The Origin of "Light Area" in Upset Welds of Rolled Carbon Steel

A decarburized zone can exist at the weld line of resistance butt welds, particularly upset welds, but it can also occur in some flash welds

BY J. ŽÁK AND P. RYŠ

ABSTRACT. Light etching areas of certain metallographic structures may be observed at the weld line of some resistance butt welds in carbon steels. This distinct form exists mainly in upset welds of rolled carbon steel wires; however it can occur in some flash welds.

Several theories exist explaining the origin of this metallographical defect that deteriorates weld joint properties, but none has been proved directly by experiments. Both the nature of the light area and the mechanism causing the specific structure were the objects of our investigation.

Rolled wire of "C54" grade (0.54%C), 5.5 mm in diam., was employed in the main experiments. The existence of a decarburized zone was proved by two different methods: quantitative structure analysis and X-ray microanalysis.

The weld zone is deprived of carbon during upsetting because the metal is heated in the neighborhood of the weld line above the solidus line (thus partially melted) and the carbon-rich liquid phase is extruded out of the weld.

Both authors are associated with The Czechoslovak Academy of Science, Institute of Metallurgy, Brno, Czechoslovakia.

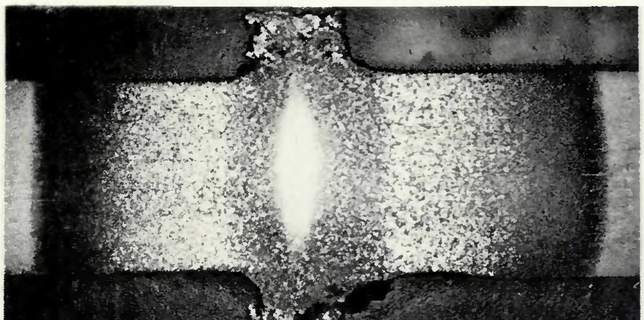
Introduction

The structure of resistance butt welds differs considerably from that of fusion welds because of the absence of weld metal. The weld itself is limited to the nearly imperceptible weld line where the crystals usually grow across the interface securing the perfect connection of both parts. The weld joint structure depends mainly on the structure of the heat affected zone. When compared with fusion welding, the metallurgical problems of the resistance butt welding cannot be considered as serious ones. However, there exist some metallurgical defects and structure anomalies the origin of which are not yet quite clear.

One of such defects is the light etching region ("light area") existing mainly in the resistance butt welds of carbon steels. In the upset welds of steel wires it usually has a lenticular shape not more than 1 mm wide (Fig. 1a); in flash welds its width is usually smaller and uniform through the whole weld interface (Fig. 1b).

The existence of the light area has been known for years; metallographic pictures of the upset and flash welds with this anomaly have been published[1] without any attention having been paid to it; it was introduced even as a harmless characteristic sign of a resistance butt weld.[2] However, our own experiences are different; the light area can considerably decrease both the static and the fatigue strength of welds, and unfavorably influence the drawing process in the steel wire production.[3, 4]

The assumptions about the origin of the light area in the upset and flash welds can be divided into three groups. In the first group, there are works explaining the increased content of ferrite in the light area as the result of oxidation[6] either directly by the oxygen from air[2] or by the oxide layer which covers the weld interfaces.[5] However, these theories cannot sufficiently explain the lenticular form of the light area existing in the upset welds of steel wires, since the greater extent of decarburization can be expected at the periphery of the weld, not in its middle area. As far as the diffusion processes conditioning decarburization are concerned, there



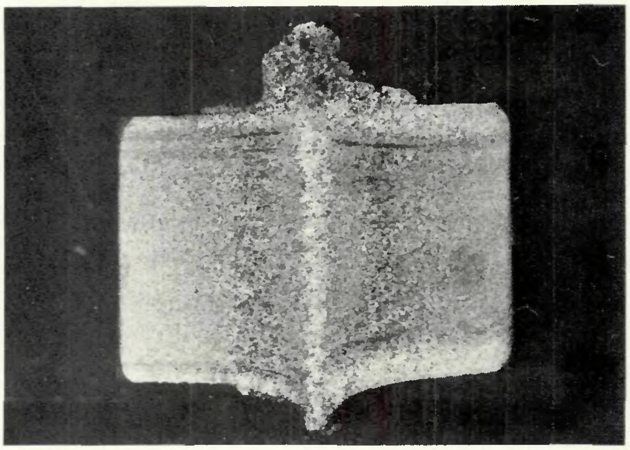


Fig. 1—Light area in: (above) upset weld of ϕ5.5 mm rolled steel wire (0.54%C). Mag: 4X; nital etch; (right) flash weld of ϕ19 mm wrought steel bar (0.15%C) overheated on welding. Mag: 1.5X; nital etch

is not time enough to create the usually observed width of the light area in such a short welding time interval.[5]

Others suggest that the light area has to be considered as a morphological phenomenon. Zitnansky[7] showed that because of overheating and a thermal gradient existing in the weld area, not decarburization but a carbon content increase is to be expected. He is supposing that the ferrite at the weld line can be oversaturated by carbon as the result of the perfect homogeneization of austenite at high overheating temperatures plus a quick cool down; the author also refers to the earlier work of Hrivnák[8, 9] who found an extraordinary fine dispersion of the carbide phase in resistance welds. The opinion that the light area is not decarburized (being of different morphology only) is experimentally well based.[7, 10]

The last group is represented by opinions stating the weld zone is really decarburized as a result of the liquid phase extruded out from the contact area to the fin.[2, 11, 12] In harmony with the distribution coefficient the liquid phase contains more carbon than the coexisting solid phase which cannot substantially change its position during upsetting. The theory of light area decarburization caused by extruding the portion of carbon rich liquid phase out to the fin seems to be very suitable; it has not yet been proved by direct experiments, but rather persuasive experiments have been carried on by Böckenhoff.[12]

