THE OVERHEATING AND BURNING OF STEEL

by

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SYNOPSIS

The symptoms, effects and causes of overheating and burning of steels are summarised, with 17 illustrations and a selected bibliography of 15 references.

When a steel is heated for forging to excessive temperatures it may be temporarily or permanently damaged. Three changes are involved as the heating temperature is raised :

1. Austenitic grain growth.
2. Overheating.
3. Burning.

The term "overheating" has been loosely used in the past to indicate the structure associated with austenitic grain growth, for instance the precipitation of ferrite in a Widmanstatten pattern. In view of the temporary nature of the effects of this phenomenon it is desirable to differentiate it from overheating as described below, the effects of which are persistent. Inferior mechanical properties of a steel resulting from coarse austenite grains can be improved by hot working and grain refining treatments. The effects of overheating and burning, on the other hand, are difficult to remove. Burning may damage the steel beyond resuscitation; it may also impair the forging properties of the steel.

The present article attempts to review summarily the present understanding of the overheating and burning phenomena, contributions towards which have been made by many investigators, particularly Preece and his co-workers, whose original papers should be consulted for more detailed information. A bibliography on factual observations on these phenomena made before 1944 has been published by the Iron and Steel Institute, London.

I. **Overheating.**

a. Symptom

When a steel is heated above a certain temperature, generally known as the overheating temperature, changes which take place at the austenitic grain boundaries reduce the resistance of these regions to fracture. After the steel is reheated, quenched and tempered so that the resistance to fracture of the matrix is increased, the steel will break, during notched impact test, along the previous grain boundaries giving rise to a fracture containing a number of mat crystal facets in a fibrous structure, as shown in Fig 7. These facets correspond to the previous grain interfaces. The optimum heat-treatment required to develop the facets in an overheated steel depends on the composition of the steel. In general, oil quenching from the austenite range followed by tempering at 600° C for 1 hour is most suitable for alloy steels. No systematic investigation has been published for plain carbon steels; tempering at 200°C has been reported as suitable for a mild steel.

The size and the number of facets in a fracture increase with increasing temperature, as shown in Fig 1. to 5. The size of the facets also increases during prolonged soaking, as can be seen from Figs. 6 and 7, but the first sign of overheating can be observed after heating only for 1 to 5 minutes.

The boundary network corresponding to sections of these facets can be revealed by the use of suitable etching reagents. The following two etchants, if used properly, give satisfactory results:

Nitrosulphuric acid: The specimen is etched in an aqueous solution of 10% sulphuric acid and 10% nitric acid three times each of 30 seconds. The brown film formed during etching is removed between etchings. The specimen is finally very lightly polished. The test can be applied independently of the heat treated condition of the steel. The structure appears as a network of pits outlining the austenite grain boundaries at which changes have taken place (Fig. 8).

Ammonium nitrate. The specimen is electrolytically etched in a saturated aqueous solution of ammonium nitrate for 3 minutes with a current density of 1.0 amp. per sq. cm. The steel should be examined in the heat-treated condition which is optimum for developing facets in a fracture test, i.e., oil quenched and tempered for 1 hour at 600°C. for alloy steels and 200° C. for a mild steel. For this reason, this etchant is not as valuable as nitrosulphuric acid. Further more it is not very sensitive to the early stages of overheating if the current density is lower than that specified above. The structure appears as a white network in a dark background (Fig. 9.)

b. Effects.

The ductility and impact toughness of a steel are reduced by overheating, but the tensile strength is not affected except when it is severely overheated. That fatigue strength of a steel is lowered. Premature failure in aeroengine components, such as connecting rods, has been attributed to overheating during forging.

The austenitizing temperature above which the symptom of overheating appear after suitable heat treatment is known as the overheating temperature. It varies from steel to steel, even from one heat to another for a steel of the same specification, but it normally lies above 1200° C. There are indications that the overheating temperature decreases when the carbon content of the steel is increased.

