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TECHNOLOGY OF FORGE WELDING ADOPTED AT MALLAPPADI - AN IRON AGE SITE IN TAMILNADU

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An iron bar was found along with other iron artefacts such as arrow-heads, wedge and iron nails from the excavation at Mallappadi in the year 1977-78. The site is located 5 km south of Paiyampalli, a neolithic and megalithic habitation-cum-burial site in North Arcot District. The cultural vestige containing iron artefact from Mallappadi is dated to c. 500 BC on the basis of C-14 determinant obtained at Priyampalli for a similar cultural level. The iron bar from Mallappadi consists of three-iron pieces, viz., wrought iron on its sides, and low carbon steel in the middle forge welded together under hot forging. The metallurgical study for the low carbon steel portion revealed that it was mainly made up of ferrite and pearlite. The EDAX analysis of the wrought iron portion indicates that the iron content is of the order of 99.9% with a copper content of 0.099%. The slag portion in the wrought iron indicates the presence of other elements such as silica, potassium and calcium. The early metallurgist from Mallappadi hot forged wrought iron with low carbon steel to get strength to the artefact.

Keywords: Ferrite, Forge-welding, Mallappadi, Paiyampalli, Pearlite.

ARCHAEOLOGICAL STUDY

The village Mallappadi is situated 2 km south-east of Barugur in Krishnagiri Taluk of Dharmapuri District. The habitation site (Fig. 1)

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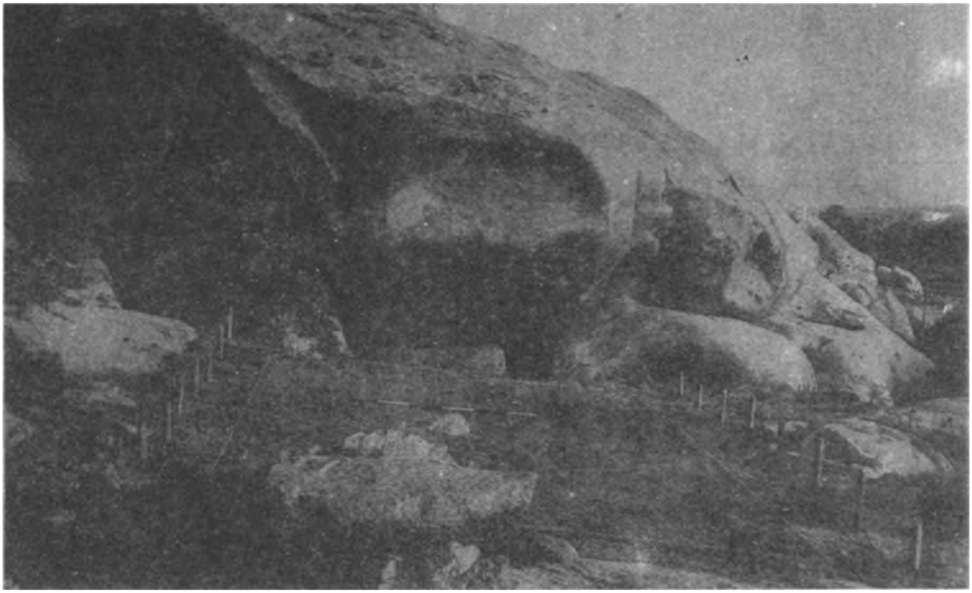

Fig. 1 : Mallappadi general view

12° 31' N 78° 15' E is located exactly on the other side of the hill opposite to Paiyampalli (a neolithic and iron age habitation-cum-burial site) and is about 5 km from the latter site. The excavations in the year 1977-78 by the Department of Archaeology, University of Madras, brought to light three cultural periods.[1] Similar to Paiyampalli except that the neolithic culture witnessed a separate entity at the latter site.[2] The megalithic culture at Mallappadi in its inception is found in assoication with the lingering vestiges of neolithic elements as in period I-B of Paiyampalli.

