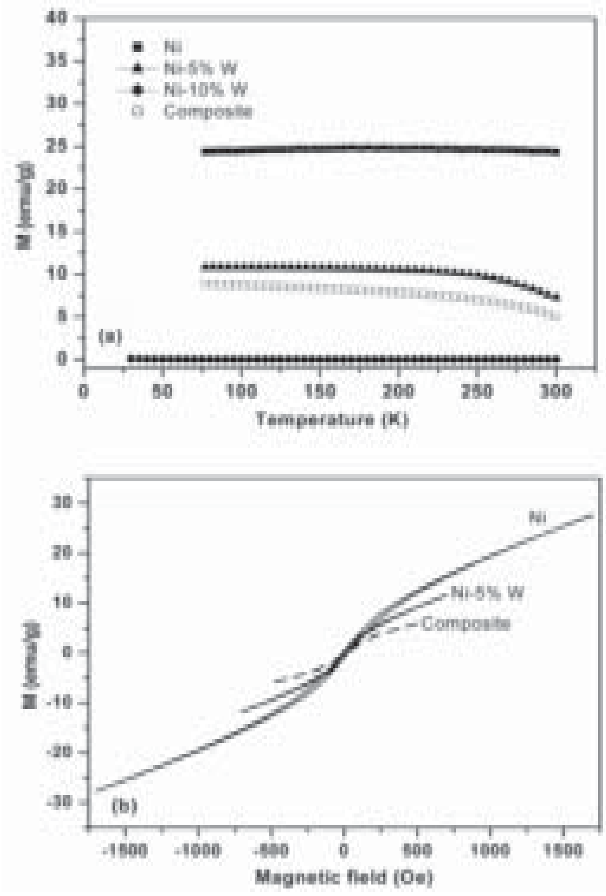

Fig. 7 : (a) Mass magnetisation of the recrystallised Ni, Ni-5% W, Ni-10% W and Ni-5% W/ Ni-10% W composite and, b) magnetisation loops at 77 K for Ni, Ni-5% W and the composite.

773 K than after annealing at 973 K to 1173 K [38]. From the above discussion, it can be concluded that strong cube texture can be realized by having large fraction of cube nuclei, which grow at the expense of the deformation orientations (Cu and S) on annealing at high temperatures. These conditions are

achieved in the TSA process in which the first step (heating to a low temperature of 973 K and holding time of 30 min.) helps the nucleation of cube grains and the second step (steady increase in temperature to 1373 K) leads to the growth of cube grains.

3.2 Tensile properties

Since the superconducting coating does not withstand a strain above 0.5% in compression and 0.2% in tension without degradation, the stress at low strains (e.g. 0.2% offset yield strength) is critical for the application as a substrate material [39]. The room temperature stress-strain response of the 80 μm thick tapes following the two-step annealing is given in Fig. 6. Stress – strain data of pure Ni and Ni-5%W substrates of 80 μm thickness and annealed at 1073 K and 1273 K respectively is also included for comparison. It can be seen that the composite exhibits increased yield strength (~ 210 MPa) i.e., by a factor of 5 when compared to pure Ni (Fig. 5). It should be noted that the yield stress of thin films is strongly influenced by dimensional constraint on dislocation motion (due to increased contribution of image forces on dislocations), which results in a pronounced size (inverse thickness) effect [40]. In the present case, the increased strength of the composite comes from solid solution strengthening of the matrix and also possibly the constraint on dislocation motion by the presence of interfaces due to the difference in texture between the outer layer and inner core.

3.3 Magnetisation measurements

The temperature dependence of the mass magnetisation M(T) of the composite measured in an applied magnetic field of 5 kOe is shown in Fig. 7a along with the data for Ni, Ni-5%W and Ni-10% W. It can be seen that Ni- 10% W is non-magnetic at 77 K and the saturation magnetisation of the composite is suppressed when compared with that of Ni-5% W substrate. The M-H hysteresis loops at 77 K (operating temperature of the coated conductor) for the Ni, Ni-5%W and the composite (after recrystallisation) are shown in Fig. 7b from which it can be seen that the hysteresis losses are reduced in the composite substrate when compared with the pure Ni and Ni-5% W substrate.

4. CONCLUSIONS

Strongly cube textured and high strength (yield strength ~ 210 MPa) composite (Ni-5 at. %W/Ni-10 at. % W) substrates with reduced magnetisation losses were developed for coated conductor application. The strength difference of ~ 40% between the outer sleeve and the core had no detrimental influence in obtaining a strong cube texture in the outer sleeve following recrystallisation. The strong cube texture in the substrate was obtained by an optimized two-step recrystallisation annealing treatment.

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