Microstructure and Impact Toughness of C-Mn Weld Metals

The formation of acicular ferrite in over half of the weld appears to be the key to improving impact toughness

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ABSTRACT. The effect of variation in carbon and manganese contents on the microstructure and impact properties of all weld metal samples has been studied. The welds were made using the shielded metal arc welding technique. Four different carbon levels, ranging from 0.03-0.12 wt-% and four different manganese contents (0.8-2.1 wt-%) were used.

It was found that significant improvements in impact toughness at low temperatures were achieved with increasing amounts of acicular ferrite. High levels of acicular ferrite could be achieved with several different combinations of carbon and manganese. At excessive amounts of alloying additions, the impact toughness decreased. This is attributed to the presence of bands of microphases being aligned with the notch in the fracture surface. For the lowest carbon content, unexpectedly low toughness was observed. This may be due to the fact that these metals contained a somewhat higher nitrogen content.

Introduction

The effect of carbon and manganese on the microstructure and mechanical properties of mild steel arc welds has been the subject of many investigations. Vuik (Ref. 1) has recently summarized the investigations made concerning the effect of carbon. Evans has published a number of papers dealing with the effect of carbon (Ref. 2), manganese (Ref. 3), silicon (Ref. 4), interpass temperature (Ref. 5), impurity elements (Ref. 6), molybdenum (Ref. 7), heat input (Ref. 8) and heat treatment (Ref. 9) on the microstructure and mechanical properties of mild steel welds. The welds that Evans examined were of the all-weld-metal type, deposited with a shielded metal arc multipass technique. In the work most comparable to the present one, Evans found that the optimum impact toughness properties were achieved with an alloying combination of 0.07 wt-% C-1.4 wt-% Mn, and attributed this to the competitive action between the progressively finer ferrite grain sizes obtained by increasing alloying additions and by the simultaneously increasing yield strengths.

In this paper, an investigation of the microstructure and impact toughness of 16 different welds, with varying carbon and manganese contents, is described. The experiment to a large extent mirrors the one of Evans (Refs. 2, 3), but the results differ somewhat. The intention of this paper is to clarify the reason for the discrepancy between the different investigations and to point out some additional microstructural effects that might be of importance for the impact toughness. However, first a short description of the role of carbon and manganese in controlling the microstructure and how this may influence the impact properties will be given.

Background

With the help of experimental (Refs. 1-9) and theoretical (Refs. 10-12) work, the effects of various elements on the microstructure of the as-deposited area in a weld is now relatively well understood.

The as-deposited microstructure of C-Mn weld metals is commonly described with three major microstructural components: grain boundary ferrite, ferrite with aligned M-A-C (martensite-austenite-cementite) and acicular ferrite. The classification of the various microstructures is based on the visual impression in the optical microscope. However, in the theoretical work based on thermodynamics, the microstructural components are described from the mechanism of formation point of view. The components are then called allotriomorphic ferrite (same as grain boundary ferrite, but a more correct name), Widmannstätten ferrite side plates (according to Dubé classification) and acicular ferrite. It should be noted that the mechanism of formation of acicular ferrite is not yet known. In the following text, the last mentioned denotation will be used.

The effect of carbon is mainly to limit the width of the coarse-grained allotriomorphic ferrite, formed at the prior austenite grain boundaries, and in influencing the rate of Widmannstätten ferrite formation. During the transformation from austenite to ferrite, the carbon atoms diffuse into the remaining austenite and the growth (or thickening) rate of the allotriomorphic ferrite is controlled by the diffusion rate of carbon in austenite. A higher carbon content gives a slower growth rate of the ferrite and, thus, a thinner layer of ferrite at the prior austenite grain boundaries.

Increasing carbon content leads to lower contents of both allotriomorphic and Widmannstätten ferrite, giving room for increasing contents of the fine-grained acicular ferrite. However, it is not known whether the actual growth rate of acicular ferrite is influenced by the carbon content.

The manganese atoms, on the other hand, are not redistributed during the transformation, but an increased manganese content reduces the driving force for the transformation. Thus, increasing manganese also leads to a thinner layer of allotriomorphic ferrite. In a way, manganese and carbon can be considered as complementary elements, and in principle, the same microstructure should be attainable

KEY WORDS

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with several combinations of these elements.