The overheating temperature of a steel is lower and hence the susceptibility to overheating is higher, the fewer the inclusions. Probably for this reason, electric steels generally have a lower overheating temperature than open hearth steels. The overheating temperature can be raised by drastic quenching or very slow cooling from the high temperature, and by the use of less sensitive tests. For instance, the overheating temperature determined by nitro sulphuric acid etch is slightly higher than that by ammonium nitrate etch or fracture test. Therefore it can be determined only for a set of fixed conditions, including the technique of etching and repolishing.

The only effective methods of reclaiming the steel known at present are:

1. Reheating the steel to the original heating temperature, followed by cooling at a rate not greater than 3°C. per minute through the overheating range.

2. Repeatedly austenitizing the steel at successively lower temperatures at 100—150°C intervals.

The properties of an overheated steel can be improved by repeatedly normalizing, but no full recovery is possible without the above treatment.

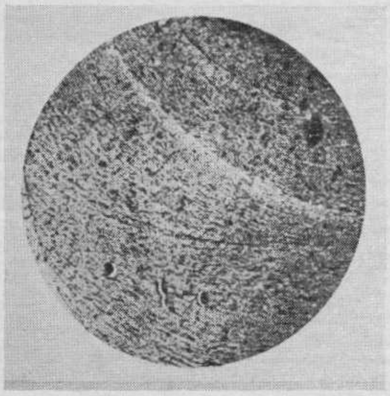

Fig. 1

Fracture of a En25 steel (0.3%C, 0.014%S, 0.64%Mn, 2.5%Ni, 0.6%Cr, 0.6%Mo) in the as-rolled condition. x 4.

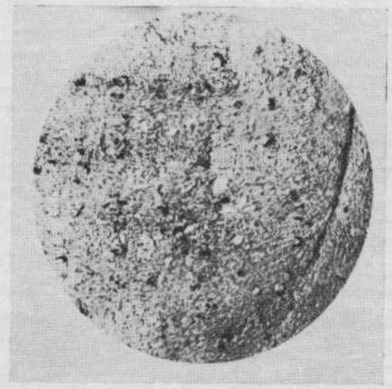

Fig. 2

Fracture of the same steel, heated at 1250°C. for 30 minutes air cooled and heat-treated at x 4.

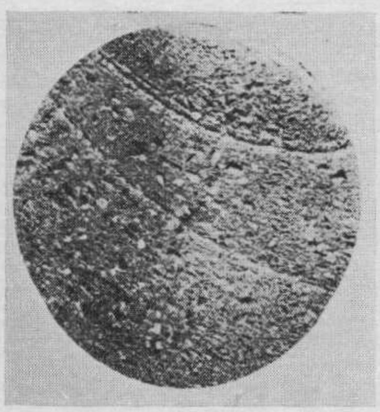

Fig. 3

Fracture of the same steel, heated at 1275°C for 30 minutes air cooled and heat-treated x 4.

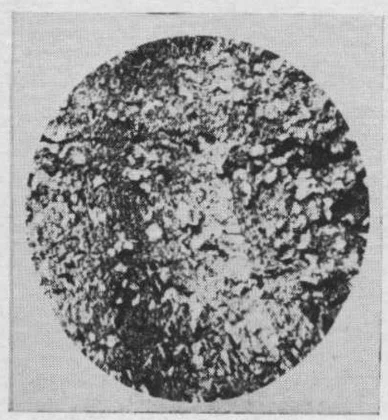

Fig. 4

Fracture of the same steel, heated at 1300°C for 30 minutes air cooled and heat-treated x 4.

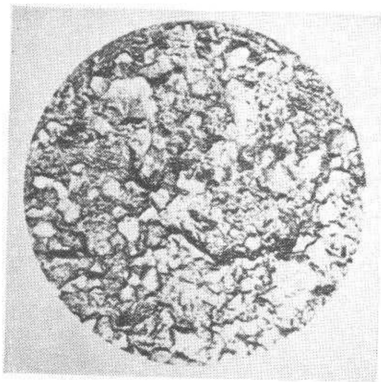

Fig. 5

Fracture of the same steel, heated at 1375°C for 30 minutes. air cooled, and heat-treated. x 4.