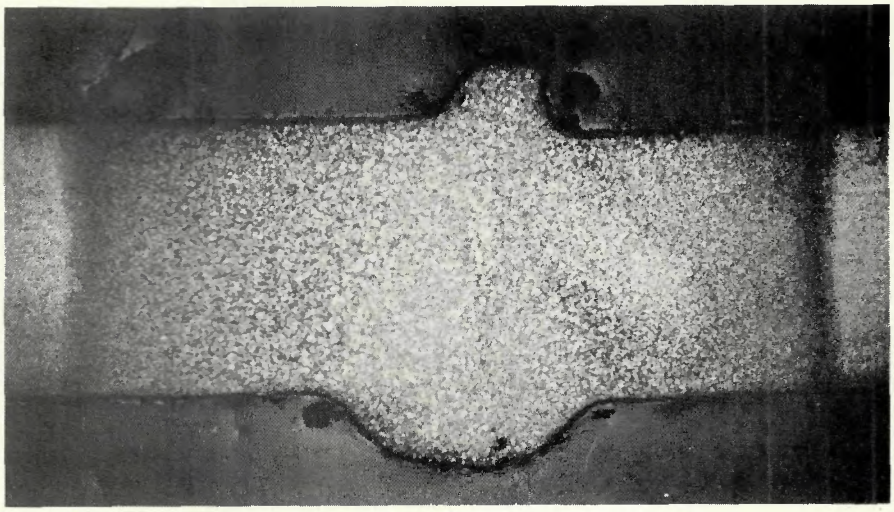
The aim of this work is to show that the light area is either a mere morphological phenomenon that arises as the result of high overheating of the weld zone and its quick cooling down or an area depleted of carbon and to explain which mechanism of decarburization is in action.

Experimental Procedures

For the study of the origin of the light area we have chosen the rolled wire of Φ 5.5 made of steel "C54" grade having the following composition: C, 0.54%; Mn, 0.44%; Si, 0.25%; P, 0.032%; S, 0.025%. The experimental upset welds were prepared by resistance butt welding on the "Schlatter" machine, MN type. Welding conditions favorable to the origin of the light area were set at the value of open-circuit voltage equal to 1.9 v and the welding time from 0.5 to 1 sec (Table 1).

The appearance of the welded samples is evident from Fig. 2.

For the purpose of unambiguous elimination of any possible oxidation effect, two sets of samples 200 mm long with a shallow circumferential



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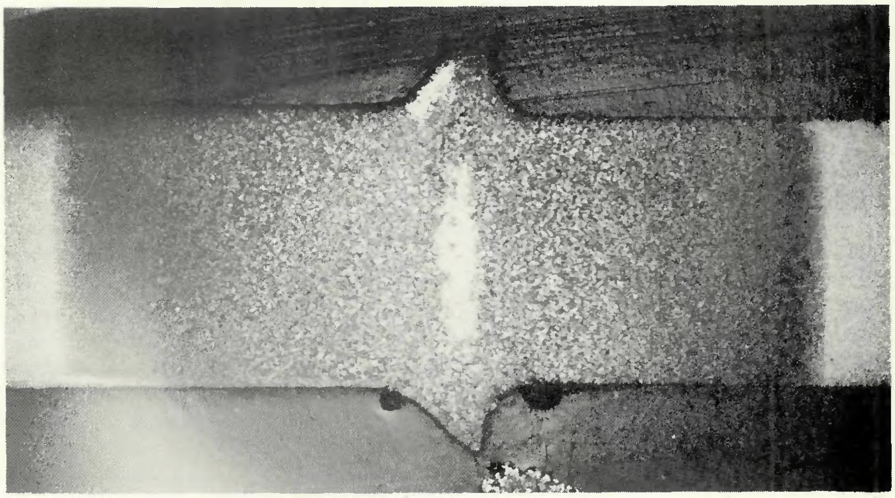

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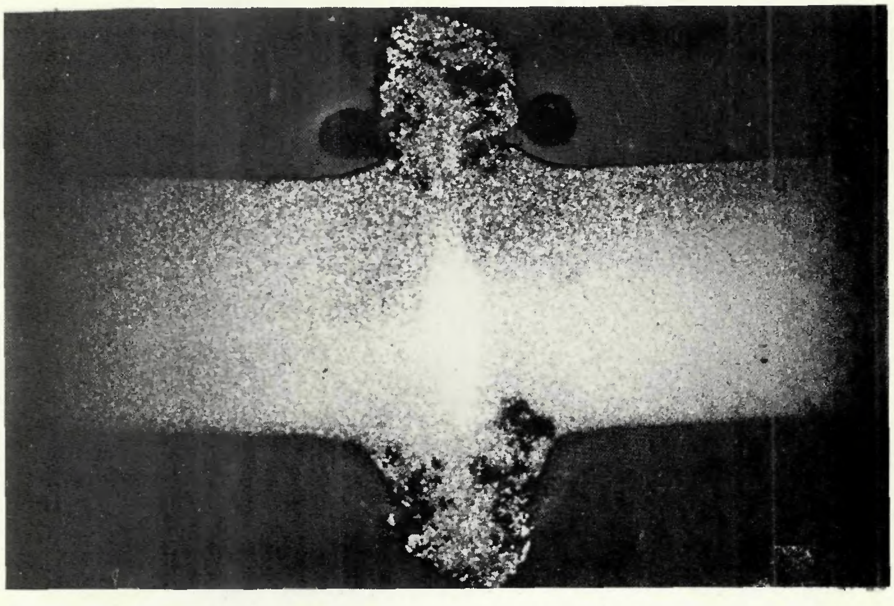