However, there is at least one point where this way of reasoning fails. During solidification, manganese segregates to the remaining melt and is, thus, enriched at the cell boundaries at the solid/liquid interface. This segregation pattern (although much less pronounced than for nickel) persists during the whole cooling sequence of the weld since manganese is not redistributed during the transformations. Especially when the weld is heavily alloyed with manganese, extensive formation of microphases (retained austenite, martensite, degenerate pearlite, bainite or carbides) takes place in areas where the manganese content is high. The term microphases indicates that the volume fraction of these phases is low and this is true also for welds with high manganese content, but the difference is that the microphases appear in bands, reflecting the solidification pattern, while in the lower manganese welds, the microphases are more evenly distributed. This will be illustrated more clearly later in this paper.

It should be noted, that in practice there are many other alloying elements used to control the microstructure. Apart from carbon and manganese, the most frequently used ones are Ni, Mo and B. The influence of inclusions on the amount of acicular ferrite has been debated for several years. It has been argued that certain types of inclusions are better nucleants for acicular ferrite than others, due to lattice matching between ferrite and the inclusions. Thus, another route for controlling the microstructure would be to choose the slag system in such a way as to obtain the most favorable type of inclusions.

Turning to the mechanical properties and the relationship between microstructure and properties, it should first of all be noted that the mechanical properties of weld metals are usually not just determined by the as-deposited microstructure, since commonly many beads have been deposited to complete the weld. Thus, a range of microstructures exists in the weld. The reheated area under a bead can be divided into a coarse-grained zone, a fine-grained zone and a recrystallized zone. The relative amounts of these zones will vary with, among other things, chemical composition, and this will, of course, influence the mechanical properties. However, it can be assumed that there is a relationship between the as-deposited microstructure and the microstructure in the other zones and, therefore, it is possible to discuss the mechanical properties with reference to the microstructure in the as-deposited region.

When designing weld metals, the most difficult thing is to meet requirements on impact properties while maintaining operational properties as good as possible. Tensile properties are, at least for mild steels, a smaller problem since usually the strength of the weld metal is higher than the strength of the steel.

Specifications on impact toughness vary substantially, but in many cases the requirement is 27 J (20 ft-lb) at a certain temperature. For more advanced applications, higher toughness values are required, *e.g.*, 34 or 40 J (25 or 30 ft-lb). These levels of toughness values are achieved with only a relatively small fraction of the fracture surface of an impact toughness test bar having a ductile, fibrous fracture, while the remaining part is a brittle, cleavage type. To achieve acceptable impact toughness at lower temperatures (which in many cases is the trend in development work today) it is necessary to avoid cleavage fracture starting too near the notch in the impact bar. This can be achieved by control of the microstructure.

To improve impact toughness, some well-known physical metallurgy principles are used. First, increasing the amount of acicular ferrite by the control of alloying elements gives a reduced grain size. Secondly, use of basic-type consumables gives a low amount of oxygen, which leads to a low volume fraction of inclusions. Finally, strict control of impurity elements like S, P, Sn, As, Sb and N helps to prevent embrittlement of the structure.

The application of the first of these principles leads us back to the main question of this paper: how can the microstructure be optimized by changing carbon and manganese contents?

As a contrast to this, Dolby (Ref. 13) suggested that weld metals with a very lean alloying content, having mainly a coarse-grained structure and a low yield strength, could have good impact toughness.

Although there have been major improvements in the toughness levels that can be achieved in weld metals during the last few decades, by application of the principles mentioned above, there is still room for further improvement. A more fundamental understanding of the mechanisms controlling the onset of cleavage fracture and the complex interrelationship between microstructure and fracture needs to be developed. Major advances have indeed already been made in this field by Knott and coworkers (Refs. 14–16) who have studied the fracture behavior of C-Mn welds in detail and combined that with their earlier experience of fracture in steels. They concluded that cleavage fracture in welds often originated from cracking of oxide inclusions, in particular those situated in the coarse-grained allotriomorphic ferrite, and that the size distribution of these inclusions had a significant effect on the fracture toughness results. In steels, where the volume fraction of oxide inclusions is much less, fracture toughness is linked more to the carbides precipitated along grain boundaries, nucleating cleavage cracks (Ref. 17). However, it should be noted that in testing fracture toughness of weld metals, Knott and coworkers used small size notched bars and tested them in slow strain-rate four-point bending, in a manner similar to CTOD testing. The observation of cleavage cracks nucleating from inclusions were numerous in these tests but similar observations on impact specimens are, in fact, fairly rare.