The occurrence of iron slag and iron artefact at the lowest level of period I in the trench Mallappadi-I (MPD.I) testifies the production of iron from the time of its occupation by the iron age people c. 500 BC. The metallurgical skill of the early iron age settlers at Mallappadi is evidenced by the analysis of an iron-bar artefact from the trench MPD.I. The metallurgical studies of iron bar and rusted iron artefact reveal that the early

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1 *Indian Archaeology : A Review,* (1997-78) 67.

2 Ibid, (1967-68) 31.

metallurgists at Mallappadi not only produced wrought iron and carburised them to steel but also hot forged low carbon steel with wrought iron to get strength.

METALLURGICAL STUDIES

THE LONGITUDINAL CROSS SECTION (SIDE VIEW)

The macrograph for the iron bar piece found in the Mallappadi excavation (Fig. 2) shows similarities with the currency-bar found from Sanur (iron age habitation-cum-burial site in Chingleput District).[3] The microstructure in the longitudinal section revealed a coarse grained structure with a network of ferrite. The morphology of ferrite and pearlite is similar to widmanstatten structure (Fig. 3). Some regions of the microstructure revealed streaks of sulphide inclusions, which look like manganese sulphide. There are zones in the microstructure where pearlitic grains are found segregated. At higher magnification, the pearlitic structure is not resolved into lamellar structure. However fine particles of carbides can be observed in the pearlitic structure. Pearlitic structure is noticed in almost the entire region of the micrograph indicating high carbon area in the steel. The microstructural study revealed corrosion in the iron bar and the brownish corrosion product is observed in the longitudinal view of the iron bar.

THE LONGITUDINAL CROSS SECTION (TOP VIEW)

Microstructural scanning of the top surface of the iron bar clearly revealed that the iron bar was made up of three layers of metals joined together by forge welding such as hammering of hot metals. The thickness of the metal layers A, B & C respectively consisted of 0.8 mm, 3.4 mm, and 4.5 mm as shown in Fig. 4. The microstructure in the longitudinal surface (top) shows the interface between the two metal layers B and C at the centre region (Fig. 5). A thin layer of slag is found at the interface of the materials A and B. The structure in the interface region has cracked

[3] *Ancient India*, 13 (1959) 35

Fig. 2 : Macro figure of the iron bar - Mallappadi

Fig. 3 : Micro structure in the longitudinal section showing a Widmanstatten structure.

The Longitudinal cross section (Top view)

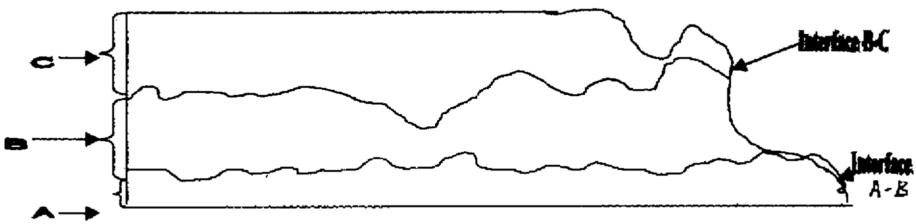

Fig. 4 : Line drawing of the forge-welded iron bar — longitudinal top view
Legends : A-Equi-axed B-Widmanstatten C-Equi-axed

