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Microstructural studies of composite Mughal period cannons of Daulatabad Fort, India, by electron backscattered diffraction and scanning electron microscopy

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Historical data on ancient Indian cannons have systematically been researched, but there is lack of archaeometallurgical studies on bimetallic cannons. This study revolves around 16th–17th century bimetallic Indian cannons: copper barrel with inner iron sleeve at an approximate ratio of 5:1. Scanning electron microscopy and electron backscattered diffraction techniques have been employed to know the changes in the microstructures of the metals used in making cannons. Energy dispersive spectrometry confirmed that the outer copper barrel, with 4.5 wt% tin, had inclusions of cupric oxide (Cu_2O) and contained lead and sulfur. The inner sleeve, on the other hand, was primarily iron but contained fayalite ($FeSiO_4$) and inclusions with silicon and phosphorous. Both inner (bloomery iron) and outer (copper) material had strong signatures of plastic deformation, and the cannons were stipulated to be forge welded. Deformation twinning in recrystallized iron grains of inner iron sleeve and near-perfect extensive twinning in the inner copper barrel indicate exposures of the respective materials to such active usage. It is concluded from the deformed structures and from the presence of clear joints that the bimetallic cannons were made by a process of forge welding. This study brings actual manufacturing practices of bimetallic cannons in ancient India.

1 | BACKGROUND

The high status of iron and steel technology in ancient India is reflected in the manufacture and use of numerous large and small iron forge-welded cannons.[1–3] The wrought iron cannons found in different parts of India were manufactured from individual iron rings that were forge welded.[4,5] Unfortunately, the forge-welded cannons have not been so far properly cataloged like their European counterparts.

Cannons have a long interesting history.[6–8] The early fire-lance barrels, tubes made of bamboo/paper filled with gunpowder, were soon replaced with cast iron and then bronze cannons.[2,3] Interesting innovations took place in design, manufacturing, materials, and deployment.[6] For example, calculation of projectile trajectories involved complicated mathematics. Design of cannons, on the other hand, developed with considerations of windage, recoil and chamber, and so forth. No less important were the aspects of manufacturing and material: subjects of direct relevance to this manuscript. Cannons were traditionally made of cast iron and bronze.[6–8] Ancient Indian iron-steel technology of forge-welding bloomery iron predates Christ. On the other hand, the Rewari metal working, casting–forging of brass to make cannons, was immediately after Babur's invasion. The two technologies had distinct Hindu and Mughal origin. They joined together and produced bimetallic cannons.[6]

Cast iron cannons were cheaper but unreliable. The apparently durable cast iron cannons may burst without prior signatures of failure. This made them dangerous to operate. Whereas the wrought-iron cannons were manufactured by separately fabricating the chamber and barrel and later joining them together, the cast-iron cannons were fabricated at one piece. It appears that Indian metallurgists were familiar with the idea of structural design for improved fracture toughness as solid structure created with successively larger diameters rings possessed a better impact resistance compared with a single solid piece of wrought iron. Bronze cannons were more expensive, less durable, and offered challenges in alloying and bore design.[6–8] Appropriate alloying of copper and tin was nontrivial to the ancient metallurgists, although final products were often "spongy about the bore."[6] An obvious choice would have been bimetallic cannons: bronze or copper barrel with iron core.

The historical data on ancient Indian cannons have systematically been researched,[9] but there is lack of archaeometallurgical studies as observed from published literature.[2,10] The cannons in India was used in the battle of Panipat in April 1526 fought between the Delhi sultan, Ibrahim Lodhi, and invading Mughal, Babur, who overpowered Lodhi by the fire of cannon. Thereafter, casting and forged welding played a major role in the construction of Indian cannons. It appears that cannon technology reached India from four different sources, namely, middle east-Islamic state, from Central Asia, through contact with the Portuguese and from China through sea and land route of North-East India.[11] The Indian cannons were primary based on iron- or copper-based objects. As it was not possible to extract iron in molten state (melting point 1540°C) using traditional Indian furnace, the reduction of iron ore was performed at a temperature of 1000–1200°C in bloomery furnace, which was utilized for fabricating cannons and commercial objects.[12] This process of extraction of iron continued for a very long time. As regards with the cannons, they were manufactured either by casting or by forge welding. The significant technology practiced in India is the production of large number of massive forge welded iron cannons, which had few parallels in the world.[1]

