

The source of increased carbon content in gas cut steel surfaces

By F GOLDBERG*

1. Introduction

It is an established fact that carbon migration at the surface of a cut does occur, although as yet there appears to be no complete agreement between investigators as to exactly how this enrichment near the cut surface is brought about. (1)

To mention a few different opinions that have been put forward, Zobel (2) indicates that "the cutting oxygen, which is released at high velocity in the centre of a small acetylene flame, passes directly through the kerf almost without mixing with the surrounding gases. It is these surrounding gases that fill the kerf after the passage of the oxygen stream that might be supposed to carburize the edge of the steel while it is still heated above the critical temperature". Seymour Semper (3) states that "tests on mild and carbon steel have shown what appears to be a tendency towards migration of carbon to the cut surface. The surface itself shows an increment of carbon while just below a narrow decarbonized band is to be found. It is thought that carbon may migrate from relatively colder metal to hotter metal. Possibly, too, under some conditions of reaction there may be a pick-up of carbon from metal oxidized in or removed from the kerf. That the surface carbonization cannot be attributed to the pre-heat flame is proved by the fact that the effect is the same either with coal gas or such carbon rich gas as acetylene".

In an article entitled "Transformations and reactions in the heat affected zone during the welding and oxygen cutting of steel" a summary of the problem is given by Professor Jurgen Ruge. (4) He mentions the following possibilities :

* Mr. Goldberg is with the Royal Institute of Technology (Dept. of Welding Technology) Stockholm, Sweden. This document of commission I of International Institute of Welding is being published with permission of the author and IIW.

- (a) Carbon diffusion from central regions to areas at the edge of the plate.

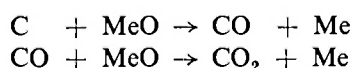
If this assumption is correct, then a reduction in the carbon content at some distance from the surface of the cut would result. As, however, no such reductions could be observed, this hypothesis is probably incorrect.

- (b) Carburization due to the cutting flame.

In this case the replacement of acetylene by, for example, hydrogen for the preheating flame should have the effect of preventing carburization. In actual fact, however, it has been proved that, even when hydrogen is used as the heating gas, a considerable degree of carburization takes place (5). As, however, no carburization has been observed as a result of the oxygen cutting of carbonfree iron, the carbon cannot originate from the cutting flame. On the contrary, it is known that the carburization of the outer case increases with the increases in the carbon content of steel (6). Finally, it was found that carburization took place even when the heating flame was dispensed with altogether and the plate was pre-heated to ignition temperature from the reverse side of the plate.

- (c) The restriction of the oxidation of carbon.

When a metal or its constituent elements are oxidised, an oxide skin is formed between the metal and the oxygen which then divides the two reacting elements from each other. In the case of steel, the oxidation of carbon takes place at the phase boundary steel/wustite. A noticeable diffusion of carbon through the oxide film is considered impossible, whereas a diffusion of iron through the oxide film is unlikely. The reaction of oxygen with carbon in accordance with the formula



can only progress if the gases formed can escape. If this is not the case, the reaction comes to a halt and a carbon pick-up in the surface area results. The fact that during the formation of scale, albeit at lower temperatures, at the commencement of the oxidation process, noticeably less carbon is oxidized than would be expected with a uniform oxidation of iron and carbon, has already been noted elsewhere (7). The validity of this mechanism with regard to the problem discussed should be proved by further experiments.

2. Testing Methods

The aim of the investigation was to try to find out the origin of the carbon that carburized the surface of the oxy-acetylene cut and to elucidate the possible mechanisms involved.

The method employed was to cut a piece of steel treated with radio-active carbon-14. The steel was designed to have the same properties as the common ship-building steels SIS 1411. The steel for the experiment was made at the Swedish Institute for Metal Research, Stockholm, by melting together the pure constituent elements in a high-frequency furnace. The composition of the steel was :

0.15 % C	0.04 % P
0.25 % Si	0.03 % S
0.70 % Mn	

To this was added 0.5 mC radio-active carbon equivalent to 6 milligramms of carbon. The weight of the total charge could not be made larger than 300 grams due to the risk of contaminating the furnace.