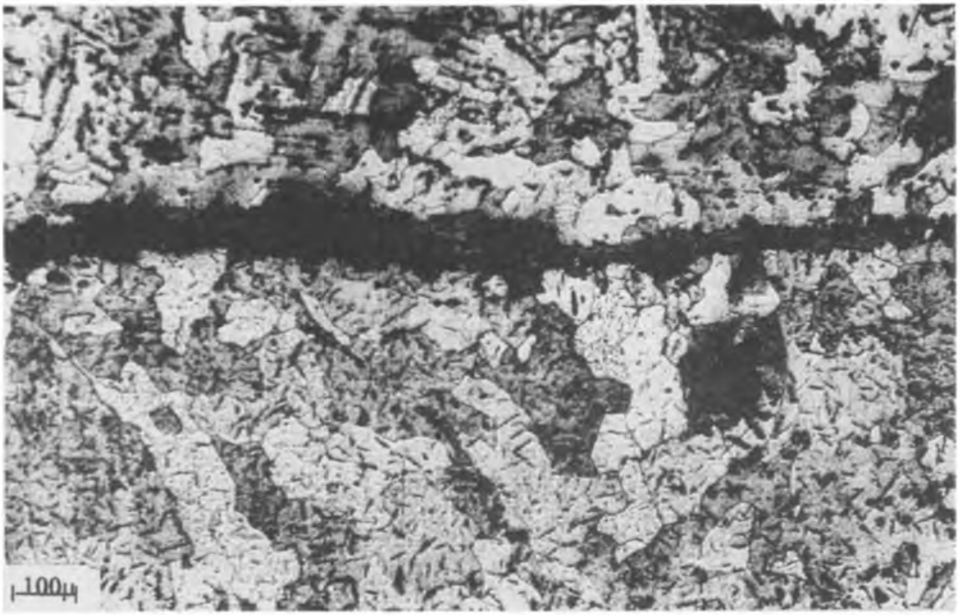

Fig. 5 : A thin layer of slag found at the interface between the metal layers B and C.

probably due to metallographic grinding and polishing of the artefact. The Widmanstatten structure containing mostly ferrite and few plates of pearlite is found in the interface region B. The other side of the interface (layer C) showed equi-axed grains of ferrite with no pearlite. The interface containing equi-axed grains of ferrite shown in Fig. 6 reveals iron carbide (cementite) distributed throughout the matrix as thin needles. Another layer of metal (layer A) is present in one side of the ironbar. The structure of this layer consisted of equi-axed grains of ferrite with small grains of pearlite.

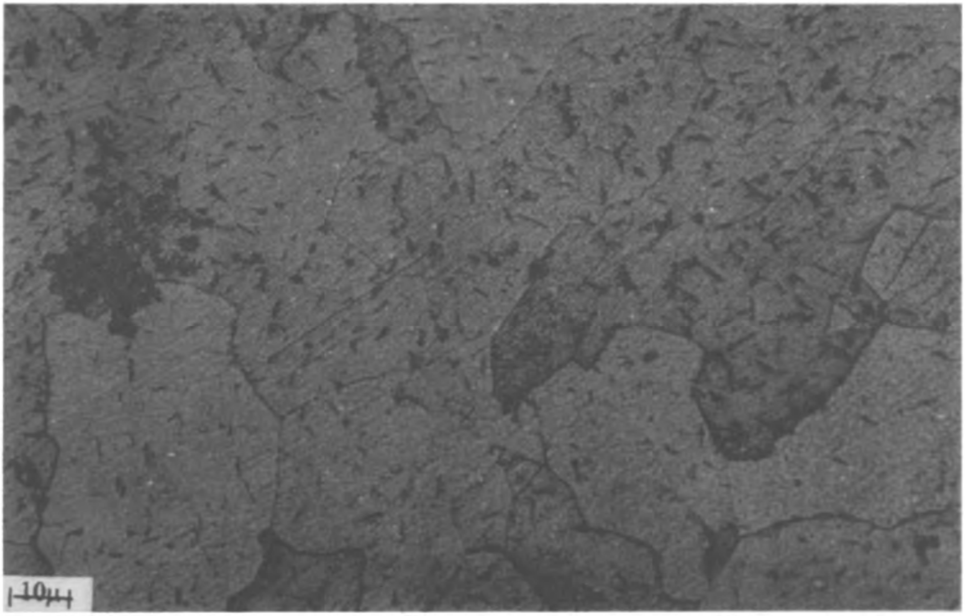

Fig. 6 : Ferritic structure in layer C conaining thin needles of iron carbides (cementite).

TRANSVERSE CROSS SECTION

The microstructure in the transverse cross section of the iron bar clearly showed three regions in the structure with demarcation lines separating them (Fig. 7). This indicates that three metals were forge welded. The outer part of the forge-welded metal appears to be pure iron with slag inclusions. The detailed examination of the artefact revealed that the structure also contained slag inclusions (Fig. 8). The microstructure in Fig. 8 indicates not much of pearlite but mainly ferritic grains.

EDAX ANALYSIS

Table 1 shows elemental composition in different regions of the transverse cross section of the sample (layers A, B and C). The slag elements in the iron material are revealed by the presence of silicon, potassium, and calcium.