One of the most important skills burrowed from Europe at the beginning of 16th century was making of cannons out of wrought iron. Interestingly, the medieval Indians did not bother to study and adopt cast iron technology from Europe probably due to their mastery over forge-welded cannons. When cast iron cannon was introduced in Europe in the middle of the 16th century, they were not taken seriously because the cast iron cannons used to burst without notice if the casting was not done carefully. The bronze cannons were more reliable because of their toughness. In contrast to fast development of cannon technology in Europe, the development of cannon technology in the 17th and early 18th century was rather limited in India. The most significant failure was the inability of the Indians to copy the cast iron cannons technology of Europe during the above period. The European powers were able to produce cast iron cannons by the end of the 18th century, which were both light and large. The lack of cast iron technology resulted in the colonization of India. Whereas the battle of Panipat in 1526 signified entry of large-scale artillery in India, the battle of Plassy in 1757 by East-India company saw the victory of cast iron artillery and British rule in India. Immediately the Indian rulers of the 18th century established several foundries for casting cast-iron guns.

Although the Indians did not adopt cast iron technology for making cannons, they introduced several novel features such as the fabrication of composite cannons by casting of bronze over wrought iron barrels[13] and use of light cannons resting on swivels fired from the back of the camel. The composite cannon innovation may have been an attempt to economize on the use of copper (a relatively expensive metal) without weakening the barrel. European visitors admired these composite cannons, particularly the joints between the iron and bronze section.[14] During the period 1620–1670, all types of light cannons including composite iron and bronze cannons were introduced in Europe, very few of them survive today. The earliest surviving composite cannons are located at India's Narwara fort,[15] which was manufactured in 1696. An old composite cannon is in the collection of the Royal Artillery Historical Trust in England. This highly decorated cannon is dated to 1537–54 as per inscription and probably fabricated with the know-how taken from Portuguese,[16] which is however doubted.[9] The Mughals especially Aurangzeb were experts in the fabrication of massive composite cannons now located in the fort of Golconda, Kolkata, Daulatabad, Parenda, and so forth in India.

On the hill fort of Daulatabad near the ancient city of Aurangabad in western India, many 16–17th century cannons can be seen at different height (Figure 1). These include cast bronze European cannons (Figure 1a), Indian bronze (Figure 1b) and iron cannons (Figure 1c), and the bimetallic cannons (Figure 1d–f). Examples of such bimetallic cannons include the Shri Durga cannon, with its inscription in Devanagari or Sanskrit language (Figure 1f), or the Mendha (Figure 1e): destroyer of forts, commissioned during Aurangzeb's reign with Persian inscriptions. Under the Ajanta–Ellora caves development projects, the experts desired analysis of cannons metals of Daulatabad fort.

This paper presents the application of advanced material characterization techniques such as electron