Experimental

Laboratory-made shielded metal arc electrodes, 4 mm (0.16 in.) in diameter, of E7018 type with basic coatings were used for the investigation. The electrode coatings were varied to a systematic series of four different manganese contents (0.8, 1.1, 1.2 and 2.1 wt-%) at each carbon level (0.03, 0.06, 0.09 and 0.12 wt-%). All welding was made in accordance with ISO 2560, with a current of 180 A, voltage 23 V and a maximum interpass temperature of 250°C (484°F). A stringer bead technique was used giving a welding speed of about 4 mm/s (9 in./min). The heat input then was around 1 kJ/mm (25 kJ/in.).

The chemical composition of the weld deposits was measured using an optical emission spectrometer (OES), except for oxygen and nitrogen, which were determined using combustion furnaces. The OES analyses were made on the head of the tensile specimen.

Two longitudinal all-weld-metal tensile specimens (10 mm/0.4 in. in diameter) and 25 Charpy V-notch impact specimens were taken from each weld. The specimens were taken from the middle of the plate. The impact toughness was tested at five different temperatures, with five specimens tested at each temperature.

The microstructures of the weld metals were examined by conventional metallography, using light optical microscopy. The etching was made using first a solution of 4% picric acid in alcohol, followed by 2.5% nitric acid in alcohol.

The quantitative assessment of the microstructure was made using a Swift point counter. At least 500 points were measured on each specimen. The microstructure constituents were identified according to the classification of the IIW (Ref. 18). The austenite grain size was measured normal to the length axis of the grains (*i.e.*, the results are equal to L_{tn} as denoted by Bhadeshia, *et al.* – Ref. 19).

To further study the microphases, transmission electron microscopy (TEM) was used. Thin foils were prepared by polishing in a Struers Tenupol in a 5% solution of perchloric acid in methanol.

Table 1—Chemical Compositions of the Weld Metals[a]

Sample No.	C	Si	Mn	P	S	Al	Ti	Sn	As	Sb	N	O
1	0.030	0.45	0.78	0.010	0.013	0.009	0.014	0.006	0.001	0.002	95	336
2	0.032	0.45	1.27	0.010	0.008	0.009	0.013	0.006	0.001	0.003	94	321
3	0.031	0.42	1.71	0.010	0.004	0.008	0.011	0.006	0.001	0.003	109	297
4	0.032	0.45	2.05	0.010	0.002	0.009	0.012	0.006	0.001	0.005	119	320
5	0.059	0.34	0.77	0.010	0.010	0.007	0.011	0.003	0.001	0.001	66	306
6	0.059	0.33	1.09	0.010	0.008	0.007	0.010	0.005	0.001	0.005	64	310
7	0.059	0.30	1.44	0.010	0.006	0.007	0.009	0.004	0.001	0.005	65	305
8	0.065	0.33	1.83	0.010	0.003	0.007	0.009	0.004	0.001	0.005	76	291
9	0.090	0.41	0.78	0.010	0.013	0.003	0.014	0.005	0.004	0.004	36	421
10	0.089	0.35	1.18	0.010	0.011	0.008	0.012	0.005	0.003	0.003	73	404
11	0.088	0.37	1.59	0.010	0.011	0.003	0.012	0.005	0.005	0.004	77	491
12	0.098	0.39	2.25	0.014	0.008	0.003	0.013	0.006	0.005	0.005	88	330
13	0.12	0.43	0.86	0.014	0.011	0.005	0.015	0.005	0.003	0.003	54	329
14	0.12	0.44	1.35	0.014	0.010	0.003	0.015	0.006	0.005	0.006	55	326
15	0.13	0.37	1.83	0.011	0.010	0.003	0.013	0.006	0.005	0.005	63	318
16	0.11	0.36	2.18	0.011	0.008	0.003	0.012	0.006	0.007	0.008	74	342

(a) All concentrations are in wt-%, except for oxygen and nitrogen, which are given in weight ppm.

Results

Chemical Composition

The chemical compositions of the weld metals are given in Table 1. The carbon contents have successfully been kept close to the nominal values. The manganese content scattered somewhat around the nominal values, the maximum deviation being around 0.15%.