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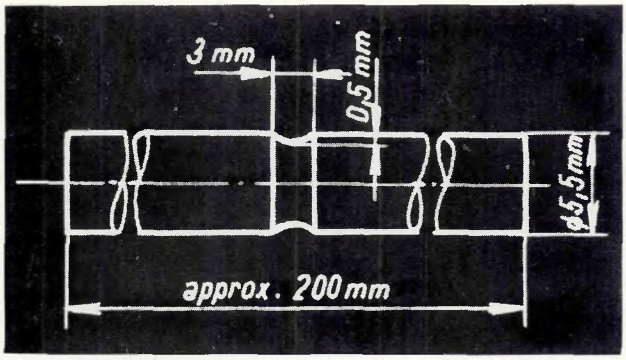
Fig. 2—Effect of upset pressure on light area size (a) weld N°C54-97, 0.25 kp/mm^2; (b) weld N°C54-50, 0.65 kp/mm^2; (c) weld N°C54-55, 1.0 kp/mm^2. Mag: 4X; nital etch



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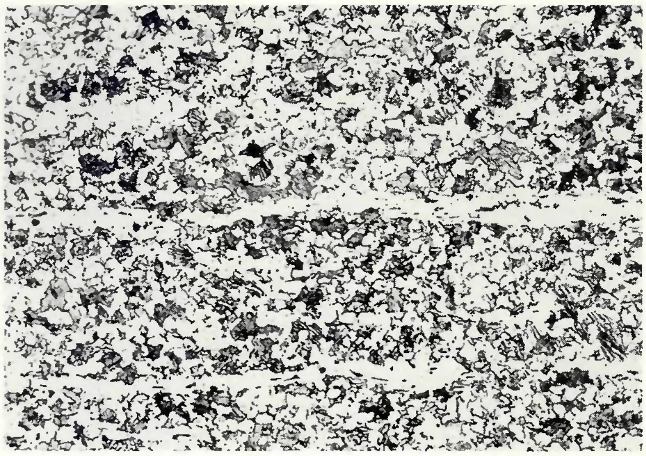
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Fig. 3—(a) Dimension of grooved one-piece sample; (b) microstructure of C54 rolled steel wire. Mag: 250X; nital etch

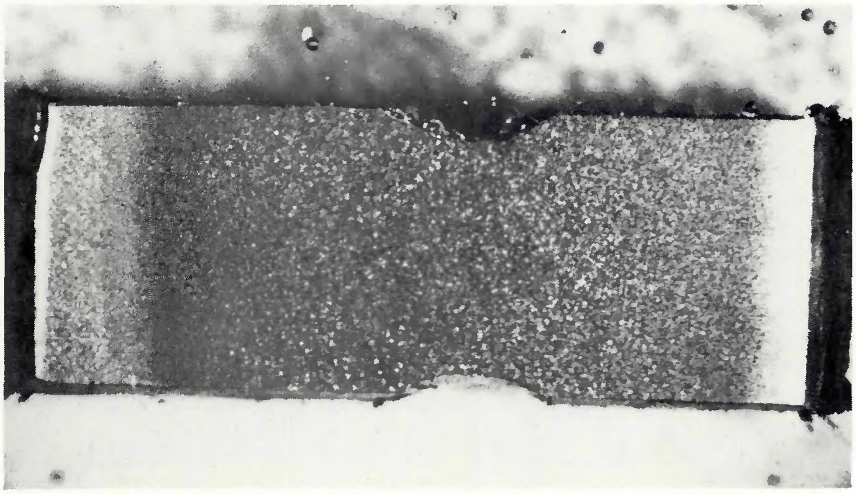
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Fig. 4—Grooved sample after simple heating cycle (no upset force was applied). (a) Macrostructure (5X, nital; (b) microstructure of overheated zone (250X, nital)

groove ground in the middle of this length were prepared (Fig. 3a). In all cases, the samples had fine grained structure of ferrite and pearlite showing a prominent banding (Fig. 3b). All the samples were locked into clamping dies of the welding machine (the groove amidst the dies). The first set samples were merely heated till the partial melting of the groove surface was noticed; no upset force was applied, the movable platen being not released. The second set samples were clamped in the same way but the movable platen was released; thus the conditions fully met those of the real upset welding and simulated upset welds were obtained.

In the first case of merely heating, the secondary grain of the groove zone has become coarse due to overheating (Fig. 4b), but no light area was found at any heating condition (Fig. 4a). In the second case (after heating and upsetting) the samples had exactly the same appearance and structure as the actual upset welds; the "fin" has been created in place of the previous groove and in the middle of the sample we could find the distinct light area (Fig. 5a). Besides a considerably coarsened grain, the microstructure shows also the presence of the ferritic network at the austenitic grain boundary and locally even a Widmannstätten structure (Fig. 5b).

For exact determination of the carbon content in the light area, first of all the method of quantitative structural analysis was used with automated quantitative television microscope (QTM) made by Metal Resarch, Cambridge. The portion of ferrite and pearlite in the areas of 0.32 by 0.4 mm has been evaluated at a magnification of 700 times (on the monitor). As the equilibrium nonditions cannot be supposed to be achieved after a quick cool down, the grooved samples subjected to the imitated welding cycle were heat treated before analysis. Good results were obtained by double annealing of samples sealed in thin-wall quartz tubes and inserted into a heated laboratory furnance. The samples were first annealed at 870C for 15 min and cooled by blowing air (10 min); the second annealing followed at the same temperature (5 min) and cooling down in the switched off furnace at the cooling rate of 200C per hour.

After heat treatment, the banded structure of the base material (Fig. 6a) was comparable with the structure of the original material (see Fig. 3b). In the center of the "light area" the portion of pearlite was considerably lower (Fig. 6b); closely adjacent the amount of pearlite was higher (Fig. 6c). In these areas, the portion of ferrite and pearlite has been stated quantitatively by five measurements in all cases (Table 2).