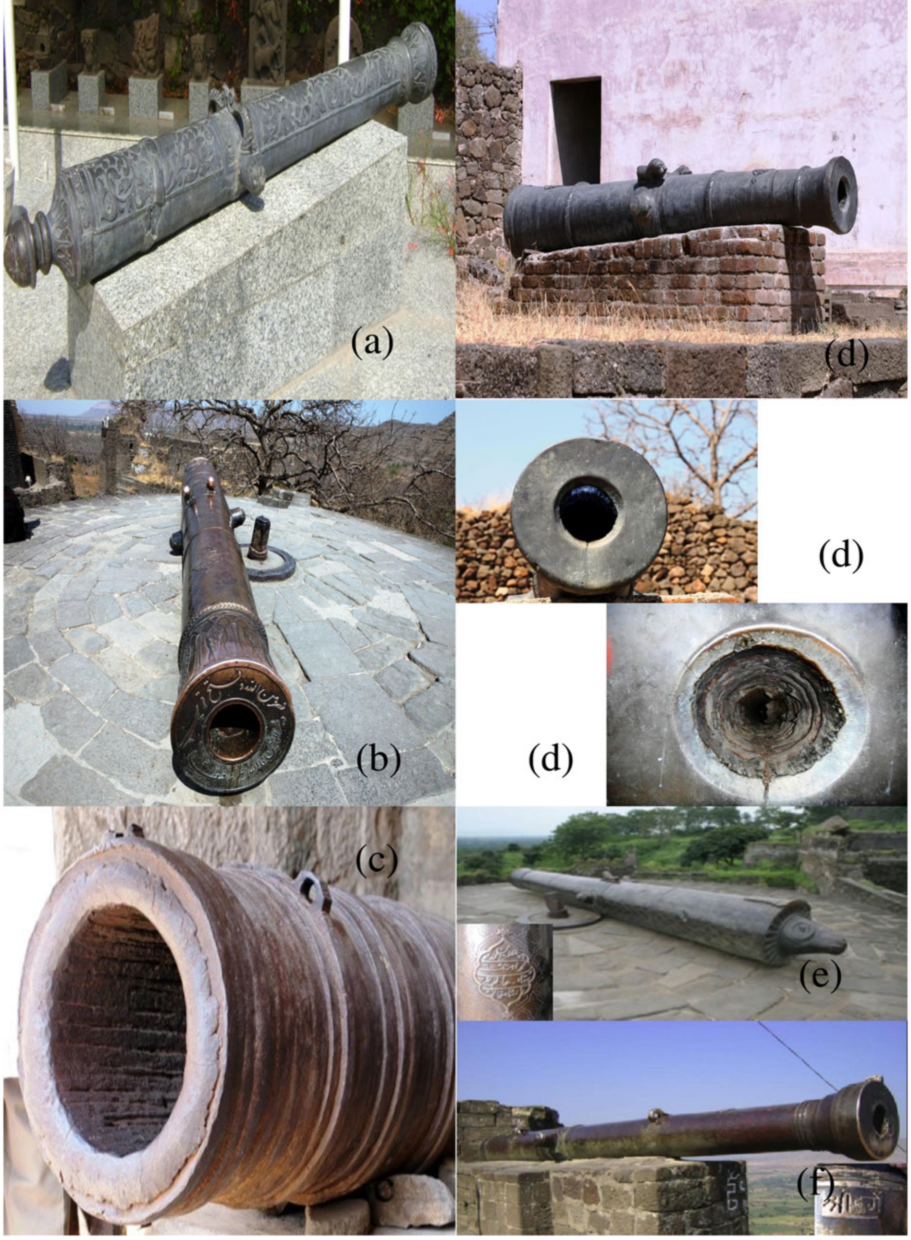


FIGURE 1 Cannons from Daulatabad (Aurangabad, India) Fort. These include (a) cast bronze cannon of European origin and Indian (b) bronze and (c) iron guns. There are also bimetallic cannons with bronze/copper barrel and inner iron sleeve: (d)–(f). Examples of such bimetallic guns: (d) unmarked gun in front of the museum, (e) Shri Durga cannon (placed on a platform on top of Daulatabad hills), (f) Mendha cannon (on an elevated/circular platform between Chini Mahal and Rang Mahal). (d) also shows presence of the inner iron sleeve, whereas names are inscribed on the sleeve in Sanskrit (Devnagri) and Persian, respectively, on (e) Shri Durga and (f) Mendha

backscattered diffraction (EBSD) and analytical microscopy to elucidate information on the materials and microstructures of these bimetallic cannons.

2 | MATERIAL AND METHODS

Shri Durga (Figure 1f) was made in the Moghul period, though the Sanskrit inscription (engraved close to the vent of the gun) indicates Hindu influence. Persian inscription on Mendha, (Figure 1e) on the other hand, records the name of emperor Aurangzeb, the name of the gun as Top-i-Qail'a-Shikan (breaker of the fort), and of manufacturer's name: Husain Muhammad Arab. Shri Durga is 5.8 m long and 0.18 m in caliber. Barrel plus sleeve thickness varied from 0.48 to 0.42 m, and the taper of the cannon was relatively minor. The bimetallic Shri Durga, with effective range of 2–5 km, was a defensive cannon: expected to target the approaching enemy in open plains and the surrounding mountain ranges.

Mendha was of 0.2 m caliber, 5.3 m long, and had a higher (than Shri Durga) taper of 0.7 to 0.5 m. This, as the inscription indicates, was an assault or siege cannon.

