Nondestructive studies on iron pillar at Kodachadri, Karnataka, India

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We present here results of a study carried out on the iron pillar located in the Adi-Mookambika temple at Kodachadri in Karnataka, India. The iron pillar is 8.7 m high with almost square cross-section and an average perimeter of 27.5 cm. The surface of the pillar is not as smooth as those at Mehrauli (Delhi) and Dhar (Madhya Pradesh). The top 1 m of the pillar shows excessive corrosion specially on the surface facing west towards the Arabian Sea, which is located about 30 km away. The in situ metallography at various locations on the pillar and scanning electron microscopy on a small sample from the pillar clearly established that the iron is produced by the age-old indigenous solid-state reduction process that is used for making the so-called Adivasi (tribal) iron. Presence of slip lines in the microstructure at various locations indicates heavy forging of the iron pillar. The phosphorus content in the iron pillar is found to be much less than those reported for the iron pillars at Delhi and Dhar.

Keywords: Corrosion, dimensional measurements, iron pillar, metallography studies, visual assessment.

ANCIENT and medieval India did its countrymen proud and made tremendous impact on the world scene through many spectacular achievements in iron and steel technology. The technology of iron making in India culminated in major achievements during 2nd–6th century AD. The iron pillars at Mehrauli in Delhi and at Dhar in Madhya Pradesh (MP) have been studied in great detail for over a century. In situ metallography, corrosion and nondestructive studies on the Delhi iron pillar have provided detailed information about the microstructure and the internal structure of the pillar. Even though several studies have been reported on the iron pillars at Delhi and Dhar, the iron pillar located in Adi-Mookambika temple at Kodachadri village in a remote forest area of the Western Ghats in Karnataka has not received much scientific attention so far, also because the concerned village is difficult to reach and also because the pillar itself is not as massive and imposing as the Delhi and Dhar monuments. There is only one preliminary scientific study reported on the iron pillar at the Mookambika temple at Kodachadri hill. The iron pillar is popularly known as the Dwajasthamba (flag staff) of the Adi-Mookambika temple. Kodachadri is about 40 km from Kollur, a town located about 120 km north of Mangalore in the South Canara District of Karnataka. Local tradition indicates that the flag staff is actually the top portion of the trishul (trident) with which the ‘Mother Goddess nailed down the demon into the bowels of the earth!’6, Anantharaman9 estimated the height of the pillar to be not less than 10 m above the ground. He also reported an optical microstructure and a X-ray diffraction pattern obtained from a small piece of iron taken from the pillar. Based on the preliminary investigations on the small iron piece, Anantharaman6 suggested that the pillar would have been made by the age-old indigenous methods for making the so-called Adivasi (tribal) iron with pure iron ore and wood charcoal. It was also speculated that the top of the pillar would have melted frequently due to lightening and perhaps rapidly solidified through removal of heat by the iron of the pillar itself.

The present article reports results of in situ studies on the Kodachadri iron pillar. Various nondestructive studies were carried out on the pillar at several locations. Detailed scanning electron microscopy (SEM) study on a small sample (~50 mg) taken out from the pillar is also discussed.

Experiments

In order to carry out investigations on the complete length of the pillar, a wooden scaffolding was fabricated around the pillar (Figure 1). Various nondestructive studies such as dimensional measurements, visual examination, in situ metallography, in situ hardness measurements, in situ X-ray fluorescence (XRF) and low-frequency ultrasonic velocity measurements were carried out on the pillar at several locations.

Thickness in two perpendicular directions and perimeter of the pillar were recorded at every 200 mm along the height. In situ hardness measurements were carried out...
using M-295 Leeb hardness tester. A small area of about 2 cm diameter was coarsely polished at every 500 mm along the height for hardness testing. An average of five readings taken at close-by locations is reported here. The maximum variation in hardness was observed to be ± 10 Vicker’s Hardness Number. A few locations where hardness was measured, viz. 1.2, 1.7, 3.3, 3.7, 4.2, 5.2, 6.2 and 8.7 m (top of the pillar), were further polished for in situ metallography. Polishing on the side surfaces near the top portion of the pillar for in situ metallography was difficult as both the pillar and the scaffolding would swing with even a small push and also due to the heavy breeze. Hence, in situ metallography was carried out on the top face of the pillar and then the next location was at 2.5 m below the top surface. In order to get the microstructure of the pillar in the top portion, a small piece (~50 mg) of iron was taken out from a sharp protruding point at 0.25 m below the top. A detailed scanning electron microscopy (SEM) study was carried out on this sample. XRF studies were also carried out on the pillar at a few of the in situ metallography locations using portable XRF system (M/s Bruker, Germany). Ultrasonic measurements were carried out in transmission mode using a pair of 500 kHz transducers, a broadband pulser-reciever and a 100 MS/s digitizer card.