Considering that 0.54% carbon corresponds to the mean portion of 62.71% pearlite in the base metal and assuming linear dependence, we can admit the content of 0.46%C in the light area (Φ 53.32% of pearlite) and a content of 0.56% adjacent to the light area (Φ 64.43% of pearlite). In the similar way, we have stated the portion of pearlite and the corresponding contents of carbon along the longitudinal axis of the sample (perpendicularly to the light area) and in the transverse direction (i.e. from fin to fin). Results are presented in Fig. 7.

In spite of the fact that results can be considered as fully proving decarburization of the light area zone, we followed directly the carbon displacement both in the simulated and real upset welds; the method of linear microanalysis and JEOLCO JXA-3A X-ray microanalyser were applied; measurement conditions were as follows: the lead stearate crystal, accelerating voltage of 10 kV and an electron beam about 1 μ in diameter were used; the sample was moving at a speed of 0.1 mm per min. The carbon percentage scale was plotted by using electrolytic iron as standard for a 0% C point. The 1000 sec integrated mean carbon content of the C54 steel was used as the 0.54% C point.

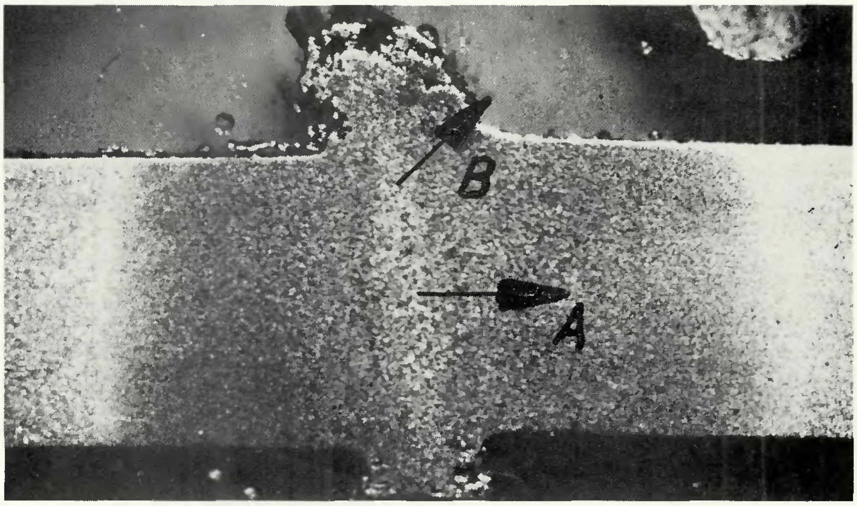
Samples were analyzed in the "as welded" state, without any subsequent heat treatment; they were carefully polished and very slightly etched (1% Nital); the end points of the analyzed zone were marked by microhardness indentations. The analysis was done twice in two different directions, A and B (see Fig. 5a). A graphical record of the carbon and manganese concentration in both directions is represented in Fig. 8.

Table 1—Influence of Welding Conditions on Origin of Light Area

Distance of Clamping Dies, mm	Upsetting Pressure — kp.mm^{-2} — Initial	Final	Upset Travel mm	Light Area	Weld N°	Refer to
12.6	0.25	0.15	2.5	Imperceptible	C 54–97	Fig. 2a
16.3	0.65	0.5	2	Significant	C 54–50	Fig. 2b
18.6	1.0	0.5	4.3	Very significant	C 54–55	Fig. 2c

Table 2—Results of Quantitative Structural Analysis

Area	Amount of Pearlite, % — Measurement N° 1	2	3	4	5	Mean Value
Base metal beyond heat affected zone	62.51	61.62	63.15	64.38	61.92	62.71
Light area	53.62	53.07	53.50	51.84	54.59	53.32
Adjacent to light area	64.93	65.24	63.68	64.75	63.54	64.43



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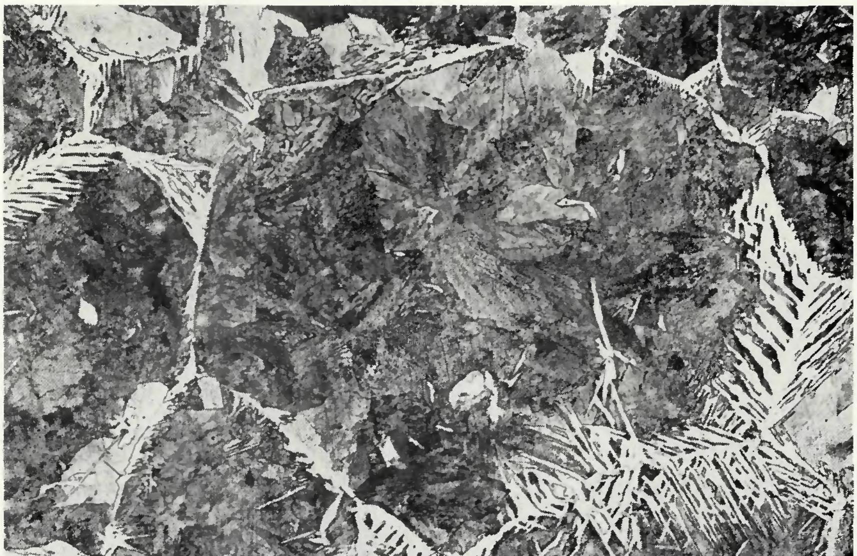