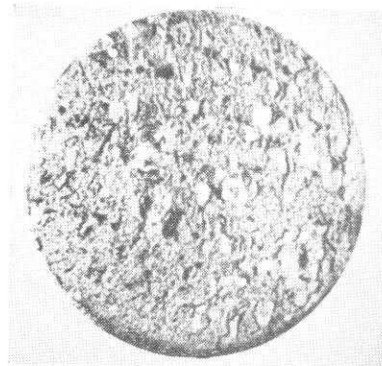

Fig. 6

Fracture of another En25 steel with very similar composition heated at 1350°C for 5 minutes, air cooled, and heat treated. x 4.

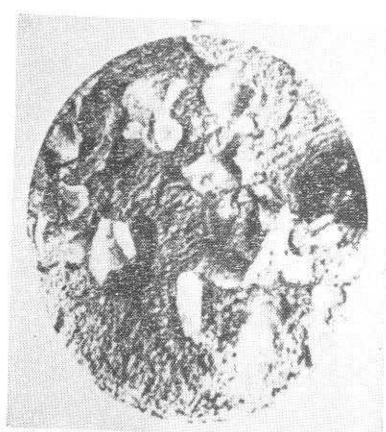

Fig. 7

Fracture of the same steel, heated at 1350°C for 5½ hours, air cooled and heat-treated. x 4.

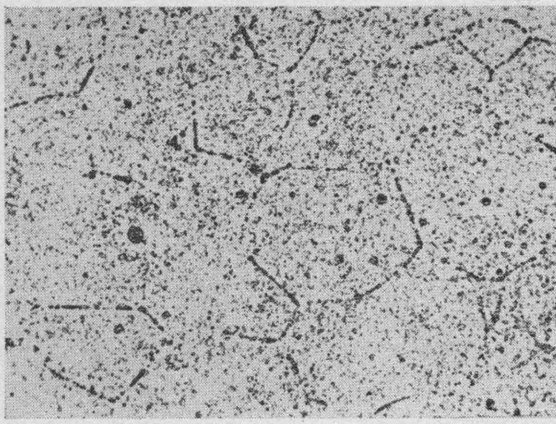

Fig. 8

Overheated steel etched with 10% H_2SO_4 and 10% HNO_3 and repolished. x 50.

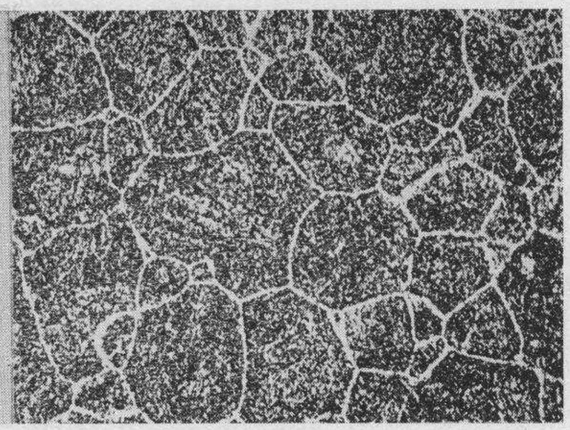

Fig. 9

Overheated steel etched with ammonium persulphate. x 30

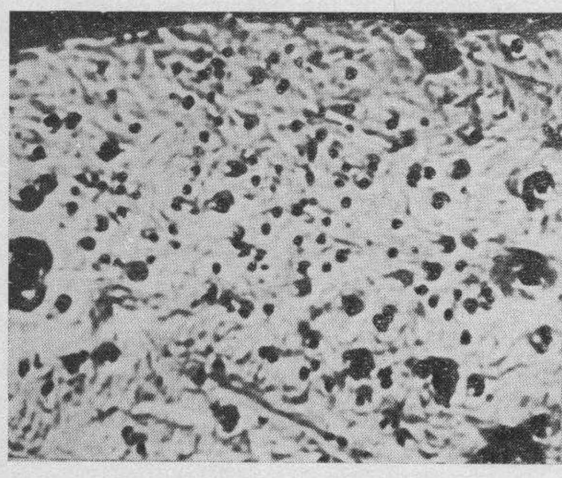

Fig. 10

Sulphide inclusions on the austenite grain interface in a eutectoid steel heated to 1325°C. x 1200.