Results and discussion

Dimensional measurements and visual assessment of the pillar

The height of the pillar above the ground level is 8.7 m (28’6”), including 1 m in the concrete platform at the ground level. The concrete platform was built in 1994 to provide better stability to the pillar. The cross-section of the pillar is rectangular with average dimensions of about 7.75 cm × 7 cm (3” × 2.75”). Figure 2 shows the variation in the thickness of the pillar in two perpendicular directions as a function of height of the pillar. Thickness varies in the range 6.4–7.7 cm and 6.8–8.6 cm throughout the pillar in the two perpendicular directions, except in the top 0.20 m where it was found to be 89 and 92 mm respectively. As the surfaces are not exactly parallel, the variation in perimeter is also plotted in Figure 2. The perimeter of the pillar is essentially uniform in the 24.2–30.1 m range throughout its height, with an average of 27.4 m.

The general appearance of the pillar is rough and reddish-brown in colour. In general, the pillar exhibits more corrosion compared to the other two pillars at Delhi and Dhar. The roughness (corrosion) of the pillar increases with increasing height, as shown in Figure 3. The top 1.25 m (4’) of the pillar exhibits extensive erosion/corrosion (Figure 4). The top portion of the pillar from north, east, south, west and top is shown in Figure 5. It is seen that the corrosion of the pillar is high on the west side (Figure 5d), which is exposed to direct breeze from the Arabian Sea that is about 30 km away.

The top of the pillar exhibits signs of hammer forging (Figure 5e). Unlike the iron pillars at Delhi and Dhar, the top of this pillar does not have any groove for further attachment. The top seems like the end of the pillar, with heavy forging leading to flattened end and increased thickness in the top 0.20 m of the pillar (Figure 2). This is
In line with the local tradition which indicates that the ‘flag staff’ is the top portion of the *trishul*. Contrary to the view expressed by Anantharaman, the top portion of the pillar does not show any signs of melting or flow of material.

**In situ XRF and metallography studies on the pillar**

*In situ* XRF study carried out at different metallography locations indicated that the pillar is made of almost pure iron (>99.5 wt%). This is in line with the *in situ* XRF results reported for the Delhi iron pillar. The XRF results also showed varied amount of silicon in the range 0.15–0.35%. This is attributed to different amounts of slag in the regions of measurement as slag contains high amount of Si, as discussed in the next section.

Figures 6 and 7 show the microstructure obtained at different elevations of the pillar, including the top surface, at low and high magnification respectively. The pillar exhibits typical microstructure as reported earlier for the iron pillar at Delhi and Dhar. A large variation in the microstructure with ferrite grain size varying in the range 30–300 μm has been observed at different elevations of the pillar. The microstructure essentially consists of ferrite, or ferrite with varying fractions of pearlite. A maximum of about 15% volume fraction of pearlite is observed in the microstructure, indicating a maximum of about 0.15% of carbon in the iron pillar. In the middle portion of the pillar (3.5–5.2 m elevation), slip bands were observed in the ferritic grains at most of the locations (Figure 6 c–e). The presence of slip bands in ferritic grains indicates large extent of plastic deformation in the iron pillar. Similar slip bands have also been observed in the microstructure of the Delhi iron pillar.

**Hardness**

Hardness was found to be in the range 120–195 VHN at different elevations of the pillar (Figure 8). The variation in the hardness is attributed to the difference in the carbon content, grain size and extent of deformation at different elevations. For 0.15% carbon (estimated based on the maximum volume fraction of pearlite) with ferritic–pearlitic structure, the hardness in the annealed condition is estimated to be ~120 VHN (ref. 7). The higher hardness is attributed to the considerable extent of deformation/forging of the pillar.

**Ultrasonic measurements**

Low-frequency ultrasonic measurements were carried out on the iron pillar to detect presence of any interface, which is expected to be present in pillars made by solid state reduction process employed in ancient India. However, because of the rough surface, it was not possible to
Figure 5. Top of the pillar from various directions.

Figure 6. Low magnification optical microstructure obtained on the replica taken at different elevations of the pillar: (a) 8.7 m (top of the pillar), (b) 6.2 m, (c) 5.2 m, (d) 4.2 m, (e) 3.7 m, (f) 3.3 m, (g) 1.7 m and (h) 1.2 m.

locate any clear interface. As velocity of the ultrasonic wave can provide the quality of the iron in terms of the presence of distributed voids/cracks, ultrasonic velocity measurements were carried out at the locations polished for hardness measurements. Figure 8 also shows the variation in ultrasonic longitudinal wave velocity in the pillar at different elevations. The ultrasonic velocity is found to be in the range 5500–5900 m/s. As shown in the next section, the microstructure of the iron pillar consists of ferritic–pearlitic structure with varying volume fraction of slag. The longitudinal wave velocity in wrought iron and carbon steels with ferritic–pearlitic structure is reported to be 6000 m/s (ref. 8) and the velocity of various silicate glasses and ceramics is reported to be in the range 5900–6500 m/s (ref. 9). Lower ultrasonic velocity in the pillar material compared to the steels and slag (silicates) indicates presence of defects/discontinuities in the pillar.

