A Wrought Iron Railing of the 16th Century

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Abstract

Specimens from a wrought iron railing placed on the Marcus Aurelius Column during the 16th century have been examined with metallographic methods. They show a very heterogeneous structure with many oxide and silicate inclusions and frequent mechanical twins in the ferrite grains. The inclusions have been studied with microanalysis EDS apparatus. The results of the study of the bloomery iron are discussed also in comparison with the iron-making techniques as described by Biringuccio in order to infer additional informations on the manifacturing methods that were used.

Riassunto

Si sono studiati con metodi metallografici dei campioni provenienti da una ringhiera collocata nel XVI secolo sulla Colonna di Marco Aurelio. Essi presentano una struttura molto eterogenea, ricca di inclusioni di ossidi e silicati, con frequenti geminati meccanici nei grani di ferrite. Le inclusioni sono state caratterizzate con microanalisi effettuate al microscopio a scansione. I risultati dello studio di questo ferro da riduzione diretta vengono discussi in relazione alle tecniche siderurgiche descritte da Biringuccio in modo da ottenere ulteriori informazioni sui metodi di fabbricazione impiegati.

1. Introduction

The Marcus Aurelius column, called also "Antonina column", has been settled as is now in the year 1589 during the urban refurbishing of the Rome town under the pope Sisto V (1585-1590). On that occasion a bronze statue of Saint Paul was placed at the top of the column on a platform that was surrounded with a wrought iron railing as a man tall (fig. 1).

Thereafter the monument has undergone, also recently (1956), several restoration and maintenance works, either concerning the roman part or the Renaissance one. During the last maintenance work (1988) there was the opportunity to examine some samples from several parts of the railing. There was a request to recognize through metallographic study the original rail components and distinguish it from the more recent ones. On this occasion there was the interest to carry on a more deep study considering the epoch of the original railing. It was shaped and settled approximately in the same years when the two most important treatises of mining engineering and metallurgy were published at the beginning of modern epoch, "De la pirotechnia" of Vannoccio Biringuccio (1537) and "De re metallica" of Georgius Agricola (1556). It is well known that the iron-making processes in use at the time, are described in details and critically examined in these treatises. Besides Biringuccio worked at ironmaking shops in the territory of Siena, not far from Rome were the railing was placed.

The aim of the present work is that of checking the correspondence of the structural characteristics of the rails material with the methods of iron smelting and of shaping the iron-works described by Biringuccio in his book. We hope also to contribute to the determination of process temperature through the metallographic and microanalytic examination of inclusions of slag and more generally to the knowledge of the technology then used.

2. Experimental work and results

A part of the railing is represented in the sketch of fig. 2, that shows where from the samples for the metallographic examination have been taken and their shortened indication. The bar C has been easily recognized to be made of middle carbon rolled steel of modern production, as it result from its homogeneous ferritic-perlitic structure typical of steel produced in liquid state (fig. 3). The other parts of the railing (round and flat bars) resulted to be made of ancient bloomery iron.

Chemical analysis - The results of chemical analysis are given in Table I. The impurity content is low, in particular that of sulphur, as effect of the use of good purity and rich ores and of charcoal as fuel. This may be the case of hematite of Elba island, where from the ores may possibly come. Only silicon reaches an approximate 1% in weight, and this may be the consequence of the reduction process of acid iron ore in the presence of free silice.

TABLE 1 - Chemical analysis of the samples

Sample position	%C	%Si	%Mn	%P	%S	%Ni	%Cr	%Pb
A	0.084	0.58	0.18	0.27	0.045	≤0.1	≤0.1	tr.
B*	0.17	≈1	0.05	≈0.2	0.013	≤0.1	≤0.1	abs.
C*	0.014	≈1	0.05	≤0.2	≤0.022	≤0.1	≤0.1	abs.

* Semiquantitative analysis for the small size of the sample.

Metallographic examination - All the samples have a metallographic structure very heterogeneous, either those cut from round bar (A, D) or from the flat bar (B). The macroetching of sample D (fig. 4) shows several zones differently etched: it apparently consists of a texture of several iron particles, each showing peculiar flow lines of deformation under the hammering, separated by numerous holes and containing many nonmetallic inclusions also of large size.