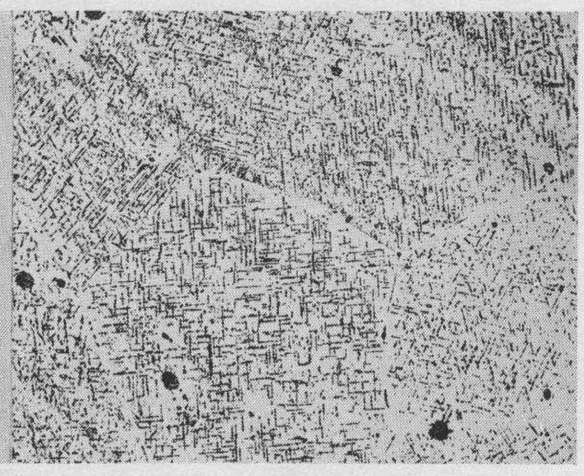

Fig. 11

Widmanstatten precipitation of sulphide in a En28 steel (0.27% C, 0.034% S, 0.36% Mn, 3.8% Ni, 1.7% Cr, 0.5% Mo) heated to 1420°C. Etched with 2% H_2SO_4 in water. x 175.

c. **Causes.**

The appearance of overheated structures occurs when numerous fine manganese sulphide inclusions are observed on the grain interface (Fig. 10), which can be exposed by suitable techniques. These inclusions are too thin to be seen in a normally polished metallographic specimen. Ko and Hanson concluded that the solubility of sulphur in austenite in the presence of manganese increases with increasing temperature. When a steel has been heated to high temperatures, sulphide inclusions are dissolved during heating, and subsequently, during cooling to below the overheating temperature, reprecipitated (*i*) on residual sulphide inclusions, (*ii*) on austenite grain interfaces, and (*iii*) sometimes on (100) crystallographic planes of austenite (Fig. 11), giving rise to a Widmanstatten pattern of sulphide inclusions. The presence of inclusions at the grain boundaries of small curvature weakens the resistance to fracture of these planes and, when the matrix is toughened by suitable heat treatment, the fracture will propagate along these planes of sulphide precipitation. These conclusions have been subsequently confirmed by Irvine. (Journal of the Iron and Steel Institute, London, 1952, Vol. 171, pp. 142—147).

II. BURNING

The term "burning" is misleading as it implies the effect of combustion in air or oxygen. In fact, burning, similar to overheating, is independent of the furnace atmosphere, and can take place even in vacuo.

a. **Symptom**

The burning of a steel is indicated by the presence of a light etching network outlining the austenite grain boundaries, (Fig. 12), when the steel is etched with alcoholic solution of nitric acid, and of a dark-etching network when picric acid is used. The structure in a burnt steel, revealed by etching with nitrosulphuric acid and ammonium nitrate are the reverse of those obtained in the overheated steel, (Fig. 13 and 14). Strings of sulphide inclusions can often be seen along the grain boundaries (Fig. 15), which are covered with a two dimensional network of iron manganese sulphide. The sulphide was precipitated as one component of a eutectic during cooling after burning, (Fig. 16), the other component being iron. Burning can occur at a temperature well below the solidus of an alloy of the same chemical composition but free from sulphur.

b. **Effects.**

The presence of a liquid at the high temperature, as evidenced by the presence of eutectic after cooling, reduces the ductility, and tensile strength, and in severe cases the steel may disintegrate during forging giving fractures of distinctly intergranular appearance.