When the different ingredients had melted together, they were poured into a casting with the dimensions 20 × 30 × 70 mm. (fig. 1). The casting was then treated in a rolling mill at the Swedish Institute for Working of Metals, KTH, Stockholm. It was rolled four times and was reduced to a thickness of 4.8 mm. After rolling, one side of the steel plate was ground free from mill scale and straightened. The steel plate then was cut in a hand-cutting machine, being kept, during this operation, inside a box of perspexglass. The box was filled with argon gas at 2 atmos pressure in order to eliminate the influence of CO₂ from the air in the room and its possible participation in the chemical reactions when the steel was being cut.

The cut was made with the AGA nozzle JMN-00, under acetylene pressure of 1.1 atmos and oxygen

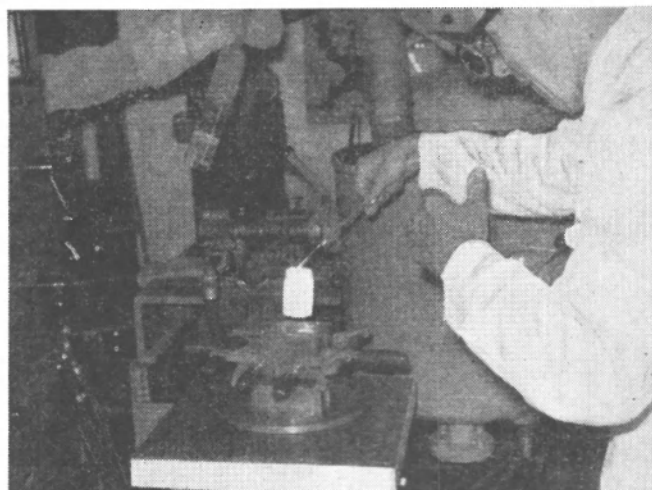


Fig. 1.

pressure of 4 atmos. The speed of cutting was approximately 600mm/min.

When the cut was completed, two pieces were taken out and prepared for microscopic studies. Piece No. 1 was cut out perpendicularly to the kerf and piece No. 2 was cut out at an angle of 10 degrees to the kerf (fig. 3).

Afterwards, the two pieces were polished and placed on top of very fine grained film. The radiation from the carbon-14 isotope exposes the film. To get the films sufficiently exposed, they had to be subjected to an exposure time of three weeks. If a coarse-grained X-ray film had been used, an exposure time of 12 to 18 hours would have been enough. The use of a very fine-grained film allowed the image to be studied microscopically after exposure.

3. Results

3.1. Autoradiography

Figures 5 and 6 clearly show a carbon concentration at the surface of the cut. This indicates that the carburized edge contains carbon which comes from the steel itself and not from the acetylene.

When studying in the microscope the film exposed to radio-activity, it was not possible to observe a zone behind the carburized edge which was lighter than the original material. This indicates that there was no carbon diffusion from central regions to the areas at the edge of the plate. The carbon must have come from the material that was burnt off in the kerf (see fig. 7).

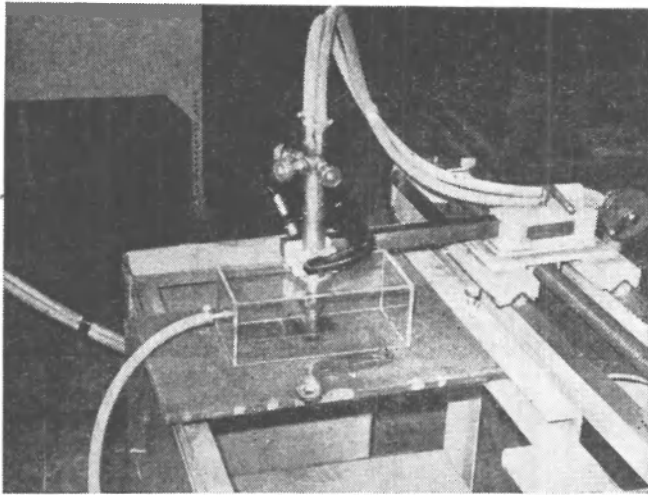


Fig. 2. Picture taken just after the cutting operation was completed.

Fig 5 also shows that the carbon concentration increases towards the bottom of the cut, which was also observed by Miller in 1925.