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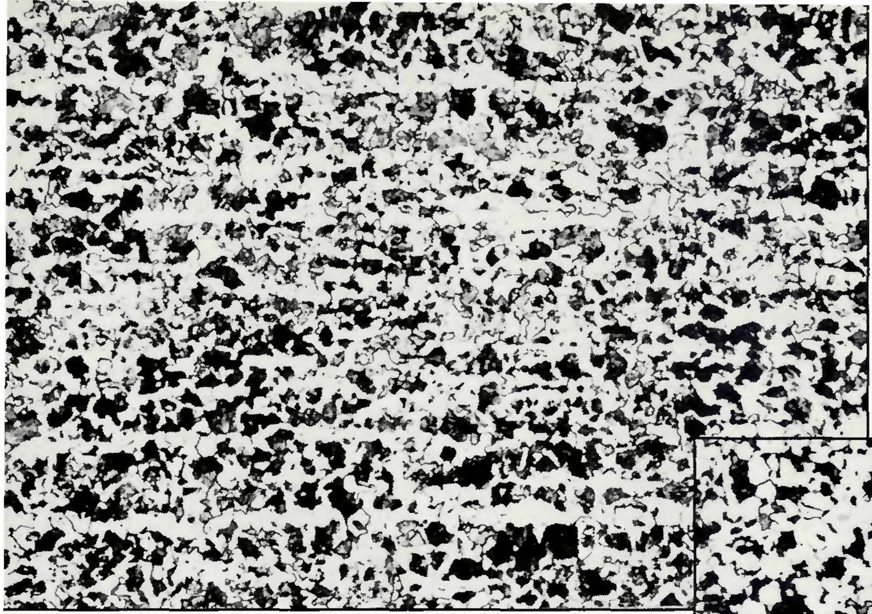
Fig. 5—Simulated "upset weld" of one-piece sample (a) macrostructure (5X, nital; (b) microstructure of light area (250X, nital)



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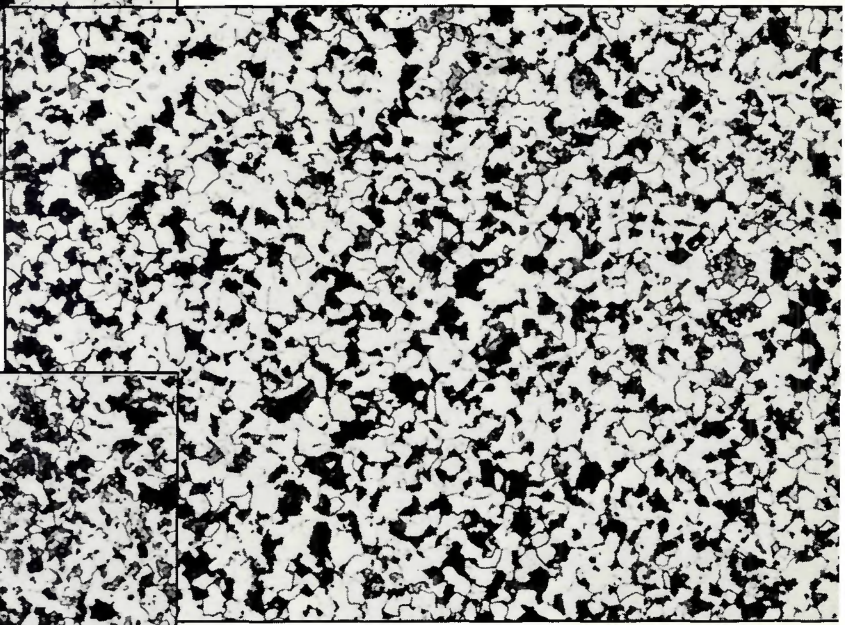

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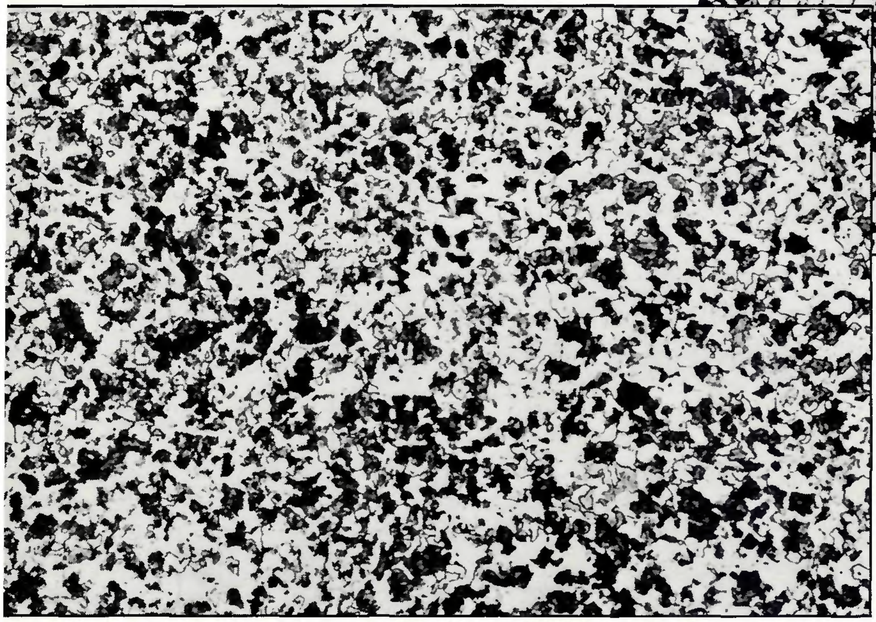

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Fig. 6—Microstructure of simulated upset weld after annealing; (a) base material not affected by thermal cycle; (b) light area; (c) heat affected zone adjacent to light area. Mag: 100X, nital