But the liquid at the grain interface is not necessarily present as a continuous film covering the whole interface. The eutectic at the grain interface in a severely burnt steel is often observed in colonies (Fig. 17), and hot tensile tests made by Winterton of British Welding Research Association on a eutectoid carbon steel (Steel T mentioned in Ko and Hanson's paper) well above the solidus showed that, unlike commercially pure aluminium, considerable ductility remained at these temperatures:

Testing Temperature °C	Tensile Strength Tons per sq. in	Elongation on in.	Reduction in Area
955	4·7	77	99
1302	1·7	76	100
1351	1·2	100	100
1388	1·0	77	88
1397	0·9	24	58

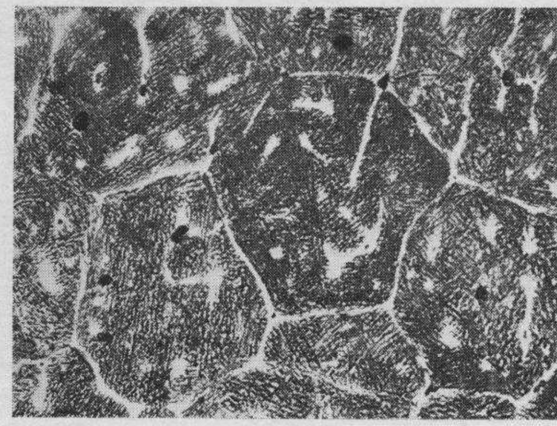

Fig. 12
Burnt steel etched with nital. x 150

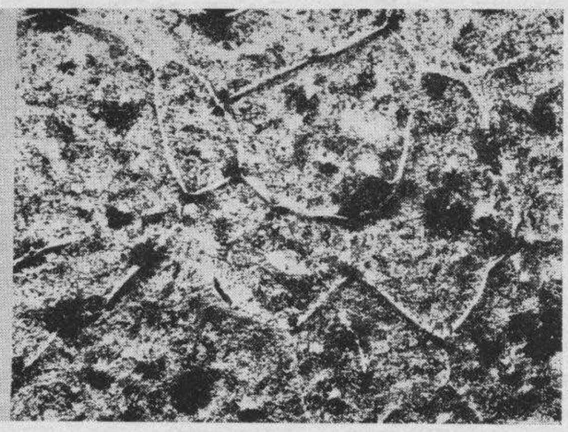

Fig. 13
Burnt steel etched with nitrosulphuric acid. x 30.

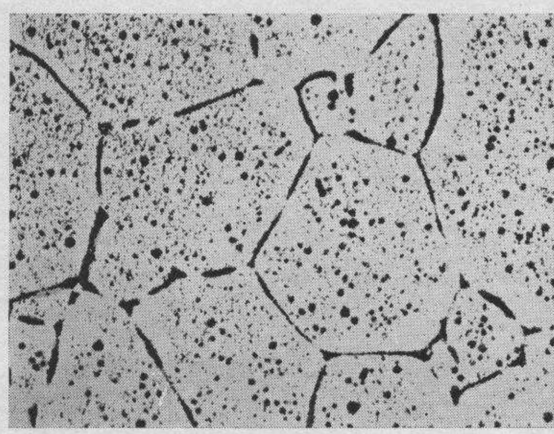

Fig. 14
Burnt steel etched with ammonium nitrate. x 50.

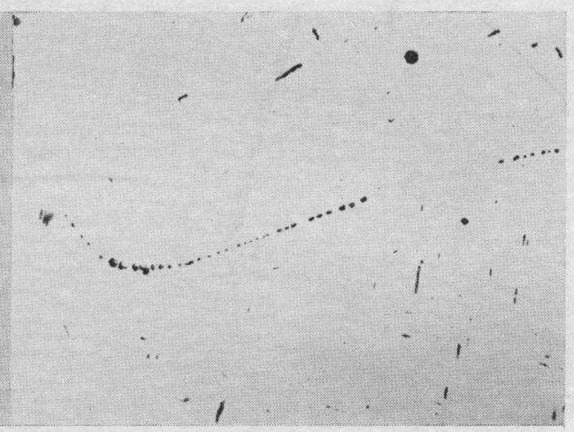

Fig. 15
Sulphide inclusions along the austenite grain boundary in a burnt steel. x 500.