The picture further reveals that there was no carbon migration at the very top of the kerf. In fact, when comparing the autoradiographic picture and a metallographic picture, it is found that a small area near the top is missing on the autoradiographic picture. This indicates that the area has been decarburized and this is confirmed when the microstructure is studied (Fig. 12). This decarburization is probably caused by the acetylene flame, as it is a known phenomenon that an open flame decarburizes a steel surface. The decarburization of the cut steel plate is also disclosed by the light bands across the piece parallel with the cut (Fig.4). From the autoradiographic picture it is easy to measure the thickness of the carburized zone. It was here found to be approximately 0.04 mm.

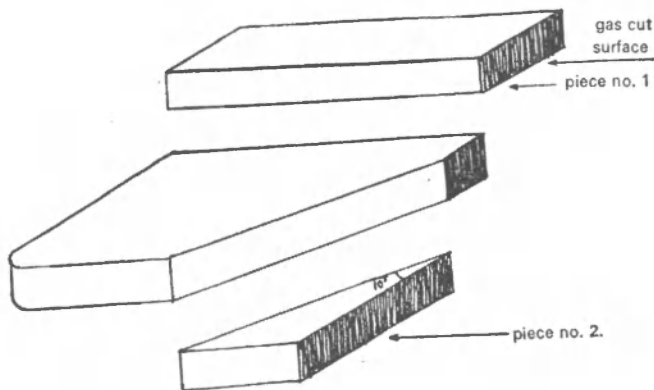


Fig. 3.

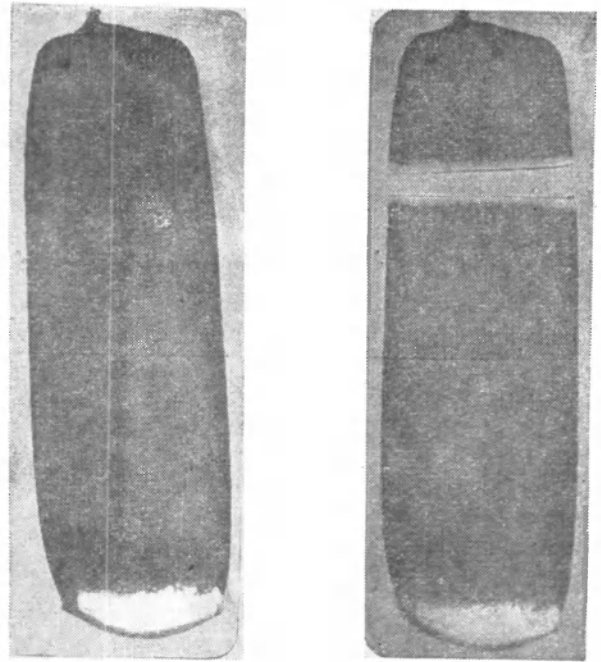


Fig. 4. Autoradiographic picture on X ray film of steel plate before and after the cut. Dark parts show the exposure to radioactive carbon-14. The light area at the bottom is mill scale which the radiation could not penetrate. The exposure time was 18 hrs. scale 1 : 1.

3.2 Microstructure

The original microstructure of the steel plate, (Fig. 8), consists of ferrite and pearlite in a typical band structure. At a distance of 2 mm from the cut surface the microstructure is influenced by the heat from the cutting process and turns into a fine-grained structure (Fig. 9), while at 0.5 mm from the cut surface

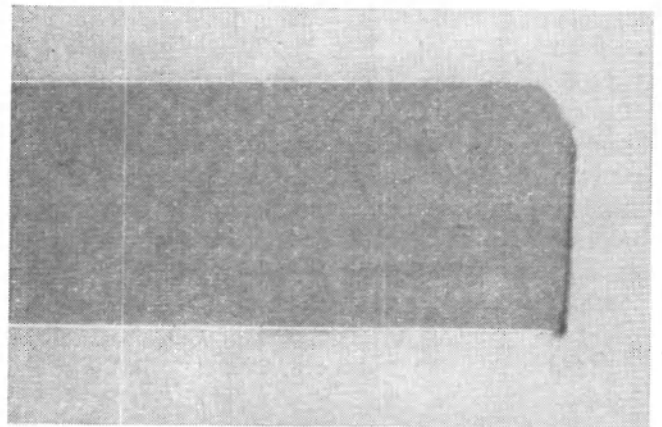


Fig. 5. Autoradiographic picture of piece No. 1 with the cut surface on the right side.