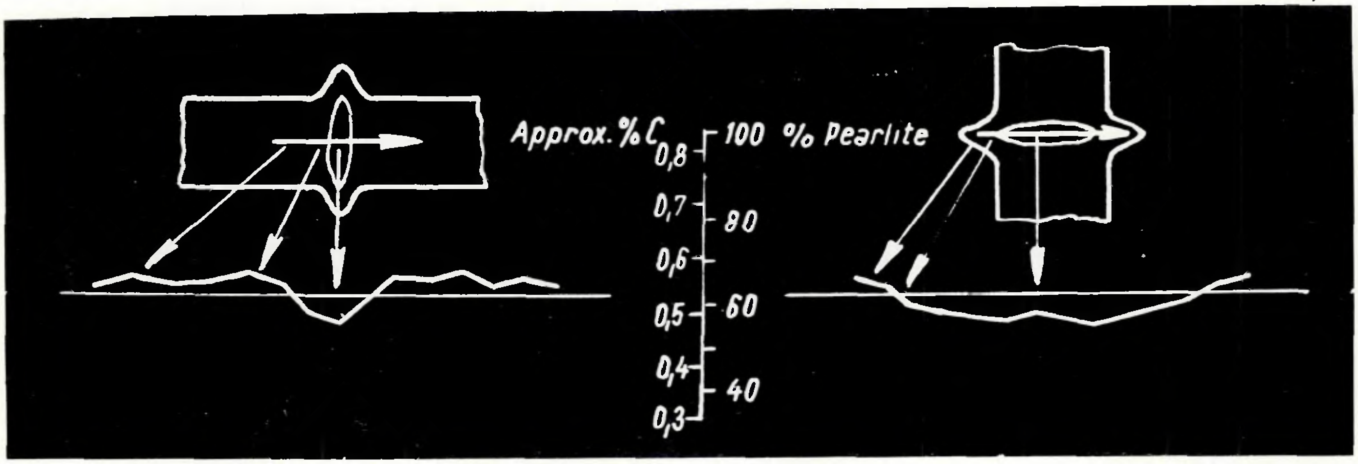

Fig. 7—Pearlite distribution in annealed simulated upset weld (results from QTM structural analysis)

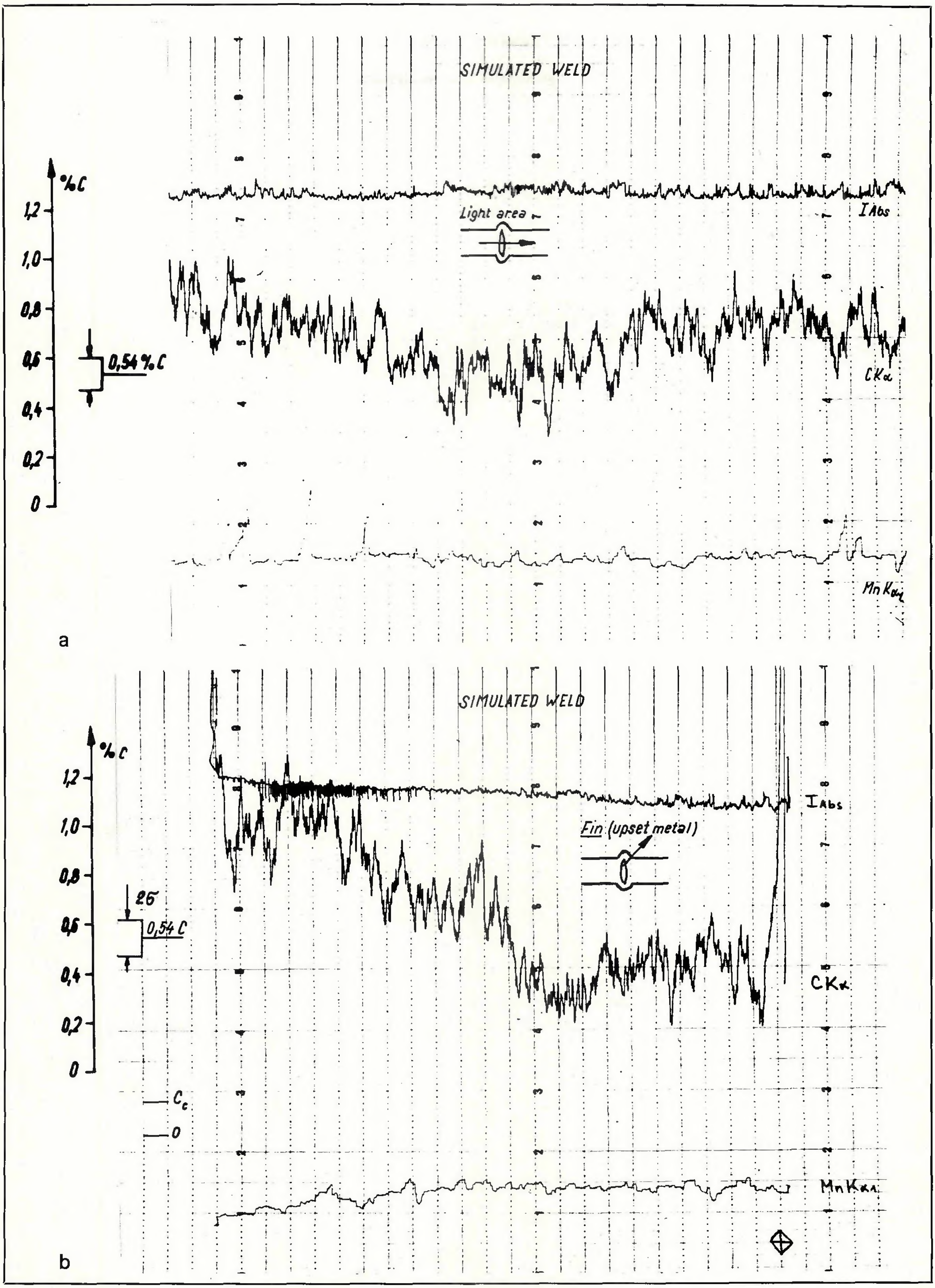

Fig. 8—Simulated upset weld; results of X-ray linear microanalysis (a) longitudinal direction; (b) transverse direction