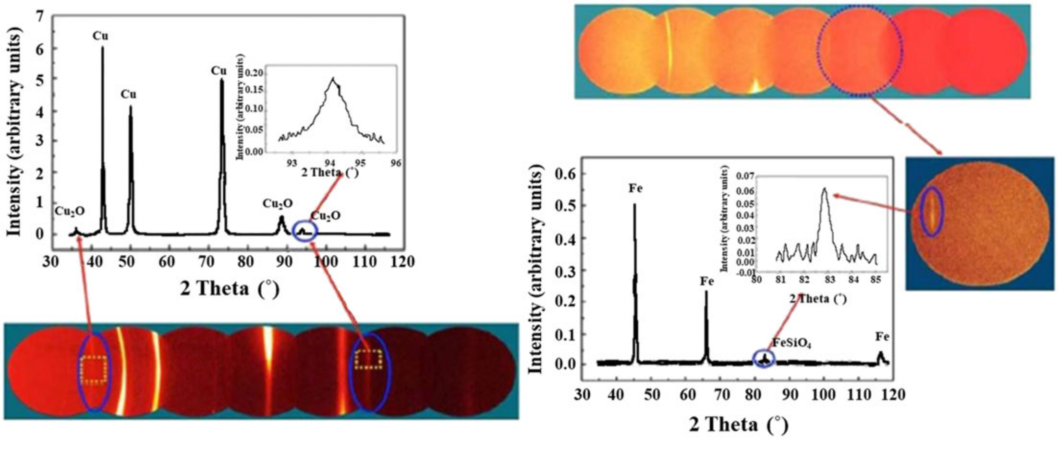
Representative samples were obtained by chiseling and drilling and utmost care taken while taking samples not to disfigure the cannons. Sample chips of about 10 mm × 6 mm were selected for microscopy, which were obtained from depth of about 8 mm. Samples were obtained from both outer barrel and inner sleeve (Figure 1e,f). Drilled holes were subsequently filled with inert material. The analytical investigations have been performed with the help of many scientific institutions. Though this paper reports characterization results on samples from Shri Durga cannon (Figure 1f), similar results were obtained from Mendha (Figure 1e). The samples were collected from Shri Durga and Medha cannons, and analysis was performed by EBSD and scanning electron microscope (SEM) analysis. Because the results were the identical, the report about Shri Durga cannon is presented here.

Metallographic examination were carried out by preparing chip samples through normal standard procedure[17] using submicron colloidal silica polishing. These samples were further subjected to detailed characterization using X-ray and electron diffraction[18] and analytical microscopy.[19] X-ray measurements were made on a Brukers D8-Discover™ system with Vantec-500™ area detector. A copper Kα microsource, 300 μm spot size with Montel™ mirror, was used. A Quanta 3d-FEG (field emission gun) SEM with EDX-TSL™ EBSD system was employed for the electron diffraction.[20,21] EBSD data above 0.1 CI (confidence index) were used for subsequent analysis. CI or confidence index is a statistical measure[18] of accuracy in automated indexing: CI >0.1 represents above 95% accuracy. An EDX™ silicon drift detector, on the same SEM, was used for the analytical microscopy: namely, energy dispersive X-ray spectroscopy. Beam and video conditions and step sizes were kept identical for the EBSD and energy dispersive X-ray spectroscopy scans.

3 | RESULTS

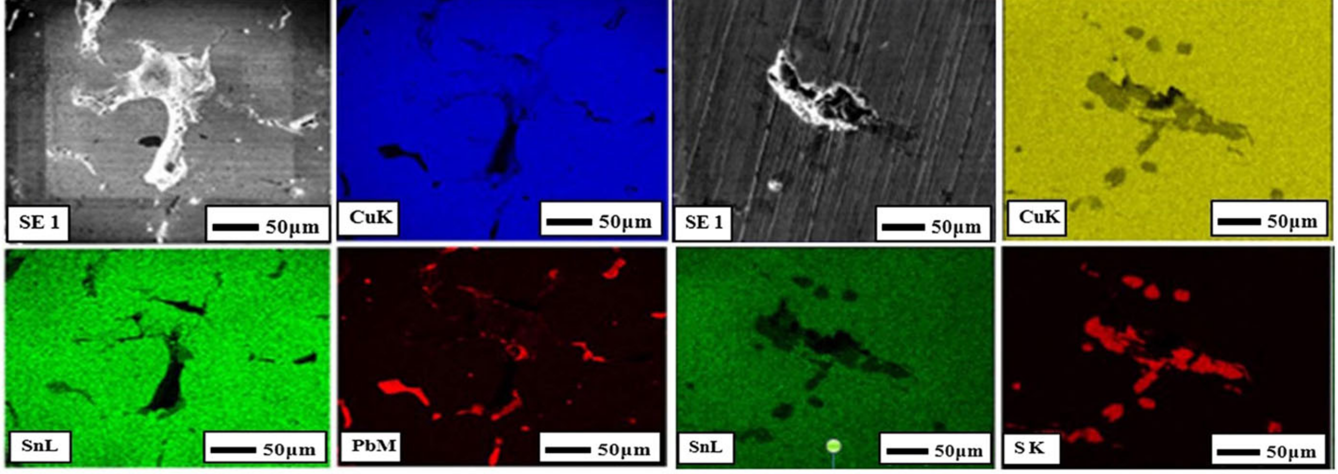
Figure 2 consolidates the results of the X-ray diffraction on the outer barrel and inner sleeve of the Shri Durga cannon. The results include images from the area detector and integrated intensity-2θ plots. Use of the area detector and bright microsource with Montel™ mirrors were essential in capturing the minor second phases. For example, the outer barrel (Figure 2a) clearly shows presence of both copper and Cu_2O (cupric oxide) phases, whereas inner sleeve shows iron and fayalite ($FeSiO_4$) peaks. Though different locations showed significant differences in peak/phase intensities, Cu and iron were clearly identified as the major phases. The minor phases, on the other hand, were often within restricted Bragg space (Figure 2b). Thus, their detection through conventional point or line detector is/was rather difficult in a nonpowder monolithic sample.