The micro-examination also shows no uniformity in ferritic grain size and carbon distribution (fig. 5). There are hard zones (higher carbon and smaller grain size) and soft zones (lower carbon and larger grain size). Also the presence of Widmanstätten structure has been noticed in the higher carbon areas; probably this effect has been caused by the last operations of shaping by hot hammering (fig. 6).

Mechanical twins are frequent in the ferrite grains in all the samples. It is well known that the mechanical twins in the b c c metals give indication of a deformation at high rate under shock load. In the α-ferrite the twinning and contact plane is the plane (211), fig. 7 and 8 show two different twinning sistems active in the same ferrite grain: the angle formed by two twinning planes corresponds exactly to the angle between (211) and (121) planes (33,6° in fig. 7) and between (211) and (211) planes (70,5° in fig. 8).

Non-metallic inclusions examination - The study of the non-metallic inclusions may give some informations on the raw materials used and processing conditions. Micrographic study (optic and SEM microscopy) and EDS microanalysis with routine standardless program have been done.

Two inclusion types have been characterized and are represented in fig. 9 and fig. 10; examples of their analysis are given in Table II. The Fe oxide in inclusions is supposed to be wüstite, since it is in equilibrium with metallic iron. The inclusions of the first type (fig. 9) are constituted of a fayalite matrix within which wüstite dendrites are contained; in the fig. 9b the silicon distribution between matrix and dendritic constituent is reported.

The inclusions of the second type (fig. 10) are characterized by high phosphorus content and by a structure of primary needle shaped crystals less rich in phosphorus in a matrix more rich in phosphorus; in the fig. 10b the phosphorus distribution is reported.

TABLE 2 - Microanalysis results of the inclusions slags

I - Dendritic inclusion fig. 9					
Matrix					
$SiO_2 = 20$	$P_2O_5 = 2$	$FeS = 8$	$CaO = 4$	$MnO = 5$	$FeO = 61$
Dendritic crystals					
$SiO_2 = 2$		$FeS = 1$		$MnO = 2$	$FeO = 95$
II - Phosphate inclusion fig. 10					
Matrix					
$SiO_2 = 6$	$P_2O_5 = 29$				$FeO = 65$
Needle shaped crystals					
$SiO_2 = 4$	$P_2O_5 = 17$				$FeO = 78$

3. Discussion

Process temperature - Process temperature may be tentatively established through the slag inclusion composition and morphology with the aid of phase diagrams. Melting point estimation derived from phase diagrams may be regarded as yelding hazardous results and it is object of some criticism. The melting temperature of the real slags estimated with the use of simple diagrams may really led to inaccuracies. However the method may be used for an approximate maximum process temperature estimation, considering the largely spread temperature values of the old processes and furnaces [1, 2].

The slag inclusions constituted of wüstite-fayalite may be evaluated with the help of ternary oxide diagram $CaO\text{-}FeO\text{-}SiO_2$ [3], that gives a melting temperature for the composition range of interest of 1200-1300°C; in the binary system fayalite-wüstite the minimum temperature for a homogeneous liquid phase formation is under 1200°C. The presence of MnO raises the wüstite melting point; on the other side the FeS lowers it.

The phosphate inclusions may be examined with the help of the binary system $FeO\text{-}P_2O_5$; the small quantity of silica present only narrows the liquid miscibility gap present in the system $CaO\text{-}FeO\text{-}P_2O_5$. In the binary system of fig. 11 [4] it is suggested the formation of a compound labeled X with lower phosphorus content, in the temperature interval of 940-960°C and of an eutectic with $3FeO\text{-}P_2O_5$, more rich in phosphorus, at the minimum temperature. The needle shaped primary crystals of fig. 10a may possibly correspond to the X compound precipitation when a homogeneous liquid slag slowly crosses the temperature gap 940-960°C; the composition interval for X compound formation fits quite well to the slags inclusion composition of Table II. It may mean that the material has been processed at higher temperature and that it has been at this temperature interval for some time or it has crossed it rather slowly.

The Iron Smelting Technique according Biringuccio - In his metallurgy treatise Biringuccio, describes the technology of iron ore reduction: the charge of ore and charcoal of selected size is surrounded with an enclosure of larger size iron ore pieces and of sandstone in order to get a better thermic insulation. The process is conducted in a low furnace or bowl furnace: a bowl of burning charcoal is blown with an air supply through a tuyere. B. considers the ores from Elba island specially suitable to be treated in this way; it requires rich, reducible ores with low impurity content. According to B. the iron ores from Elba island were enough to meet the need of italian peninsula. B. in the description of the reduction process does not give any indication of slag forming addition. The quality of the ores is of upmost importance in regard to this point; other types of iron ores as those of Val Camonica in Italy or of Middle Europe, were reduced in higher furnaces, blown with more powerful bellows, with limestone additions in order to have a lower iron oxide content in the slags (see the description in "De re metallica" of Agricola), or with a charge of self-fluxing ore or of mixed silicious and basic ores [5].

