Neutron non-destructive structural analysis of cultural heritage materials: applied interdisciplinary studies

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The cycle of papers consists of 19 works.

Comprehensive research of cultural heritage objects, which takes us back centuries and allows us to trace the formation and development of civilizations and ethnic groups, is one of the most significant tasks of interdisciplinary research in natural sciences, archaeology, and other humanities science. In recent years, there has been a global trend towards the widespread use of natural science methods, including nuclear physics, to analyze the internal structure and various structural characteristics of archaeological artifacts. This allows us to obtain the most comprehensive information about the chemical composition, structural features, presence of internal defects, hidden structures, or interior decoration of ancient objects, as well as the phase composition and spatial distribution of components in unique cultural heritage items of high scientific and historical significance, using non-destructive research techniques.

Frank Laboratory of Neutron Physics at the Joint Institute for Nuclear Research has implemented a comprehensive approach to non-destructive structural analysis of cultural heritage objects. This includes the use of neutron radiography and tomography, neutron diffraction, X-ray diffraction and Raman spectroscopy. The deep penetration of neutrons into matter and the high contrast of their methods to hydrogen-containing materials allow us to obtain scientific information about the internal structure and phase composition of ancient objects that are often inaccessible using other experimental methods. The non-destructive nature of the neutron research ensures the careful treatment of unique objects with great cultural and historical significance [1-19]. New approaches to analyzing three-dimensional neutron tomography data have been developed for these applied studies [1-3, 5, 7, 9, 10, 13, 14, 16, 18], certain structural markers for ancient technological processes such as ceramic production, coinage [1, 4, 6, 15] or metal casting techniques [17, 18] have been identified [8, 9, 13, 19].

The work series vividly demonstrates the possibilities of neutron radiography and tomography methods, and their role in identifying ancient technological processes used for the production of cultural heritage objects from certain historical and cultural periods. Thus, using neutron techniques, it has been possible to identify the nature of development of ornamental motifs and areas of gilding or blackening on ancient jewelry [2, 3, 5, 7, 10, 14-16], to restore the internal structural features [2, 3, 5] and fasteners of the casement bracelet from the Tver Treasure (2014), the gold vial [2, 5] of a noble Sarmatian woman, the cult silver vessel [10] from the archeological excavations of the ancient temple of Demeter and Kora, the golden amulet [14] from the excavations of some ancient settlement in the Crimea. Three-dimensional models of ancient Russian encolpion crosses and jewelry obtained using neutron tomography data [2, 3, 5, 7, 10, 14-16]. The neutron data allows us to separate the metallic and corrosive phases on the surface and in the volume of these cultural heritage objects, and as a result, we can obtain unique information about hidden structural features, identify fragments of internal content, and simulate the penetration of corrosion into the volume of metal products.

Important results have been obtained in the study of ceramics fragments from ancient pottery workshops. The results of structural studies of ceramic fragments [9] from the Byzantine fortress in the area of Dobrudja (Romania) and ancient settlements of southern modern Kazakhstan [13, 19] are presented. The study of fragments of ancient Roman mosaics [8] from the city of Constanta (Romania) should also be noted. The results of structural studies made it possible to restore the production technologies of ceramic objects [9, 13, 19], the conditions of temperature annealing [13], and the locations of raw materials sources.

Detailed studies of the physic-chemical properties of ancient coins [1, 4, 6, 12, 15] are one of the important directions in the non-destructive testing of cultural heritage items. Numismatic materials provide valuable information about the trade, economic and social development of ancient civilizations and states. On the other hand, coins are convenient model objects for studying the processes of corrosion and cracks occurring in copper or bronze, silver or gold archaeological finds. The awarded works present the results of detailed neutron studies of the numismatic material of the Bosporan kingdom [4, 12, 15], as well as bronze and silver dirhams of ancient Bulgaria [1, 6]. The phase composition of the coins and the geometry of the surface layers of the patina allowed us to make assumptions about both the location of ancient ore sources [4, 6], and the features of coinage [4, 12, 15] processes in ancient times. The features of the structural characteristics of internal pores in fragments of cast-iron cauldrons dated to the medieval period of the Golden Horde directly indicate the specific features of iron casting [18] and allow us to reconstruct not only information about the technology of the process, but also correlate cast-iron products with different foundries in that ancient state. This work cycle also includes results from unique studies on a copper battle axe from the territory of the Malo-Kizilsky settlement, which belonged to the Abashev culture dating back to about 3000 BC. The analysis of structural data [7, 11] and the nature of injuries on the skulls of the inhabitants of the settlement suggests the using this axe in intertribal conflicts.

The results achieved through the use of non-destructive neutron analysis of cultural heritage objects have widely opened up new opportunities for archaeological communities in a number of JINR member countries. These techniques have played a key role in solving important archaeological problems that were difficult to solve using other methodical approaches.

The main results of the interdisciplinary research have been published both in leading specialized archaeological journals, including *Applied Sciences, Journal of Archaeological Science: Reports, ArcheoSciences, Russian Archaeology, Brief Reports of the Institute of Archaeology,* and in natural science journals: *Crystallography, Surface, Eurasian Journal of Physics and Functional Materials, Physics of Particles and Nuclei Letters, Journal of Imaging*.

List of publications:

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