Scanning electron microscopy

Figure 9 shows typical SEM backscattered electron images (BEI) obtained from the small piece (~50 mg) of the
Figure 7. High magnification optical microstructures obtained on the replica taken at different elevations of the pillar: (a) 8.7 m (top of the pillar), (b) 6.2 m, (c) 5.2 m, (d) 4.2 m, (e) 3.7 m, (f) 3.3 m, (g) 1.7 m and (h) 1.2 m.

Figure 8. Variation in perimeter, hardness and ultrasonic longitudinal wave velocity at different elevations of the pillar.

sample removed from a sharp, protruding point at 0.25 m below the top of the pillar. Ferrite matrix with pearlite, iron oxides and slag (confirmed by energy-dispersive X-ray spectroscopy (EDS)) is indicated in Figure 9. The constituent phases are typical for iron produced by ancient iron-making route in India\(^1\). Figure 10 shows a SEM BEI image and X-ray energy mapping for Fe, C, P, O, Si, Al and Ca in the sample. The EDS mapping exhibited presence of O, Al, Si, Ca and P in the regions of slag, and O and Fe in oxides. A typical EDS spectrum and composition of a slag particle are shown in Figure 11\(a\) and Table 1 respectively. The EDS spectrum for the matrix away from slag regions is shown in Figure 11\(b\). The composition of the slag in the iron pillar is similar to that reported by Prakash and Igaki\(^{10}\) for slag obtained in the iron produced by ancient iron-making route. The above
results clearly demonstrate that the iron pillar at Kodachadri is produced by the ancient iron-making route by solid state reduction process.

One major difference in the composition of the matrix and slag of the iron pillar at Kodachadri and other ancient Indian iron objects reported earlier\(^1\), is the amount of phosphorus. Presence of phosphorus is considered to be one of the major factors for high corrosion resistance of the iron pillars at Delhi and MP\(^{5,11,12}\). The amount of phosphorus obtained in the slag in Kodachadri iron pillar is about 1\% (Table 1), whereas it is reported to be in the range 6–11\% in the slag in ancient Indian iron objects obtained at other locations\(^{11}\). Further, the amount of P in the matrix is estimated to be about 0.02 wt\% by \textit{in situ} XRF
and P could not be detected in the EDS spectra obtained at various locations in the matrix. The amount of P in the matrix of ancient iron objects as obtained by micro XRF under focalized synchrotron radiation is reported to be in the range 0.08–0.23% (ref. 12). The high amount of P in ancient iron and slag is attributed to the absence of CaO, which is a well-recognized dephosphorizing agent. The presence of CaO in the slag could be a possible reason for lower amount of P in the Kodachadri iron pillar. The amount of C (<0.15%) in the Kodachadri iron pillar is also found to be on the lower side compared to that observed in the Delhi iron pillar (<0.28%).

Conclusions

The in situ nondestructive studies carried out on the Kodachadri iron pillar and SEM studies on a small piece (~50 mg) of sample removed from the pillar revealed the following:

1. The presence of iron oxide particles and slag in a ferritic/ferritic–pearlitic microstructure demonstrates that the iron pillar at Kodachadri is produced by the ancient Indian iron-making route using solid-state reduction process.

2. The carbon content in the Kodachadri iron pillar is estimated to be less than 0.15% based on the volume fraction of pearlite.

3. Hardness was found to be in the range 120–195 VHN at different elevations of the pillar. Higher hardness value compared to that expected for 0.15% C steel in annealed condition and presence of twins in microstructure indicate considerable extent of deformation/forging of the pillar.

4. The amount of P in the Kodachadri iron pillar is found to be much less compared to these reported for the iron pillars at Delhi and Dhar.

5. The top 1 m of the pillar shows excessive erosion/corrosion specially on the surface facing west towards the Arabian Sea, which is attributed to the direct exposure to saline atmosphere with high wind velocity.

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Table 1. Typical composition of a slag particle in Kodachadri iron pillar

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt%</th>
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<tbody>
<tr>
<td>O</td>
<td>44.29</td>
</tr>
<tr>
<td>Mg</td>
<td>0.85</td>
</tr>
<tr>
<td>Al</td>
<td>4.21</td>
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<tr>
<td>Si</td>
<td>15.97</td>
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<td>Ca</td>
<td>9.56</td>
</tr>
<tr>
<td>Fe</td>
<td>23.33</td>
</tr>
</tbody>
</table>

Figure 11. Typical energy-dispersive X-ray spectrum obtained from (a) a slag particle and (b) ferrite matrix.