Recently either on the base of theoretical considerations or of experimental works it has prevailed the opinion that a high temperature may be reached also in a low furnace (1600°C) in a small volume at tuyere level with very steep temperature gradient [5, 6, 7]. The examination of slag inclusions here discussed suggests a temperature interval of reduction 900-1300°C and possibly higher. At these temperatures it is well possible the production of pig iron.

It is well known that in China in the 5th Century B.C. it was developed the iron smelting for the production of white cast iron possibly at the mines and after its remelting to make castings where they were required [6, 8]. The famous indian "Wooz" high carbon steel was directly smelted in liquid state in a crucible from high purity iron ores at temperature as high as 1450°C.

Several conditions and maximum process temperature fix the limits between the production of pig iron and bloomery iron: coal/ore ratio, air supply rate and continuous or intermittent operations (this last condition is of paramount importance). In the direct reduction of iron ore for the production of bloomery iron the materials during the processing could reach carburization at different levels and could be partially melted. In intermittently operated furnaces oxidizing conditions can develop in the furnace with a possible decarburization during the cooling period before the final discharge of the material.

Hot working - According B. the sponge iron lump was hot worked by drop forging: "...and the hot blooms are worked with the hammer, they are cut and elongated; they are shaped to get bars, square or flat sections according the requests...". As result of the hot working with high strain rate under impact load there are frequent mechanical twins in the ferrite grains. On the other side there is no indication of strain-hardening in the metallographic structure (as slip markings, broken and elongated grains, etc.); the hammering work has been done at a temperature sufficiently high for an active recrystallization process.

4. Conclusions

1. The metallographic examination of a wrought iron bar of the 16th Century in Rome is in agreement and confirm the description of the iron ore smelting technique of B.

2. The material is highly heterogeneous with regard to carbon content, grain size, inclusions of slags; it looks as an aggregate of iron particles welded together in the formation of the iron bloom with clear evidence of the flow lines.

3. The structure and analysis of the inclusions give indications of a process temperature at least in the range of 900-1300°C, with very strong temperature gradients. It is possible the formation of more or less carburized metal and of decarburization processes during the cooling period after the reducing treatment.

4. There is metallurgical evidence of subsequent drop forging.

Acknoledgment

The authors thank Professor G. Torraca and Architect G.G. Martines who have suggested the problem and given the samples and Restorer C. Usai for the friendly cooperation.

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Figure captions

Fig. 1: The railing on the top of Marcus Aurelius column during the maintenance works.

Fig. 2: Sketch of the railing with indication of the sample positions.

Fig. 3: Ferritic-pearlitic structure of carbon steel of the rolled bar: modern fabrication in liquid state, $\times 100$.

Fig. 4: Macroetch of the sample from the old round bar, $\times \approx 3$.

Fig. 5: Microstructure showing ferrite and ferrite-pearlite, different grain size of the ferritic structure, $\times 100$.

Fig. 6: Not uniform structure with low carbon ferritic areas and ferritic-pearlitic higher carbon Widmanstätten structure, $\times 50$.

Fig. 7: Mechanical twins in ferrite grains, $\times 200$.

Fig. 8: Mechanical twins in ferrite grain, $\times 1000$.

Fig. 9: (a) Dendritic structure of fayalite-wüstite inclusion, (b) Microanalysis map of silicon distribution, $\times 2000$.

Fig. 10: (a) Slag inclusion of ferrous oxide-silica-phosphate: primary needle-shaped crystals in higher phosphorus matrix, (b) Microanalysis map of phosphorus distribution in the slag inclusion, $\times 4000$.

Fig. 11: Phase diagram for the system iron oxide-P_2O_5 in contact with a metal phase, after Trömel and Schwerdtfeger.