The outer barrel had copper with approximately 4.5 wt% tin (Sn). This work hence classifies the barrel as copper and not as a more traditional bronze. As shown in Figure 3, the copper barrel contained inclusions of lead (Pb) and sulfur (S). Unmixed tin (Sn) globules (Figure 3 b) were also observed. It appears that the liquid metal processing lead to clear contamination pick-ups. It is also apparent that the processing did not achieve complete mixing of the substitutional alloying element tin (Sn).



(a) (b)

FIGURE 2 X-ray diffraction from (a) outer and (b) inner material of bimetallic Shri Durga cannon (Figure 1e). Information from two-dimensional (area) detector, also integrated in conventional intensity-2 plots, show presence of Cu (copper - major) and Cu_2O (cupric oxide—minor) peaks in (a). In the inner material, on the other hand, Fe (iron—major) and $FeSiO_4$ (fayalite—minor) peaks were noted



(a) (b)

FIGURE 3 PbM and SK signals. (a) Lead (Pb) and (b) sulfur (S) containing inclusions. (b) also shows presence globulized unmixed tin (Sn)

The copper barrel had clear signatures of plastic deformation. The EBSD images, Figure 4a,b, show large in-grain misorientations. This is evident from the color changes in the respective inverse pole figure[22] maps. Kernel average misorientation or KAM values (Figure 4 c) provide a better quantification. KAM represents misorientation of any point with respect to its immediate (six in case of the hexagonal grid used) neighbors. Typically, a cut-off misorientation (5° for this study) is kept eliminating high angle grain boundaries. KAM was higher for the outer copper barrel: 0.83° (outer) versus 0.72° (inner). This and the fact that densities of grain boundaries (length of grain boundaries per unit area in μm^{-1}: Figure 4c) were higher for the outer copper barrel clearly indicate a more significant plastic deformation in the former. In contrast, the inner barrel showed more twin boundaries: 4,810 µm versus 470 µm (see Figure 4 a,b). The inner barrel not only had higher (by more than one order of magnitude) twin boundary length, such boundaries were within a few (2–3°) degrees of ideal twin orientation of 60° <111>. This is indeed surprising. The classical deformation twinning in an fcc metal[23] usually