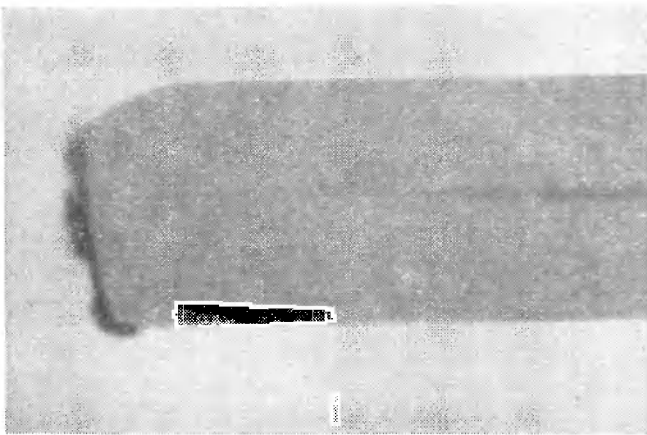


Fig. 6. Autoradiographic of piece No. 2 with the cut surface on the left side.

the pearlite grains grow larger and have grain boundary ferrite and Widmanstatten-ferrite (Fig. 10).

The very thin carburized layer on the cut surface, approximately 0.04 mm thick, has a structure very similar to 100% pearlite (Fig. 10).

Here and there on the lower part of the kerf, a layer of ledeburite approximately 0.015 mm thick has been found on top of the 0.04 mm thick carburized structure (Fig. 11).

The carbon content in the steel was analysed in a carbon analyser type AVECARBON-100, made by Avesta Jernverks AB, and was found to be 0.141% C. From the gas cut surface, a small prism was cut out. The area of the carburized surface on the prism was $2 \times 4.8 \text{ mm}^2 = 9.6 \text{ mm}^2$, and the weight was

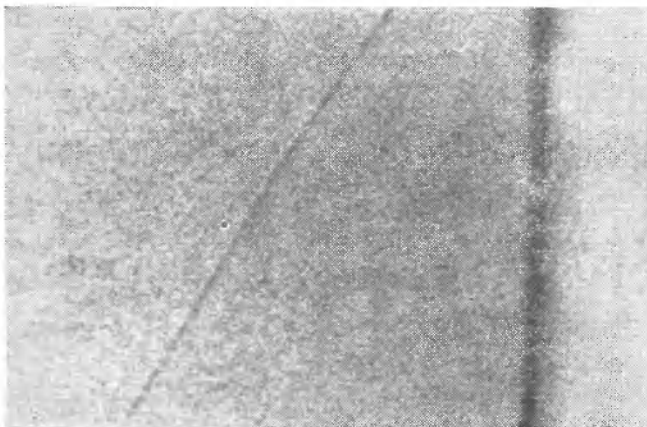


Fig. 7. Microphotograph of film exposed to radioactive carbon in steel; from left to right original material, carburized surface, unexposed film.

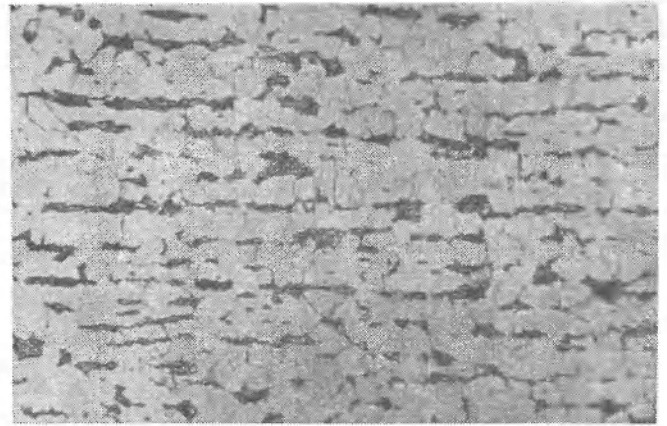


Fig. 8.