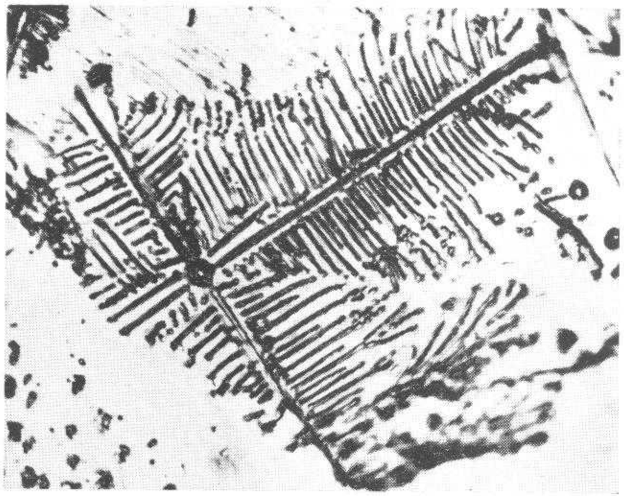

Fig. 16

Sulphide inclusions on the austenite grain interface in a burnt steel. x 800.

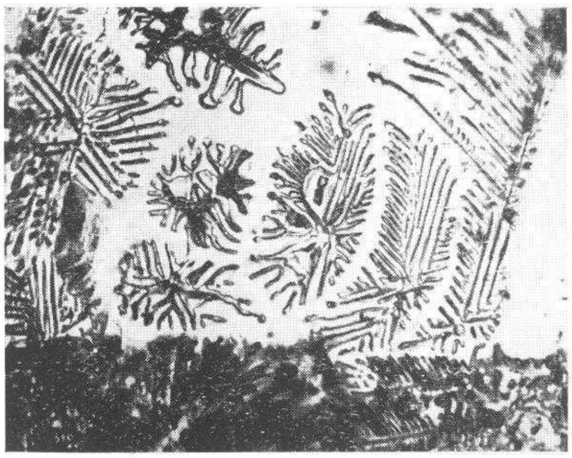

Fig. 17

Eutectic sulphide inclusions on the austenite grain interface in a severely burnt steel. x 300.

It seems that the interfacial tension between the sulphur-rich liquid and the austenite is such that the liquid does not completely wet the grain interface and certain clean regions remain to support the deformation.

The presence of eutectic sulphide at the grain interface severely reduces the ductility, the toughness and the fatigue strength of the steel at room temperature, and renders it useless.

c. **Causes.**

Investigation made with pure materials showed that burning is chiefly associated with the formation of a sulphur-rich liquid at the grain interface at high temperatures. When phosphorus is present as is usually the case in steels, it congregates in the liquid, and, after cooling, gives rise to an iron net-work rich in phosphorus, revealed by the various etching reagents as a network. Burning is normally observed at unexpectedly low temperatures, which had led various investigators to suggest that burning could not be caused by incipient fusion. Ko and Hanson showed that in sulphur-free iron carbon alloys burning does not occur below the solidus, and they suggested that the solidus of the steel has been exceeded when burning takes place, the solidus being lowered by the sulphur dissolved in the austenite.

III. CONCLUSION

From the above summary, it is clear that overheating and burning of a steel can be prevented only by not heating to above its overheating temperature, as it is impossible at present to produce steels in which the sulphur content does not exceed the sulphur solubility limit in austenite of Fe-C-Mn-S alloys, and the use of steels containing a large number of sulphide inclusions is out of the question for high duty components. The only plausible solution, which is at present lacking, is to develop a steel in which the sulphur is fixed with an alloying element which has a much higher affinity for sulphur at high temperatures than has manganese.

Unfortunately, the overheating temperature, owing to the complexity of the precipitation phenomenon, can not be predicted from any chemical, physical or metallographical analysis. In order to forge a steel at the maximum safe temperature, the over heating temperature corresponding to the practice, particularly the cooling rate and the degree of forging, must be experimentally determined for individual heats. If this is found impracticable, then an electric arc steel should not be heated above 1150—1200°C. and an open-hearth steel not above 1200—1250°C, the lower limits being for steels of high carbon, low manganese, and/or low inclusion count. Close control of forging temperature can be achieved only by the use of reliable automatic temperature controllers in a well designed furnace. Care must also be taken that the flame in the furnace is not directly impinging on the steel, and that the temperature of the forging is not greatly raised during the forging operation; both of these precautions are often neglected when the production of forging is accelerated.

ACKNOWLEDGEMENTS

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