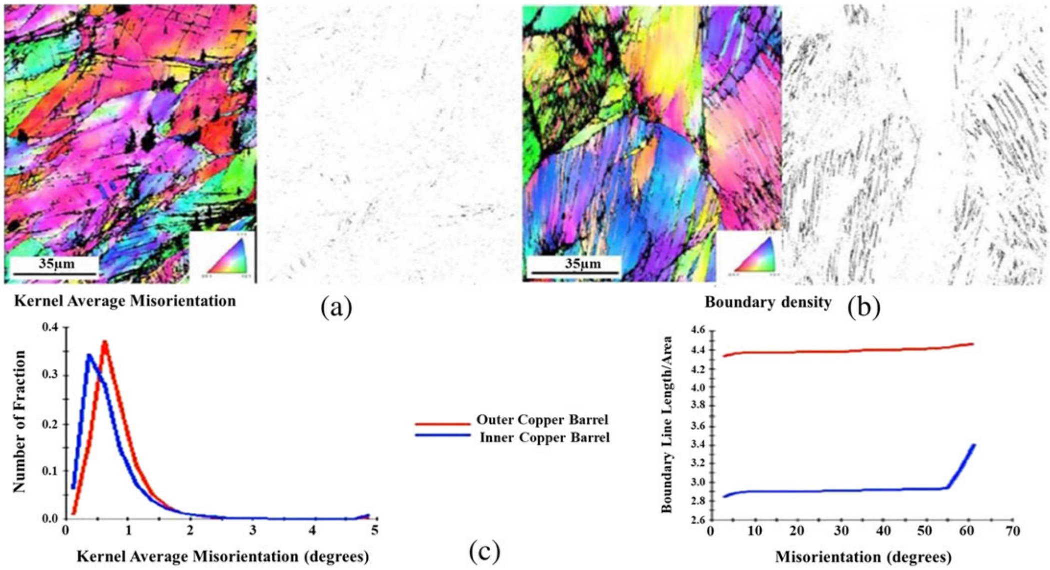


FIGURE 4 Electron backscattered diffraction maps of the (a) outer and (b) inner surfaces of the copper barrel. The color maps are plotted in inverse pole figure (IPF) [?] notations, with black representing data points below 0.1 CI (confidence index). Separate maps also show twin boundaries (within 5°of ideal 60° <111>). (c) Kernel average misorientation (number fraction vs. KAM) and boundary density (boundary length per unit area vs. misorientation) for the respective sections

have a large distribution around the exact axis-angle twin orientation relationship. This point is discussed in further details latter in the discussion.

The inner was almost pure iron, with coarse fayalite inclusions (Figure 2b) and second phases containing silicon (Si) and phosphorous (P; see Figure 5). This is an example of classical Indian bloomer[24–26] iron. EBSD showed deformed (Figure 6a) and recrystallized (Figure 6 b) grains, respectively, for the outer and inner iron sleeve. As shown in Figure 6c, the outer sleeve had significantly higher KAM (0.85° vs. 0.38° for the inner sleeve) and boundary densities. The apparently recrystallized grains of the inner iron sleeve, however, had clear twin boundaries. This is shown clearly in Figure 6b. Deformation twinning in bcc iron is not unheard of.[27] Such twinning, however, takes place at very low temperatures or very high strain rates. Twinning in iron sleeve is also deliberated further in Section 4.

4 | DISCUSSION

This study started with the "untold" story of bimetallic cannons. The artisans came from two different schools: post-Babur Rewari brass/bronze metallurgy,[28] which was primarily Mughal, and the more ancient technology of Hindu bloomery iron.[24–26] It is interesting to see a handshake between the two cultures and religions: producing Shri Durga (Figure 1f) or Mendha (Figure 1 e). The bimetallic Shri Durga, with effective range of 2–5 km, was a defensive cannon: expected to target the approaching enemy in open plains and the surrounding mountain ranges. Mendha was of 0.2 m caliber, 5.3 m long and had a higher (than Shri Durga) taper of 0.7 to 0.5 m. This, as the inscription indicates, was an assault or siege cannon. Both Shri Durga and Mendha (and other bimetallic cannons of Daulatabad fort) had commonalities in barrel-sleeve thickness (approximately 5:1) and material. Barrel was copper, whereas inner sleeve was bloomery iron. Forge-weld bloomery iron cannon was reported in southern India.[18]

Ancient Indian iron-steel technology did not involve liquid metal processing.[6] The bloomery iron was formed by direct reduction of appropriate iron ore. The hot metal pieces, with inclusions and particles of liquid slag, were then forge welded.[24–26] This was the manufacturing practice for iron cannons,[18] and appears to be the case for the bimetallic cannons as well. The signatures of plastic deformation in the copper barrel (Figure 4) and the iron sleeve (Figure 6) clearly indicate forging. The joints