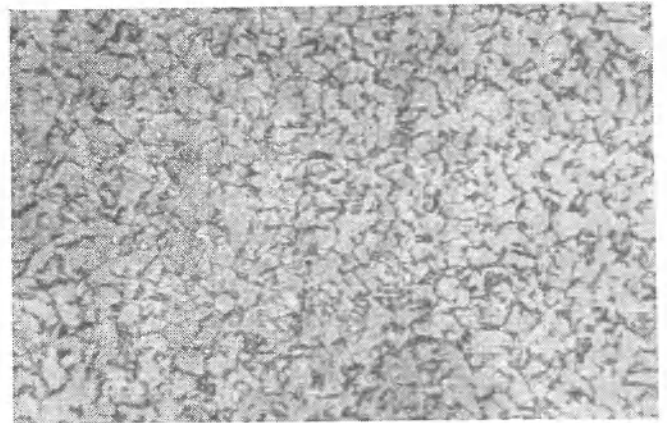


Fig. 9.

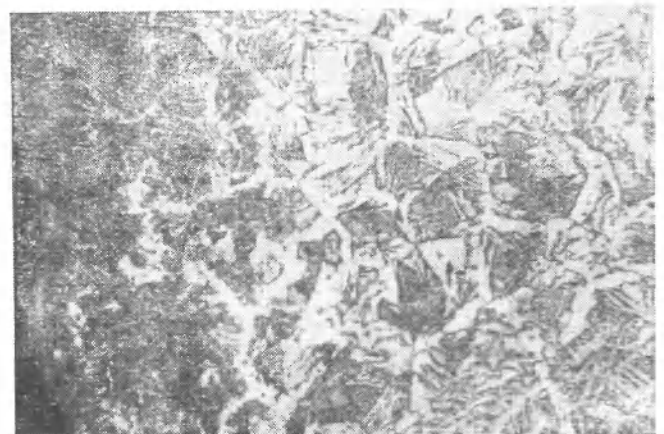


Fig. 10.

0.12 gram. The carbon content in this piece was 0.176% C. This tells us that the carbon concentration in the narrow carburized zone is about 1.5%. This method of estimating the carbon concentration is,



Fig. 11.

however, not very accurate even though the carbon-analyser is accurate to the third decimal. The carbon content in the carburized edge was also analysed with electron microprobe at the Swedish Institute for Metal Research. This method indicated a carbon content well over 2%. These figures were not expected, as 100% pearlitic steel has a carbon concentration of 0.8%.

3.3. *Hardness*

The hardness of steel increases with increasing carbon content and with the speed of cooling. The carbon content on the gas cut surface increases proportionally to the carbon content in the original material. The speed of cooling depends on the speed of cutting and the thickness of the steel. The major part of the heat developed when the iron is oxidised conducts through the steel. This implies that the thicker the steel, the more rapid the cooling of the edge.

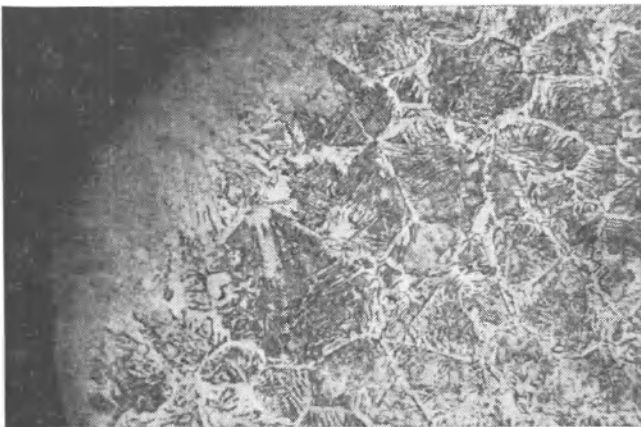


Fig. 12. Ferrite structure to the left due to the decarburization effect.

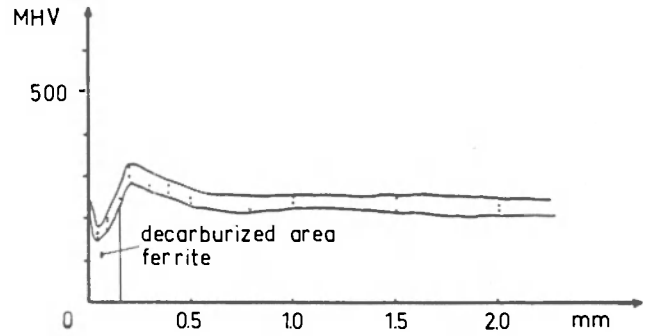


Fig. 13.