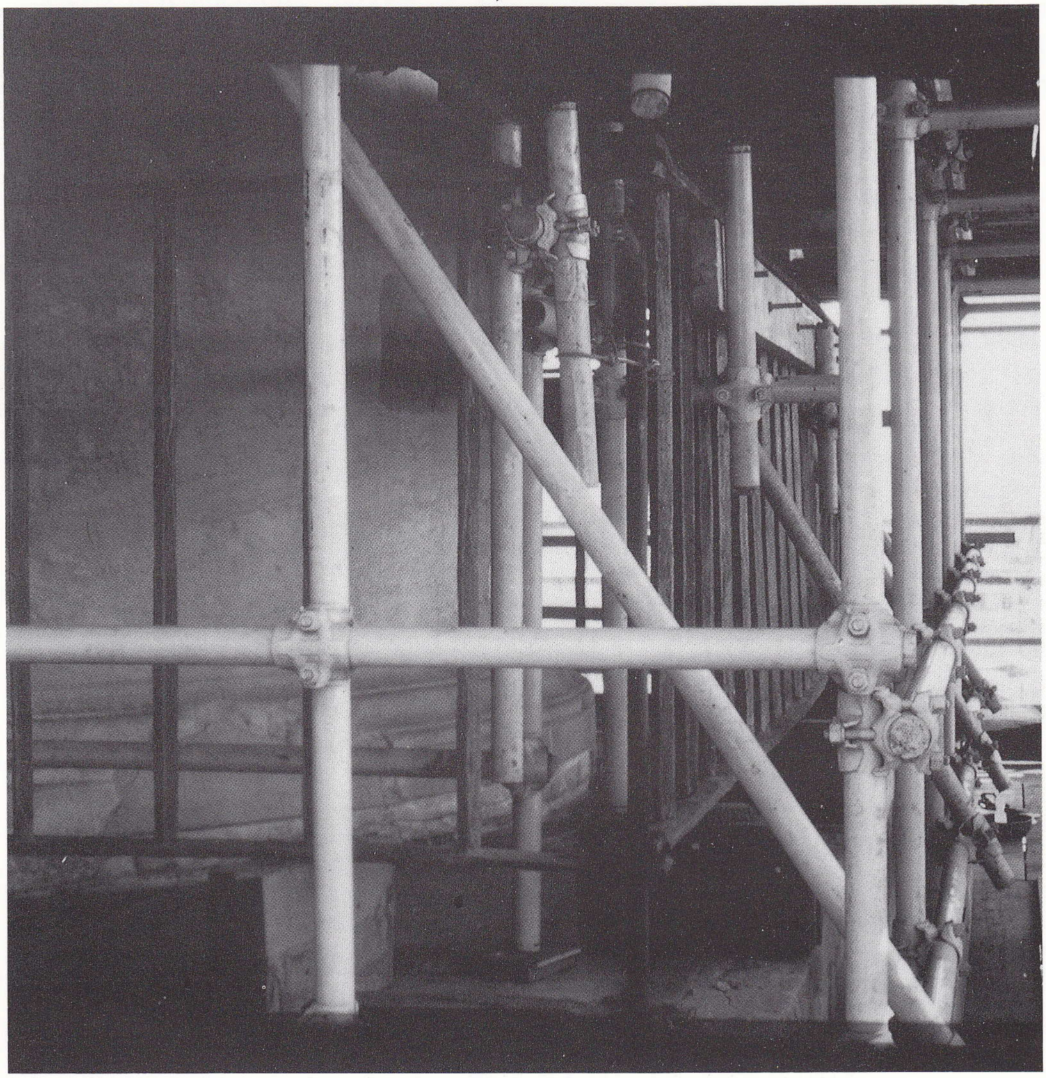

Fig. 1

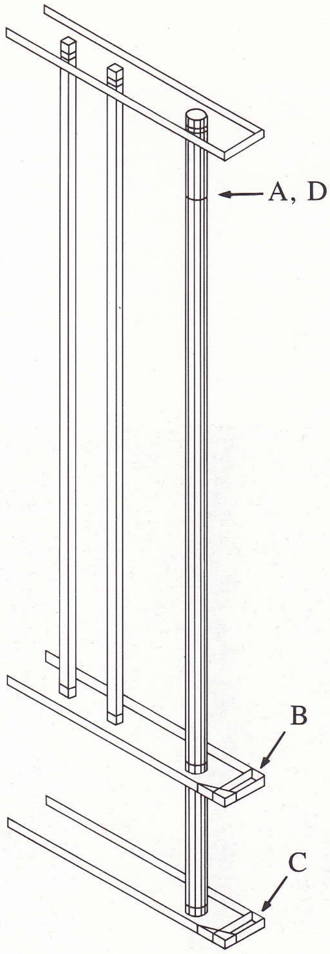

Fig. 2