The phosphorus content was relatively constant throughout the investigation, typically 0.010%. The sulfur content decreased with increasing manganese content. This decrease was especially pronounced at the lower carbon contents. The other impurity elements (Sn, As and Sb) were all on a low level, and their sum did not exceed what is considered a safe level (Ref. 20).

The nitrogen content increased somewhat with increasing manganese content, being especially pronounced for the low-carbon electrodes, while the oxygen content on the whole was constant. It should, however, be noted that the three lower manganese contents in the 0.09%C specimens had an oxygen content approximately 100 ppm higher than in the other specimens.

Mechanical Properties

The yield strength measured is shown as a function of Mn-content in Fig. 1. As expected, the yield strength increased with increasing carbon and Mn-content. The influence of Mn is relatively strong, while the influence of carbon is quite small, except for the highest carbon content.

The Charpy V-notch impact toughness curves are plotted in Figs. 2 A–D. First, it can be noted that increasing manganese content decreased the upper shelf energies, probably simply due to an increased yield strength of the matrix. The impact properties at lower temperatures showed mixed behavior, depending on the combination of C and Mn. For the lower manganese contents, increasing carbon content led to significant improvement in impact toughness at lower temperatures. At the higher manganese contents, the intermediate carbon contents gave the best impact values at the lower temperatures.

In Fig. 3, impact toughness at −60°C (−76°F) is plotted as a function of Mn content, for constant carbon levels. For two of the carbon levels (0.09 and 0.12%), optimum contents of Mn were found, while for the two lower carbon contents, the optimum Mn content seemed to be higher than the maximum contents used in this investigation.

The best impact toughness at −60°C was found for the combination 0.12C-1.35Mn, but also the intermediate carbon levels, combined with a relatively high manganese level, showed good results. At −40°C (−40°F) almost the same pattern was followed. The best impact toughness was achieved with the combination 0.12%C-1.2%Mn. Also, the combinations 0.09%C-1.2%Mn and 0.06%C-1.4-1.8% Mn gave satisfactory toughness. Increasing the manganese content above 1.4% gave a reduction in toughness for the two highest carbon contents.

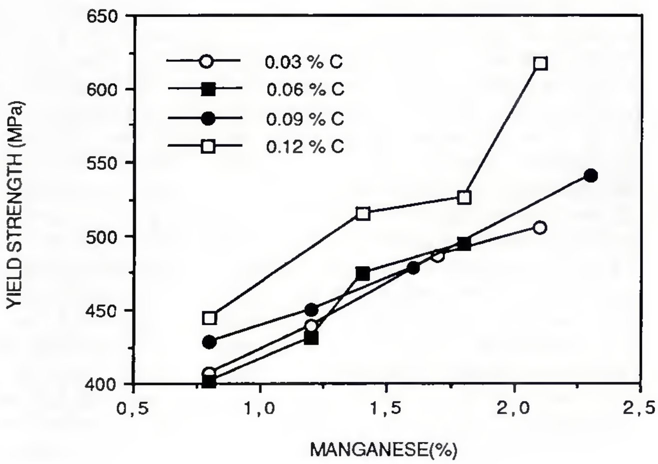


Fig. 1—Yield strength as a function of carbon and manganese content.

Microstructure

The austenite grain size, measured in the last deposited bead, decreased with increasing carbon and manganese content, except for the 0.06% carbon welds, which all had a slightly larger austenite grain size. The austenite grain sizes are given in Table 2.

There is no systematic variation in austenite grain size with oxygen content. However, it should of course be noted that the oxygen content varies within a fairly narrow range.

The results of the quantitative assessment of the microstructure are given in Figs. 4 A–D. For a given carbon content, the amount of acicular ferrite increased at the expense of both allotriomorphic ferrite and ferrite side plates with increasing manganese content. The maximum