A series of hardness measurements has been made with a Reichert micro hardness using a load of 20 gram. The first series of measurements (Fig. 13) was made in the upper part of the cut where the structure was ferritic on the edge (Fig. 12). The rise of hardness 0.15 mm from the edge is perhaps a quenching effect resulting from the heating flame.

The second series of hardness measurements (Fig. 14) was made in the middle of the cut. The diagram reveals that the hard structure has approximately the same thickness as the carburized layer, which is logical having regard to the facts mentioned above.

The unaffected original structure had an average hardness of 218 MHV and the martensite layer had a hardness of 750-650 MHV.

3.4. *Carburizing mechanism and discussion*

The results obtained indicate that carbon originates from the steel itself and from the material which is destroyed during the cutting operation. It is also observed that the concentration of carbon increases towards the bottom of the kerf, where a very carbon-

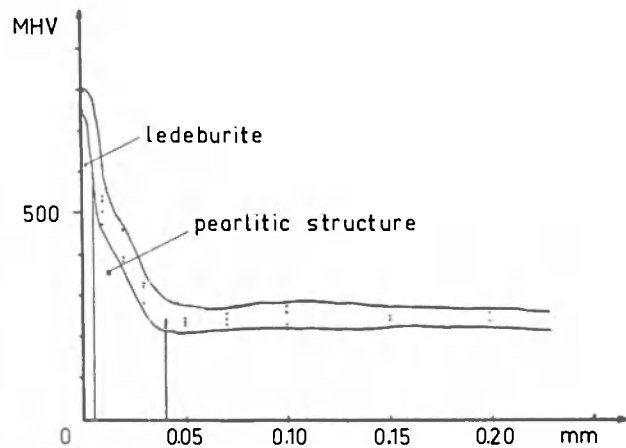


Fig. 14.

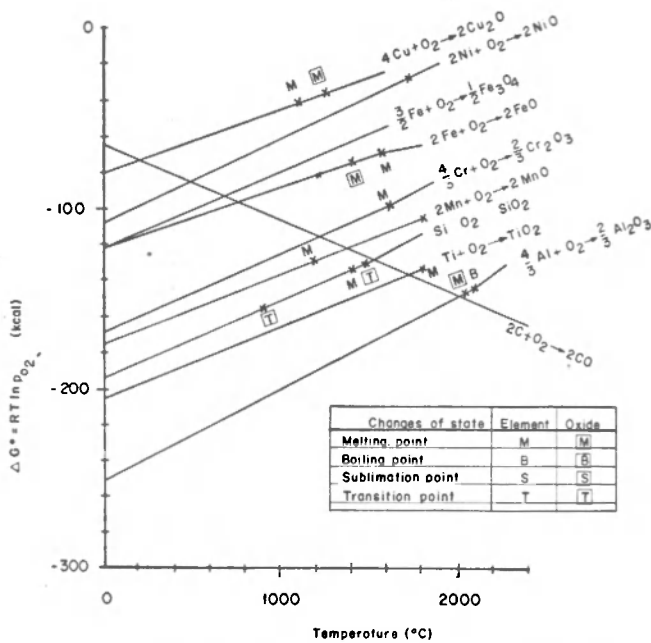


Fig. 15. Standard free energy of formation of oxides as a function of temperature.

rich drop is often found suspended. How is this carburized material produced?

When steel is gas cut, not only carbon is enriched in the cut surface but also nickel and copper (8, 9). This is because the oxygen jet causes a selective oxidation of the steel. The selective oxidation is explained by Gibbs' diagram of free energy of formation of oxides as a function of temperature (Fig. 15). The diagram shows that curves of Ni and Cu lie above the curves $3/2 \text{Fe} + \text{O}_2$ and $6 \text{FeO} + \text{O}_2$, which means that iron is more easily oxidated than the other metals mentioned above.

When the preheated iron is oxidated, FeO is found in a liquid state (melting point 1420°C) due to the heat liberated by the reaction. As carbon is insoluble in liquid FeO, the carbon is forced into the iron behind the FeO layer giving rise to the carbon concentration. It is interesting to note that the transition zone between the carburized material and the heat affected zone is rather sharp. If the carbon had diffused into the steel one would expect a transition zone with a slow reduction of the carbon concentration.