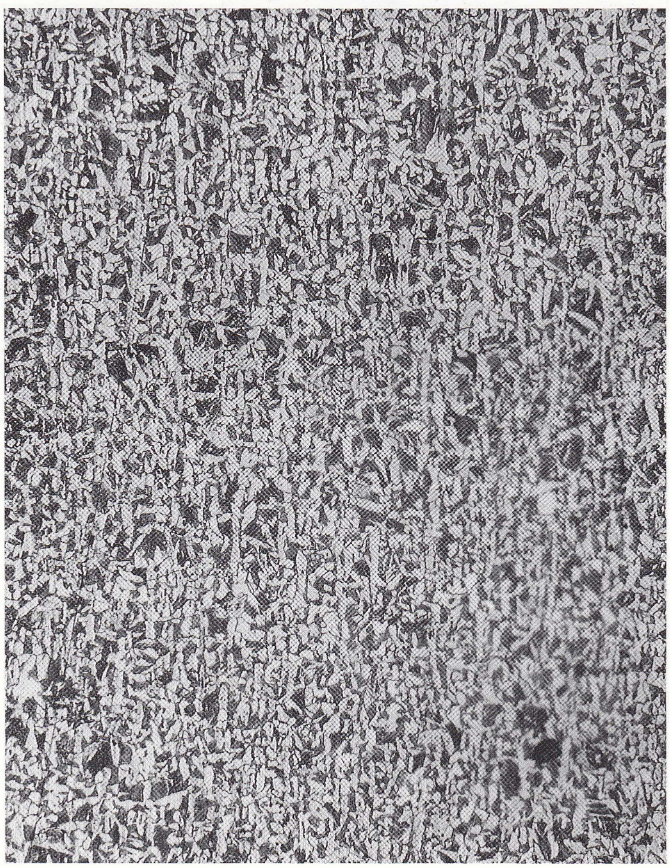

Fig. 3

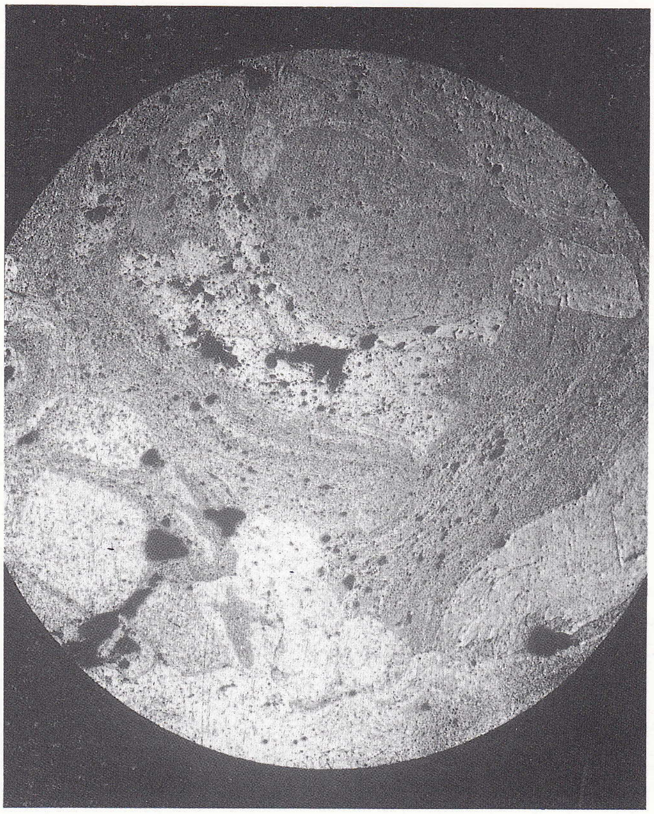

Fig. 4