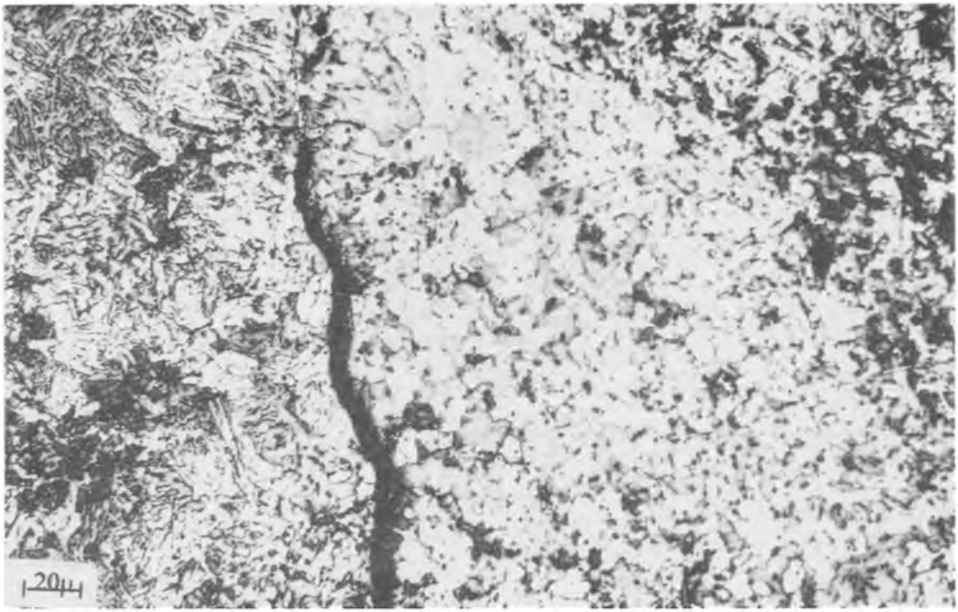

Fig. 7 : Micro structure of the transverse cross section-showing demarcation between the three metal layers.

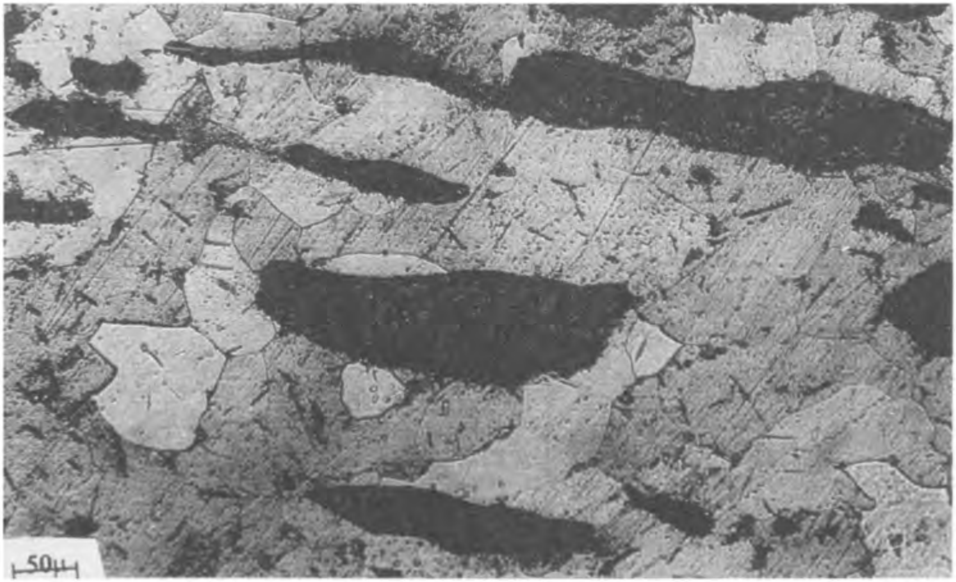

Fig. 8 : Slag inclusion in the microstructure of the artefact.