The sharp transition zone is explained by the fact that a thin iron layer just behind the FeO layer also becomes liquid (melting point 1535°C) owing to the heat released by oxidation. The carbon diffuses easily and quickly into the liquid iron but stops when it

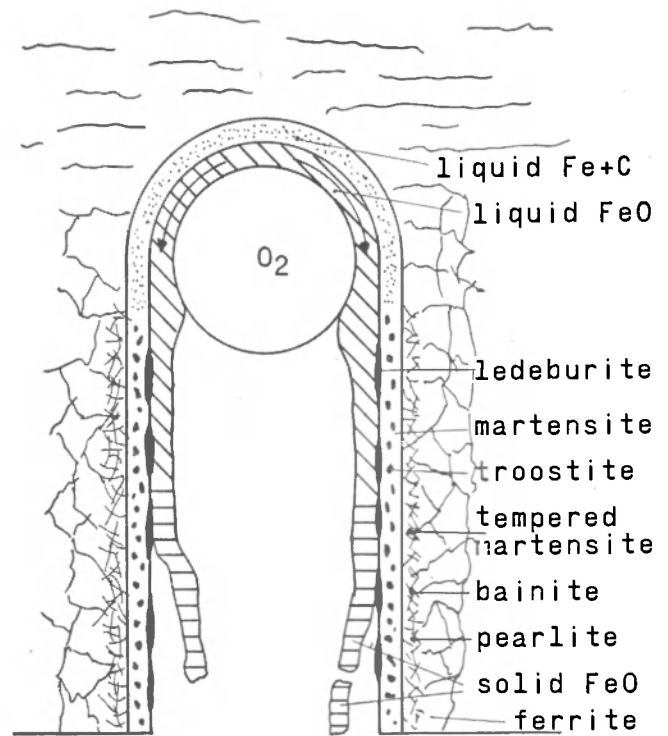


Fig. 16. This figure is an attempt to describe the oxygen cutting process. The oxygen jet oxidises the preheated iron forming different iron oxides in a liquid state. Most of the oxides are blown away by the jet action, thereby forming a cut. But on the sides of kerf there is always a thin layer of oxides which after solidification falls off by itself, while the layer of liquid iron and carbon solidifies; layers (0.015 mm) of ledeburite are formed in the lower parts of the kerf.

reaches the solid steel. This means that the carburized edge is mainly formed in a narrow band of liquid iron. This also explains why we often get carbon-rich drops at the bottom of the kerf (Fig.5). Part of the liquid Fe+C is transported down the kerf by the jet action of the oxygen, giving the cut surface an increasing carbon content with the depth. This is also the reason why there is almost no carbon at the top of the kerf.

In Gibbs' diagram (fig. 15) the carbon line crosses the 1500°C line below the iron oxidation lines which should indicate that the carbon should oxidise easier than Fe. If this really is the case, a carburization effect should not result. The explanation why the carbon oxidation does not follow the Gibbs' diagram is that the carbon monoxide cannot nucleate. The same occurs in a blast furnace where the CO is formed only along the walls of the furnace where it can nucleate, and not in the middle of the melt. An attempt to explain the cutting operation is done in fig. 16.

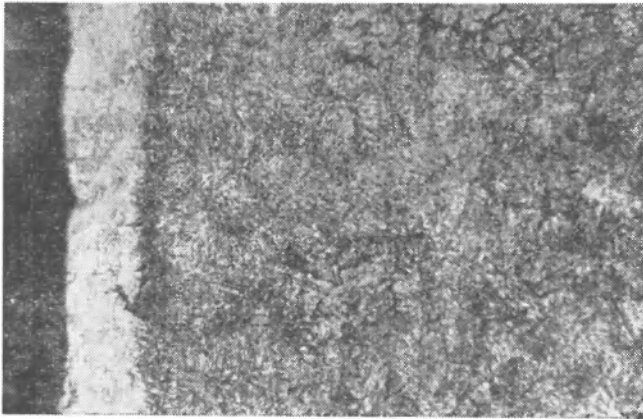


Fig. 17.

Because of the carbon concentration in the liquid iron ($\sim 2\%$ C) we get a structure which is very similar to cast iron, and, in some places, ledeburite formed when the carbon-rich liquid iron solidifies. The amount of carbon on the edge is proportional to the carbon content in the steel. In the specimen studied, there was a carbon content of 0.15% and there was more than 2% C on the cut surface. An amount of 4.3% was found in the ledeburite spots in the lower part of the cut, probably due to the higher carbon content mentioned above.