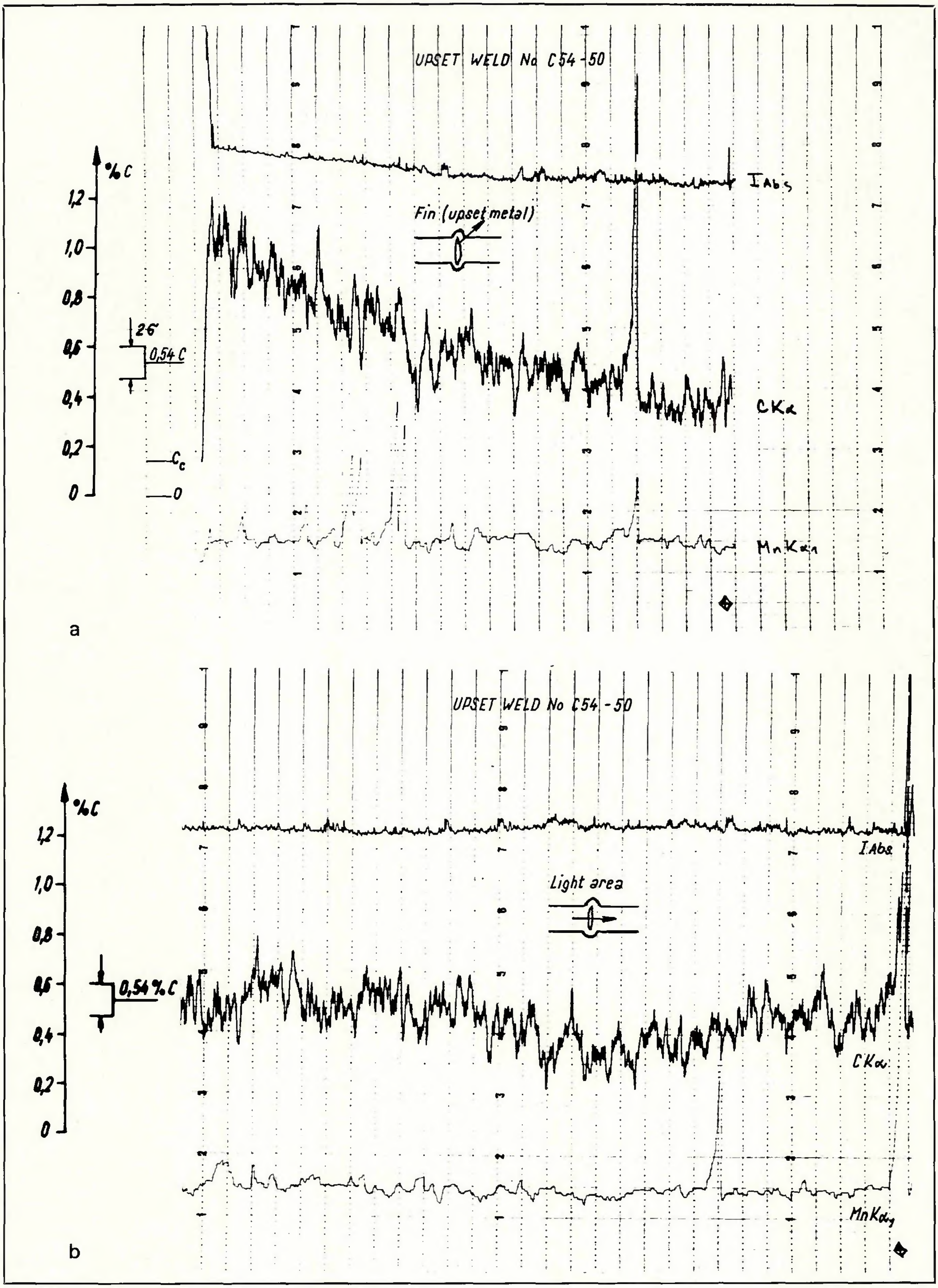

Fig. 9—Upset weld N°C54-50; results of X-ray linear microanalysis (a) longitudinal direction; (b) transverse direction

The X-ray microanalysis proved the carbon contents decrease down to 0.36 ± 0.06% C in the center of the light area. A slight increase of the carbon contents adjacent to the light area can be noticed. Displacement of manganese is practically negligible. An increase in carbon content occurs in the area of the "fin" (see Fig. 8b) where the upset metal contains up to 0.9 ± 0.06% C. Near the upset metal surface the amount of Mn is substantially decreased.

Under the same conditions we have microanalyzed the sample C-54-50 welded of two parts (see Table 1 and Fig. 2b). A graphical record of carbon and manganese distribution as shown in Fig. 9 proves that the carbon content drops again up to about 0.36 ± 0.06% C in the center of the light area and rises above 1% C at the fin surface.

Analysis of Results

Our experiments have proved the validity of Böckenhoff's opinion about the influence of upset welding parameters upon the formation of the light area.[12] As the upsetting pressure increases, the light area becomes more distinct (see Table 1).

The use of the grooved one-piece sample (Fig. 3a) enabled the imitation of both the heat and pressure cycles of the resistance upset welding and eliminates the possibility of oxidation. Under no conditions could we achieve the formation of the light area by merely heating without simultaneous application of upset force; but after application of the proper pressure (as in actual upset welding) the light area was present in the zone of the transverse groove (Figs. 4ab and 5ab). Therefore, the light area cannot be a morphological phenomenon, the result of austenite overheating and a rapid cool down only, as suggested by some authors.[7, 10]

Quantitative structural analysis proved the decreased amount of pearlite in the light area and the greater amount in the fin (Fig. 7); X-ray microanalysis proved the analogical changes in the displacement of carbon in both the samples with the imitated welding cycle (Fig. 8ab) and the samples actually welded (Fig. 9ab). Because there were no weld interfaces in the simulated upset welds, there was also no possibility of oxidation either directly by air or by any other media (slag or oxides).