TABLE 1. EDAX Analysis of Iron Bar

INTE-%:
Label = Needle Ppt of A67/5
21-MAR-97 05:05:27
107.261 LIVE SECONDS

ELEM	CPS	WT% ELEM
FE K	1402.155	99.663
CU K	4.214	0.337
Total		100.000

Elemental Composition in Layer A

ELEM	CPS	AT% ELEM
FE K	1402.155	99.704
CU K	4.214	0.296
Total		100.000

ELEM	CPS	AT% ELEM
FE K	353.283	99.821
CU K	0.642	0.179
Total		100.000

Elemental Composition in Layer B

ELEM	CPS	WT% ELEM
FE K	353.293	99.796
CU K	0.642	0.204
Total		100.000

ELEM	CPS	WT% ELEM
FE K	441.103	99.888
CU K	0.441	0.112
Total		100.000

Elemental Composition in Layer C

ELEM	CPS	AT% ELEM
FE K	441.103	99.901
CU K	0.441	0.089
Total		100.000

ELEM	CPS	AT% ELEM
SI K	50.396	8.919
CA K	23.837	3.357
FE K	777.682	87.686
CU K	0.342	0.038
Total		100.000

Analysis of the slag in the interface between the Lay A and B.

ELEM	CPS	WT% ELEM
SI K	50.396	4.740
CA K	23.837	2.545
FE K	777.682	92.668
CU K	0.342	0.046
Total		100.000

ELEM	CPS	WT% ELEM
SI K	86.145	12.315
K K	10.317	1.706
CA K	78.902	12.809
FE K	403.067	72.999
CU K	0.836	0.170
Total		100.000

Analysis of the slag in the interface between the Layers B and C

ELEM	CPS	AT% ELEM
SI K	86.145	20.766
K K	10.317	2.067
CA K	78.902	15.135
FE K	403.067	61.905
CU K	0.836	0.127
Total		100.000

The EDAX analysis of the iron bar indicates that the metal is mainly made up of iron with a small percentage of copper. The EDAX analysis of the regions containing slag inclusions reveals that the slag mainly consisted of oxides of iron, calcium, silicon, potassium, and copper. The slags are normally made up of compounds such as oxides and silicates of iron, calcium, etc.

CHEMICAL ANALYSIS OF SIDE SURFACE (B) OF THE IRON BAR

The chemical analysis of the side surface B of the iron bar at one spot was determined by spectroscopic analysis. The result indicates the presence of elements such as Carbon 0.9388%, Silicon 0.1143%, Manganese 0.0009% Sulphur 0.0230%, Chromium 0.0008%, Molybdenum 0.0200%, Nickel 0.020%, Copper 0.0131%, Vanadium 0.0041%, Cobalt 0.0076%.

HARDNESS STUDIES

The hardness measurements were taken on three layers of the iron bar. The hardness value varied from 80 to 85 VHN in layer C, 140 to 147 VHN in layer B and 80 to 95.6 VHN in layer A. The Widmanstatten structure containing large amount of pearlite revealed a hardness value of 145 VHN. The ferritic structure in layer C exhibited a hardness measurement of about 85 VHN. The layer A of the metal containing equi-axed grains of ferrite and pearlite has a hardness value of about 100 VHN. The iron bar is embedded with layers of iron oxide and slags. The hardness on this is found to be in the region of 300 VHN.

Table 2. Hardness Studies on the Iron Bar, Load : 2kg.

Sl. No.	Area of indentation	Hardness Value
	Layer-A of the metal	
1	Ferrite region	80 VHN
2	Widmanstatten structure and ferrite with some flakes of pearlite.	93 VHN
	Layer-B of the Metal	
3	Pearlitic region	144 VHN
4	Interface between layer B and C	98 VHN
	Layer-C of the Metal	
5	Ferrite region	81 VHN
	Oxide region in the metal	
6	Oxide region	20 VHN

MANUFACTURING PROCESS

HISTORICAL STUDIES

Solid phase welding is the first welding process used by man without the presence of any vapour of liquid phase in the history of welding technology. The welding of wrought iron has been carried out well above the free running temperature of the slag it contains and the presence of non-solid in the metal helps the process of welding easier.[4]