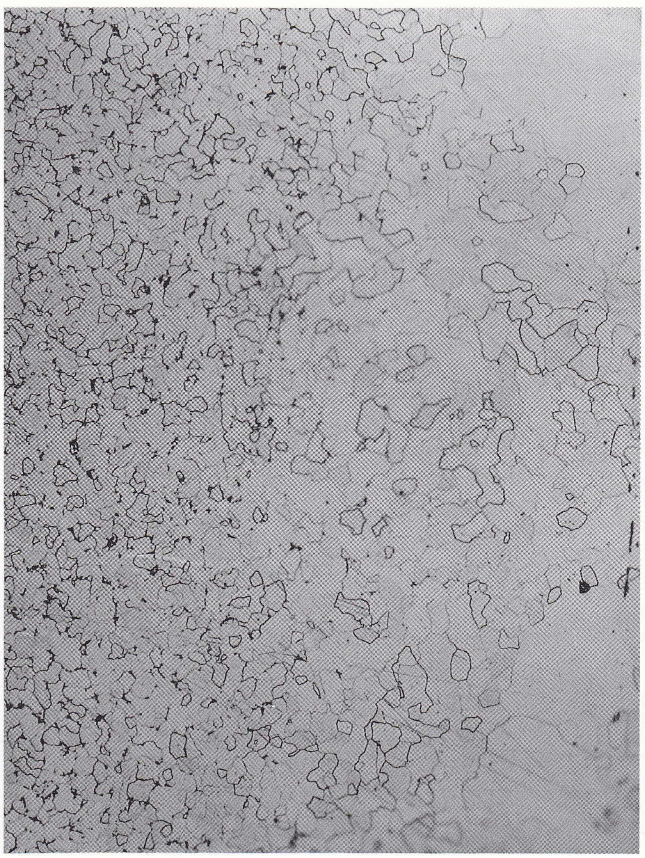

Fig. 5

Fig. 6

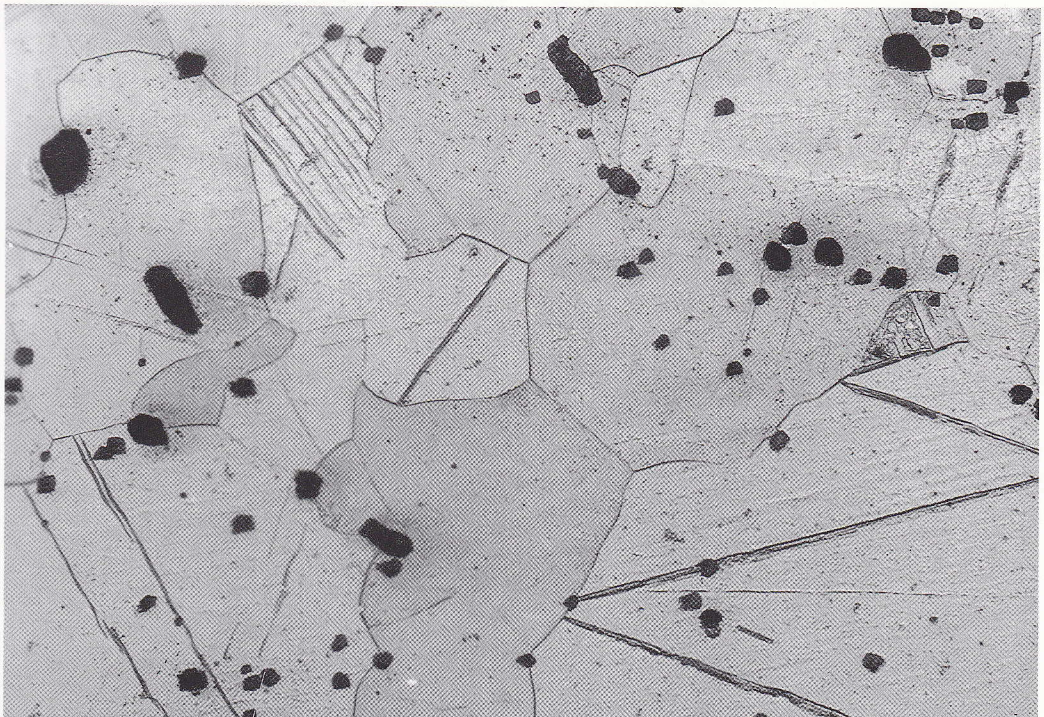

Fig. 7