The objectively proved decarburization of the light area is uniquely the result of both the partial melting and upsetting of the metal.

In the weld zone where metal is heated above the solidus line, the corresponding amount of liquid being governed by the distribution coefficient must contain more carbon than the coexisting solid phase (austenite). We can suppose that, at a very high heating rate which is characteristic for resistance welding, there is not time enough for perfect homogenization of austenite. The grains formed by transformation of pearlite contain more carbon than those created from the original ferrite and these carbon rich regions are favorable for the change into the liquid phase in the temperature range between solidus and liquidus.

Because of the effect of the applied upset force, the liquid phase is extruded through the skeleton of the remaining austenitic grains (containing less carbon); this material concentrates mostly in the fin as the upset metal. As the result, the material in the vicinity of the weld line is impoverished in the carbon-rich liquid metal; it therefore has a lower carbon concentration than average (upset metal has a higher carbon concentration). If the pressure is not applied, the liquid phase is not extruded and the original concentration remains in the entire heated section.

The effect of upset pressure on the appearance of the light area (Table 1) has been followed by different authors.[12] At a relatively low upset pressure, upsetting does not start until the steel is heated near the liquidus line and most of the metal becomes liquid. The portion of low carbon solid phase is unimportant and thus the light area is nearly imperceptible (Fig. 2a). Just the opposite occurs if high pressure is applied; upsetting starts at a considerably lower temperature, the carbon-rich liquid metal is quickly extruded out of the weld zone and the light area becomes distinct.

The typical lenticular shape of the light area in upset welds can be explained as follows. As a result of the simultaneous upsetting and heating of the metal, new low carbon austenite grains are gathering in the central zone of the weld. At the periphery of the weld, the high portion of the extruded carbon-rich liquid is mixing with the strained austenite thereby decreasing the width of the decarburized zone.

It should be noted that in flash welds the light area is rather narrow and of uniform width. The different appearance can be explained by the specific features of this process. On flash welding, the temperature gradient is very steep and consequently the amount of partially melted metal is small; thus the light area cannot be wide, unless the weld zone is overheated (Fig. 1b). Because the weld zone is not heated more during upsetting (that takes place mainly below the solidus line), the upset force and upset travel do not affect the light area size; therefore the temperature gradient plays a decisive role.

Conclusions

Results of this investigation have proven the validity of certain theories[2, 11, 12] that the light area in the resistance upset welds of carbon steels is decarburized; this is caused by upsetting of the partially melted metal. If the metal is heated above the solidus line, the coexisting liquid and solid phases differ in carbon concentration following the distribution coefficient. Due to the applied upset force, the carbon-rich liquid phase is extruded out of the weld zone; in the neighborhood of the weld line the solid phase remains partially deprived of carbon and, after cool down, it has a structure different from the surrounding metal. Decreased carbon content in the light area and increased carbon content in the upset metal were proved by two different methods.

The peculiar structure by the light area cannot be explained by decarburization only; the different morphology of the structural constitutents, as suggested by Hrivnák,[10] must be taken into consideration.

The light area must be considered as a serious metallurgical defect of upset welds that cannot be removed by heat treatment. Decarburization of upset welds in steel wires can be limited if suitable welding parameters are applied. Low upset force and a short welding time are the most important factors.

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"Interpretive Report on Effect of Hydrogen in Pressure Vessel Steels"

"Section I—Basic and Research Aspects"

By C. G. Interrante

The first and second parts of this section of the interpretive report on hydrogen in pressure-vessel steels includes background information on solubility, diffusivity, permeation, removal, and sources of hydrogen. In the third and fourth parts, the effects of hydrogen on mechanical properties are discussed, both for steels containing hydrogen and for steels exposed to hydrogen environments. The fifth part reviews the mechanisms that are proposed to explain the experimental observations. Finally, the further research that is most needed to furnish pertinent data for pressure-vessel applications is outlined.

"Section II—Action of Hydrogen on Steel at High Temperature and High Pressures"

By G. A. Nelson

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This section covers the effects of hydrogen combined with temperature. The most sensitive parameters are the partial pressure of hydrogen, the temperature, and the material chemistry. While some of the other effects of great significance at low temperature, such as the stress and cold work, are still significant, the effects of high temperature are less sensitive to these or cannot be summarized so neatly.

The areas to which this section applies are those in which hydrogen or hydrogen-containing fluids are handled at high temperatures (above 430°F) and high hydrogen pressures (up to 13,000 psia). Under these conditions carbon steel will be unsatisfactory as a constructional material because of both chemical and physical changes that occur.

Mechanisms for producing the chemical changes are discussed together with alloying requirements to prevent the damage. Additional sections are devoted to incubation periods before chemical changes occur and to effects of hardness, cold work and stress at high temperature. Methods of preventing high temperature damage to pressure vessels by specialized design or suitable alloying are also discussed.

"Section III—Practical Aspects of Hydrogen Damage at Atmospheric Temperature"

By C. M. Hudgins, Jr.

The first section of this interpretive report laid the theoretical foundation for the study of effects of hydrogen. The second discussed the effects of hydrogen at elevated temperatures. The purpose of this section is to discuss the practical aspects of the lower temperature damage by hydrogen. The selection of materials, their use, pitfalls to be avoided, and some possible problems are reviewed.

This report was prepared for the Pressure Vessel Research Committee of the Welding Research Council. The price of WRC Bulletin 145 is $3.00. Copies may be purchased from the Welding Research Council, 345 E. 47th Street, New York, N. Y. 10017.