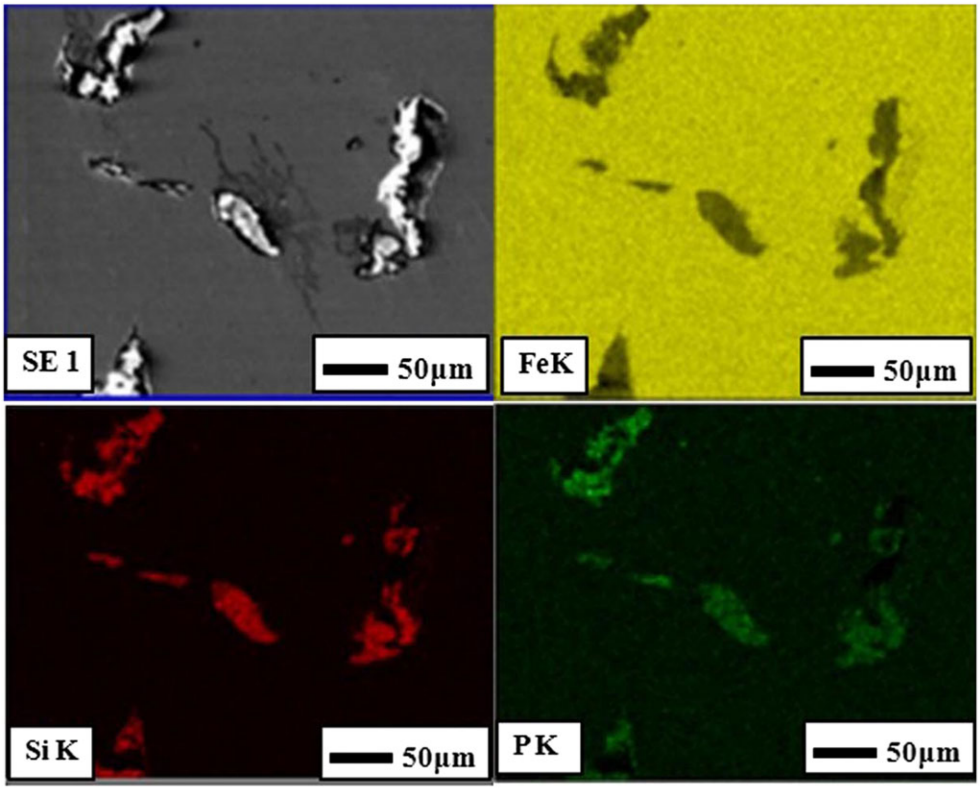


FIGURE 5 Energy dispersive X-ray spectroscopy maps showing inclusions in the inner iron sleeve containing silicon (Si) and phosphorus (P). Included are secondary electron image and corresponding energy dispersive X-ray spectroscopy maps showing presence/absence of FeK, SiK, and PK signals