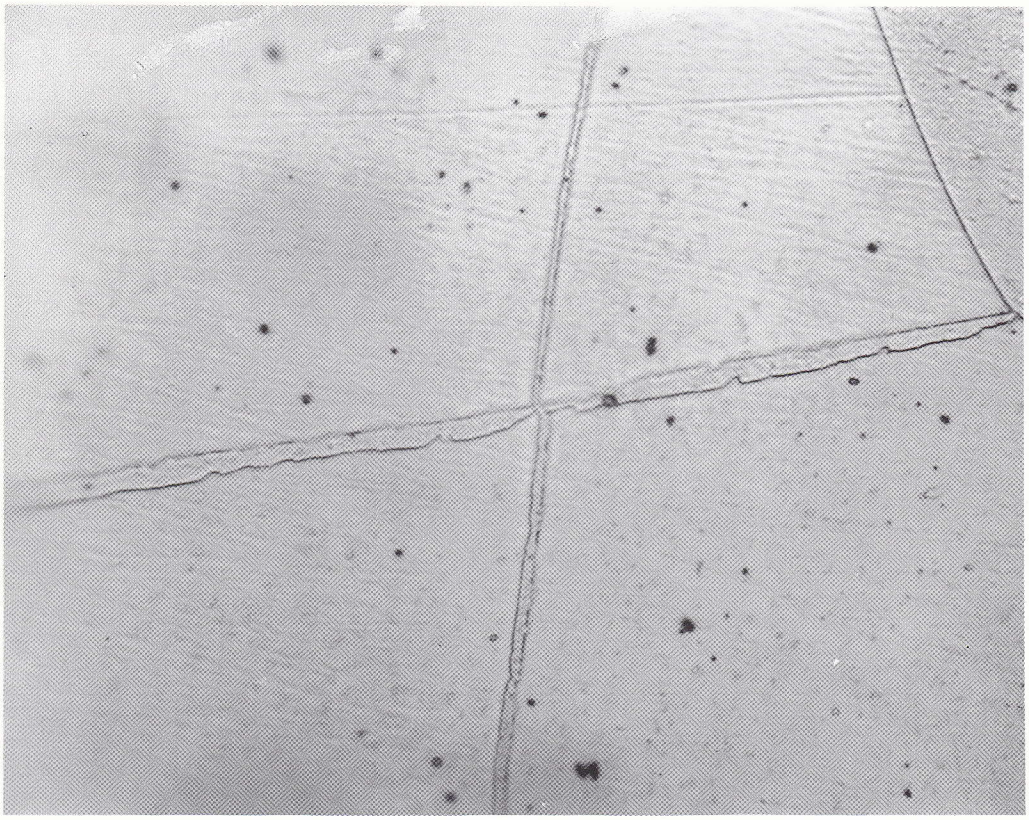
Fig. 8

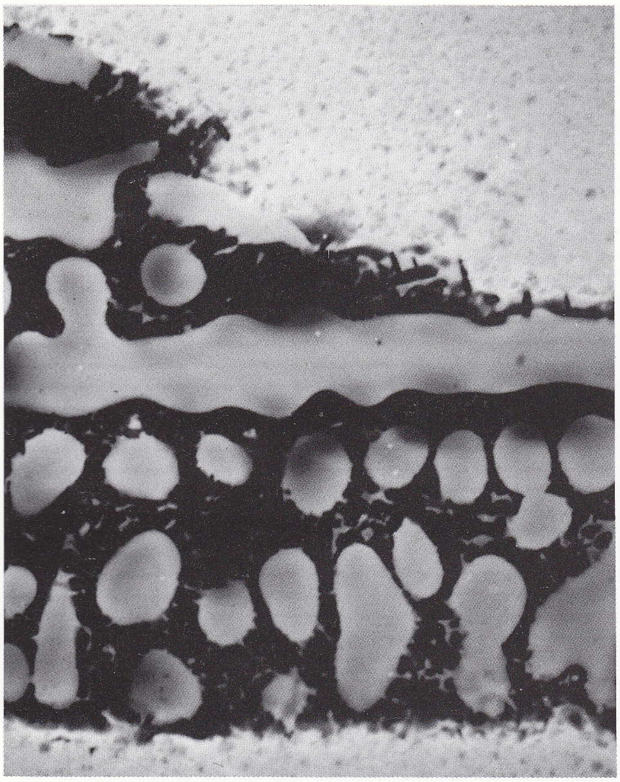
Fig. 9a