If steel with a higher carbon content is cut, it is possible to get a ledeburite structure (9) which indicates that the cut surface has more than 4.3% carbon.

The steel piece in this investigation containing radioactive carbon was a small, only 5 mm thick, plate. When cutting this piece, the cooling conditions are not the same as when cutting a thicker piece. Therefore, the micro-structure of the gas cut edge varies with different thicknesses. Fig. 17 shows the micro-structure in a plate 18 mm thick with approximately the same analysis as the radioactive steel plate.

The microstructure also strongly depends on the analysis of the steel. Fig. 18 shows the microstructure of a St-52-3 steel which is very different from the earlier mentioned steel. St-52-3 has the following analysis: 0.18 C, 0.47 Si, 1.40 Mn, 0.01 Cr, 0.02 Ni, 0.025 Nb, 0.008 Al.

Research is now being carried out at the Department of Welding Technology, Royal Institute of Technology, Stockholm, on the practical effects of the gas cutting of steel surfaces.

4. References

1. W. Spraragen and G. E. Claussen—Oxygen cutting of steel—Supplement to the Journal of the Am. Weld. Soc., July 1939, p. 230.

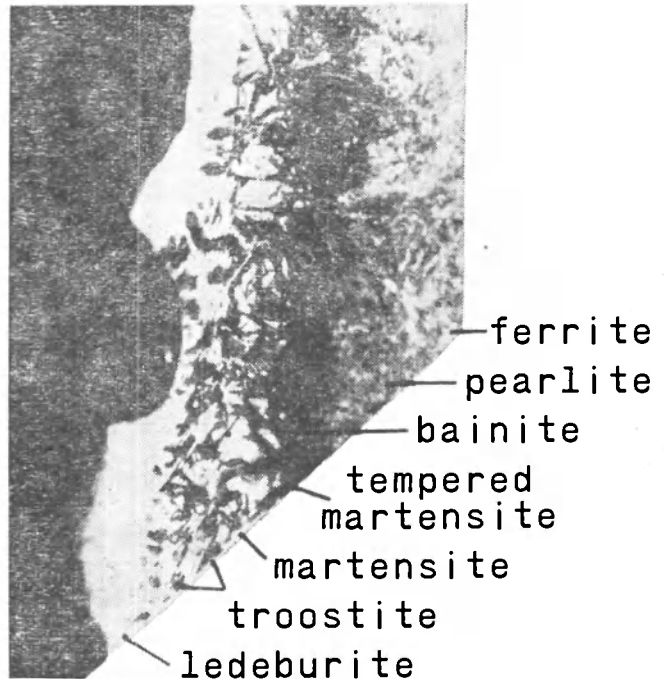


Fig. 18.

2. Theodor Zobel, Dr.—Increasing the Speed of Flame Cutting with New Forms of Blowpipe Nozzles—Verein Deutschen Ingenieure Abstract, Metall Progress 32, No. 1, p. 68, July 1938.
3. Seymour Semper—Oxygen Cutting—1948.
4. Jurgen Ruge—Transformations and Reactions in the Heat Affected Zone during Welding and Oxygen Cutting of Steel—Welding in the World, vol. 4, No. 3, 1966, p. 152.
5. V. Hofe, H. and H. Wirtz—Beitrag zur Klarung der Aufhartung der Schnittflächen beim autogenen/Contribution a l'explication du durcissement des faces de coupe au cours de l'oxycoupage—Fachbuchreihe Schweißtechnik/Collection de publications sur la technique du soudage, Vol. 23, DVS-Verlag 1961.
6. A.N. Chachkov, O. Ch. Spector and G. A. Assinovskaia—Colloque sur le coupage thermique +Assemblée de l'IIS 1965+Influence de l'oxycoupage sur le metal des bords de la section.
7. K. Bohnenkamp and H. J. Engell—Arch. Eisen-huttenwesen 33, 1962, p. 359-367.
8. James R. Cady—The metallurgical Effects of Oxygen Cutting on Steel—Supplement to the Journal of the Am. Weld. Soc., Sept. 1940, p. 340.
9. Goran Almquist—Metallografisk undersökning av snittkanten vid acetylen-syrgasskärning av St. 37 S och St. 52 S.