The welding of iron dates from the beginning of the Iron Age because it is implicit in the smithing and working of iron by the direct process. In the early iron age the need to weld at an early stage of fabrication was not well understood, and the small pieces of smelted sponge iron were first forged and then joined.[5] This method of welding would be known as smith welding or pressure welding to distinguish it from the large group of welding process based upon fusion. If the joining had been done before forging the sponge into a dense piece, the welds would not have been so visible. This point was seen appreciated since later periods of the Iron Age do not

[4] R. F. Tylecote, *Solid Phase Welding of Metals*, Edward Arnold, London 1968, p. 1.
[5] Ibid, p. 3.

show such a high proportion of badly welded artefacts. The blacksmith welding of iron requires a high temperature of more than 1000° C (white heat). The presence of slag in the metal acts as a flux, because of its ductility and freedom to weld at room temperature.[6] Iron pieces like adze or axe from the Sardis dated to c. 1000 BC and Al Mina dated to c. 400 BC indicate in the microstructure, a clear seam separating a thin carburised layer from non-carburised region.[4]

The joining of thin pieces of strips with higher carbon content (pearlitic) on to the edges of the axe or adze through hammer welding resulted in Ferritic matrix in the mid region.[7] Hadfield's structural analysis of iron nail datable to Iron Age period from Sri Lanka in the early part of the nineteenth century revealed forge welding. The welding in the iron nail was seen running diagonally across the section, and along the edges of the weld, there are carburised areas.[8] Metallographic studies of iron hoe from Dhatwa, an early historic site (c. 400 to 300 BC) in Gujarat on the banks of river Tapti, indicate that it was presumed to be made in two stages. First the red-hot bloom was forged into thin sheets on an anvil near an open hearth. In this process the surface of the sheets was carburized and casehardened. Secondly, several of these were joined laterally, one by one, by forge welding. Finally the whole mass was further forged to shape it into a hoe. The laminated structure in the metal indicates the lines of lateral welding.[9]

PRESENT STUDY

Metallurgical study of the iron bar shows that the iron artefact was manufactured by forge welding of three iron pieces. Forge welding is normally carried out by heating two or more pieces of metals at a high temperature of about 800-1000° C and hammering them to join. The joining of layers is due to the diffusion of atoms across adjoining layers. At this

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6 R.F. Tylecote, *Metallurgy in Archaeology*, Edward Arnold, London 1962, p. 152.

7 R. Madin, *A History of Martensite. Some thoughts on Early Hardening of Iron*, The Materials Society, 1973, p. 404.

8 Panchanan Neogi, "Iron in Ancient India," Bulletin No. 12, Indian Association for Cultivation of Science, Calcutta, 1914.

9 K.T.M. Hege, "Early stages of Metallurgy in India," *Radio Carbon and Indian Archaeology*, 1973, p. 404.

temperature, the metals become plastic and ductile and therefore two metals can be joined together under the force of hammering. The joining of two pieces of iron under hot forging is called forge welding. The inner material of layer B is made up of low carbon steel. The layers C and A of material is made up of pure iron or wrought iron containing considerable amount of slag inclusions. The wrought iron portion on the outer surface, being the purest form of iron, has got excellent corrosion resistant[10] and therefore protects the inner mild steel metal from getting oxidise, even though the metal was made around c. 500 BC buried under the soil for a long period of 2500 years. The inner low carbon steel provides greater strength to the iron bar.

Streaks of sulphide inclusion were also noticed on all the three layers. Elongation of the sulphide inclusions in the longitudinal direction of the iron bar indicates that the hammer forging was carried out perpendicular to the longitudinal direction, so that sulphide slag has spread out in the longitudinal direction. As the forging operation appears to have been carried out at a higher temperature, viscous slag has solidified and embedded between the layers of the metal as well as the surface of the metal. The presence of slag layer on the surface of the metal was in fact quite beneficial to the metal surface because of the protection it has given to the metal from corrosion for more than 2500 years.

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[10] L.L. Shreir, "Corrosion," *Metal/Environment Reactions*, Vol. I, Newnes-Butterworths, London 1976.