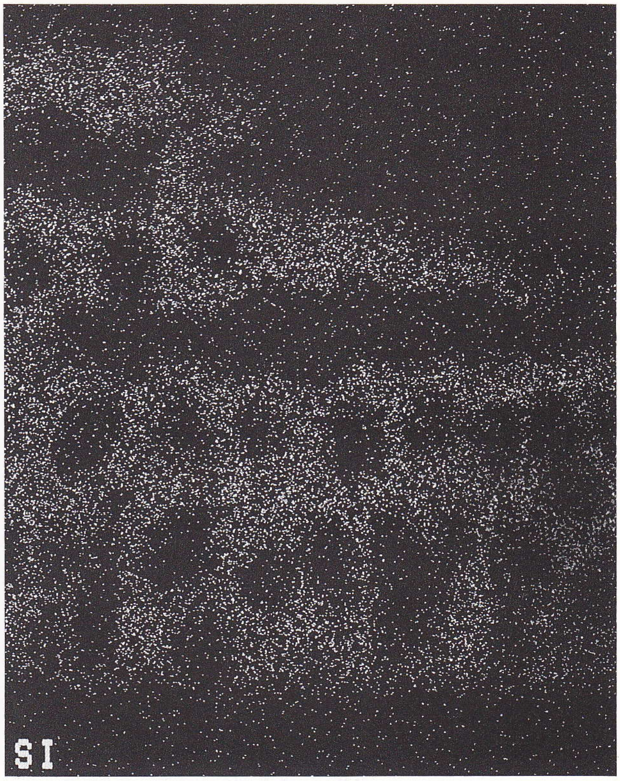

Fig. 9b

Fig. 10a

Fig. 10b

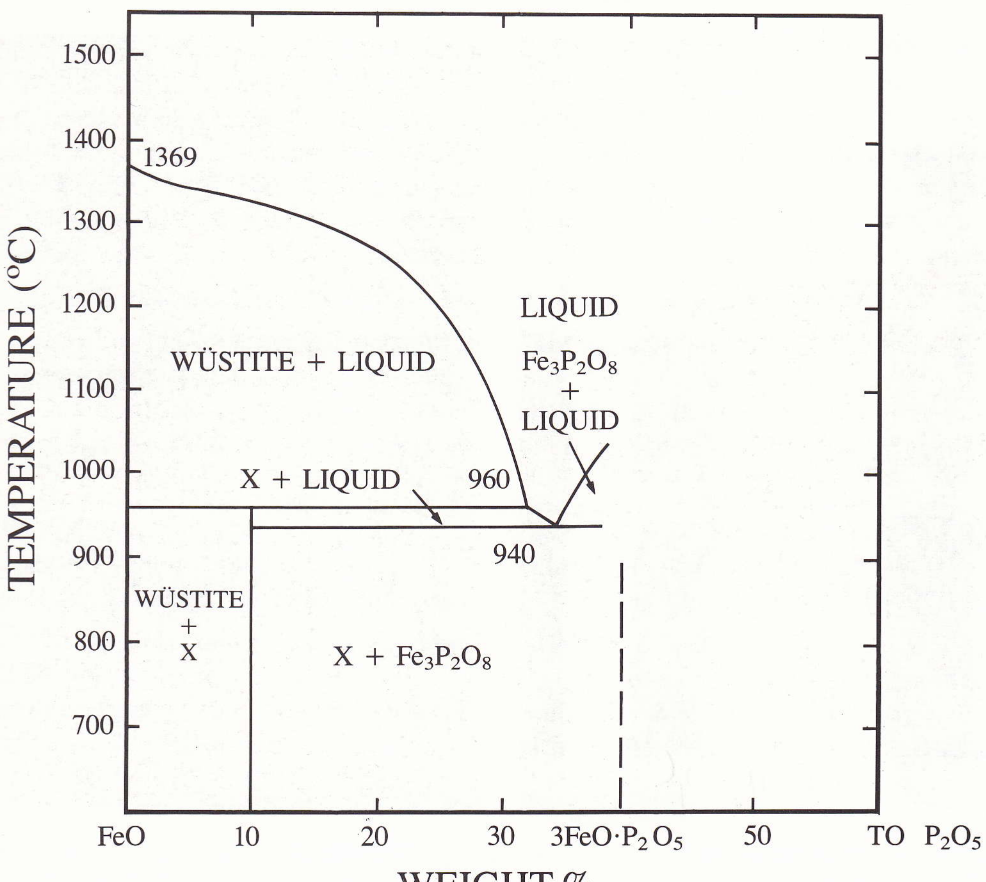

Fig. 11