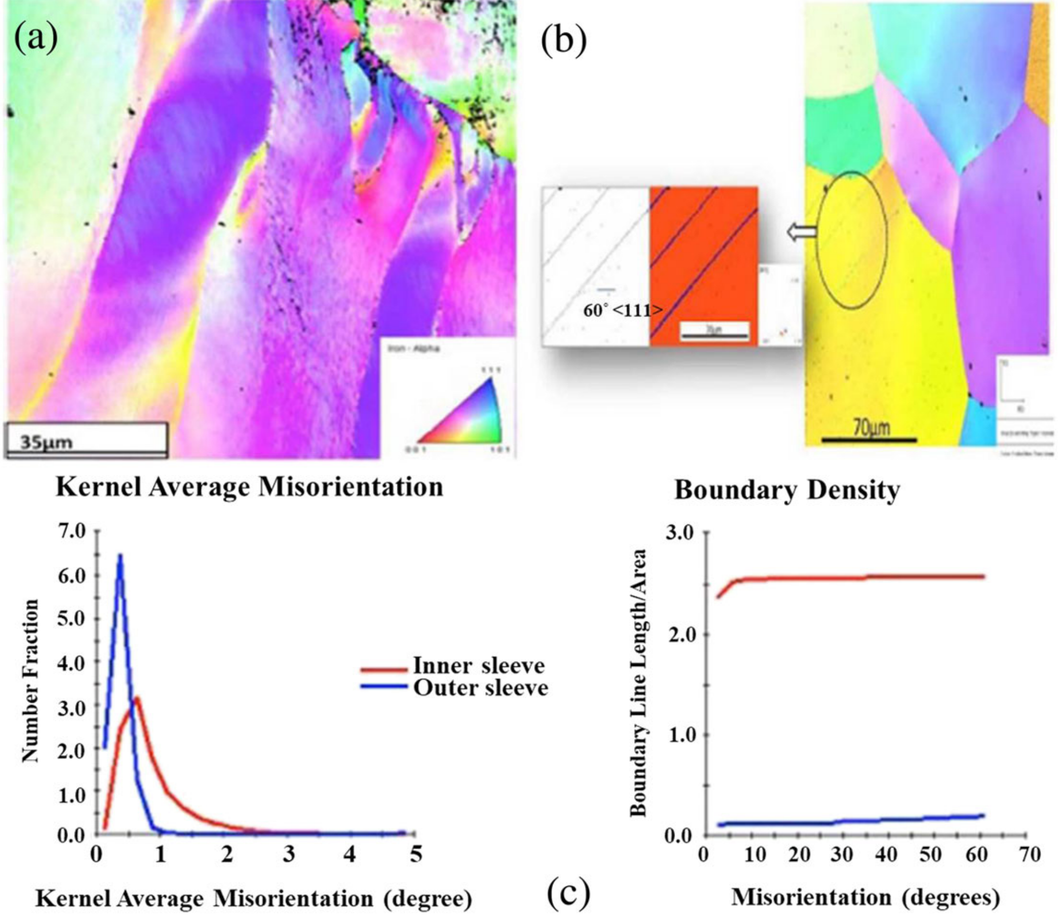


FIGURE 6 Electron backscattered diffraction inverse pole figure maps of the (a) outer and (b) inner surfaces of the iron sleeve. In (b), twin orientation relation is shown in inverse pole figure and corresponding orientation/boundary maps. (c) Kernel average misorientation (number fraction vs. KAM) and boundary density (boundary length per unit area vs. misorientation) for the respective sections

in the cannon and the fact that a typically bloomery iron pieces were shaped to appropriate dimensions indicate the involvement of forging. Clear microstructural gradients were also observed. For example, outer copper barrel or the iron sleeves were more deformed. This indicates possibilities of differential heating. But before linking microstructures with manufacturing practices, one needs to remember that Shri Durga had also seen active service. Deformation twinning, in bcc iron, was observed only on the inner surface of the iron sleeve (Figure 6b). Bcc iron can exhibit deformation twinning after very low temperature and/or high strain rate plastic deformation.[27] It appears logical that cannon fires resulted into high strain rate, but with minor effective strain, plastic deformation resulting in deformation twinning in bcc iron and in the inner copper barrel (Figure 4b). Typical deformation twinning, with significant plastic strain, have a large spread around exact twin orientation relationship.[23] This is caused by lattice reorientations associated with crystallographic slip. This makes the hypothesis of high strain rate plastic deformation, with "limited" effective strain, appears rationale. Such a deformation could only be enforced through postmanufacturing service or operational cannon fires.

The actual manufacturing practice, grossly rationalized as forge weld, raises many questions. The famous Delhi iron pillar[5] or the Thanjavur's massive iron cannon[18] were made by forge welding, where hot pieces of bloomery iron were placed together and were forge welded aided by external heating. The manufacturing of the bimetallic cannons appears to involve a similar process. It is interesting to note that the ancient Indian metallurgists who could not circumvent the problem of incomplete mixing of copper and tin successfully fabricated bimetallic cannons involving materials of unequal "elasticity, tenacity, and expansion."[6] This technology, however, had challenges. All the Indian cannons, especially the bimetallic ones, had "limited" taper. They are thus expected to have less effective usage of the chamber pressure. Much higher taper of the imported European cannons (Figure 1a), imported during the same historical period, bears indications of possible design limitations of

Indian cannons. They were useful as defensive (like Shri Durga) or assault/siege (like Mendha) weapons but had "restrictions" with respect to the lightweight and more maneuverable European cannons as effective battlefield weapons. The European guns, by 17th century, also had superior rate of fire: 20–30 times more than the Indian cannons,[29] again indicating design limitations of the Indian forge-welded guns. Finally, emerging breech-loading mechanisms made Indian bimetallic cannons a nonsustainable obsolete technology: a technology to wonder about and to appreciate its limitations. Technology left to the artisans, without serious theoretical inputs, which European cannons clearly had,[6] is bound to face obsolescence.

5 | CONCLUSION

The bimetallic guns of Daulatabad fort hold inscriptions in Sanskrit and in Persian. They had copper barrel (with 4.5 wt% tin) and inner iron sleeve. The copper contained Cu_2O, unmixed tin globules, and had inclusions of lead and sulfur. The bloomery iron, on the other hand, contained coarse fayalite ($FeSiO_4$) particles from the liquid slag and had inclusions of silicon and phosphorus. Both, however, had strong signatures of plastic deformation. It was rationalized from the deformed structures and from the presence of clear joints that the bimetallic cannons were made by a process of forge welding. The iron sleeve facing the charge and inner copper barrel also had signatures of high-strain rate, albeit limited plastic strain, deformation. This could have happened from service or actual cannon fire. Deformation twinning in recrystallized iron grains of inner iron sleeve and near-perfect extensive twinning in the inner copper barrel indicate exposures of the respective materials to such active usage. This study bears testimony to the skills of Indian artisans and demonstrates that technology left to the artisans, without serous theoretical inputs, is bound to face obsolescence.

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