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Microstructural characterization and phase-mapping distribution of Indian sword blades

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India was famed in literary and history accounts since Greek and Roman time for the traditional crucible steel. According to Will Durant, the technology passed to the Persians and from them to Arabs who spread it through the Middle East. In the 16th century, the Dutch carried the technology from South India to Europe, where it gave ride to steel mass production [1].
In this process, small pieces of iron can be separated from the bloom and then heated in a close crucible together with charcoal (which is almost entirely composed by carbon), until a partial or total melting takes place. Rapid absorption of carbon can lead to the formation of cast steel ("crucible"steel), with a very high (1.2-1.6 wt% C) carbon content, which needs further little hardening. Controlled cooling and forging can then develop a pattern, resembling watered silk, on the surface of the blade (wootz steel, misnamed Damascus steel). This was the procedure used in Iran, Central Asia and India, where it remained in operation until 19th century, with products that were high in quality but small in production scale [2-4].
However, several unresolved issues still remain about the forging methods of the so-called wootz steel, that is a hypereutectoid steel characterized by an ordered pattern of cementite grains in a pearlite matrix. How to obtain such a peculiar microstructure is still unresolved.
In order to shed light on these open questions, preliminary metallography analyses have only been possible upon some broken blades, which were very kindly supplied by the Nizam's Armoury of Hyderabad [5]. The obtained results have been consistent with the neutron diffraction data obtained from selected Indian blades from Hyderabad and other private collections [6]. Thanks to neutron diffraction, "crucible"steels have been discriminated by the cementite content and the subclass of wootz steel has been identified in a non-destructive way.
In the presented work, four Indian blades of princely quality have been selected and investigated by means of white beam and energy-selective neutron tomography on ANTARES at FRMII in Garching (DE). The samples have been made available by the Wallace Collection (London).
A preliminary white beam tomography has been done to characterize the non-metallic components (slag inclusions, mineralised and/or oxidized parts) and determine the presence of hidden cavities (cracks) into the blades. Suddenly, the energy-resolved tomography has been performed selecting neutron wavelength intervals immediately above and below the 110 ferrite Bragg edge. Since ferrite is only present into pearlite (a lamellar structure made of alternate layers of ferrite and cementite) in hypereutectoid steel, the contrast enhancement has been exploited to determine the space location of cementite inside the pearlite matrix.
Enhancing the contrast factor of the selected phase, the cementite has been mapped at a microscopic scale, complementing the available information on historical Indian blades made of wootz steel. These data allowed us to shed light on the wootz manufacturing techniques.

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Summary

In the presented work, four wootz steel Indian blades from the Wallace Collection (London) have been investigated. Enhancing the contrast factor of a selected phase by means of energy-selective neutron tomography, the phase distribution has been mapped at a microscopic level, complementing the available information on the ancient manufacturing techniques of wootz steel.

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