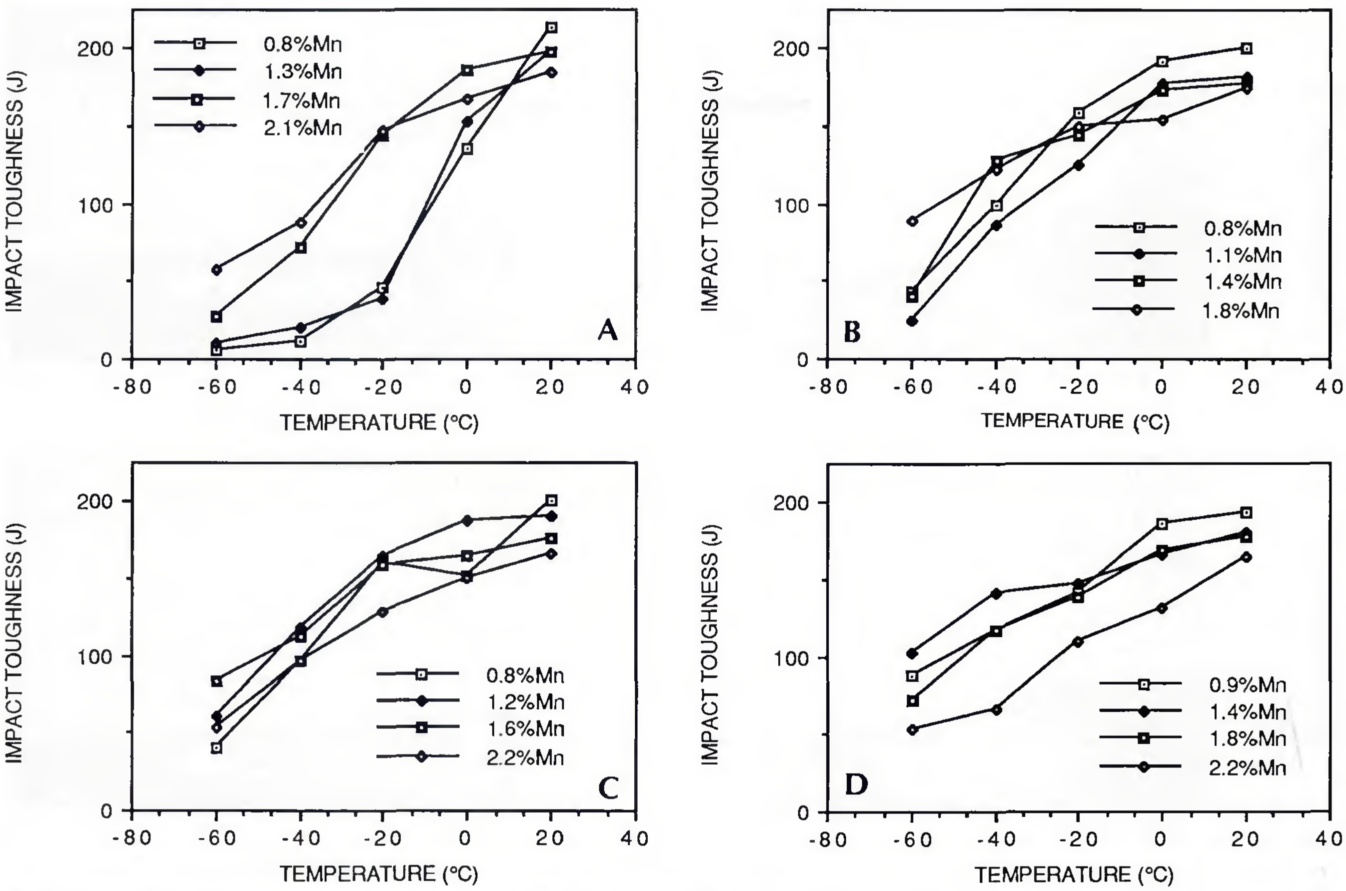


Fig. 2 — Charpy V-notch impact toughness curves. A — 0.03%C; B — 0.06%C; C — 0.09%C; D — 0.12%C.

amount of acicular ferrite achievable with only carbon and manganese additions seems to be around 65–70% for this particular set of welding conditions. Keeping Mn constant and looking at increasing carbon content, the same trends are found. However, it should be noted that for a manganese content of 0.8, a maximum acicular ferrite content of only about 50% is achieved, and for both 1.1 and 1.5% Mn, 0.12% carbon is necessary to maximize the amount of acicular ferrite. Representative micrographs of the weld metals with "extreme" compositions are shown in Figs. 5–8.

The number of microphases naturally increased with increasing carbon and manganese content. For the lower alloy contents, the microphases were evenly distributed in the microstructure. With increasing manganese content, the microphases became more segregated. This can be seen by comparing Figs. 9 A and B.

The nature of the microphases can lead to ambiguous identification by light optical microscopy. Therefore, the last bead in some of the specimens was examined by TEM to establish the nature of the microphases. For the low-carbon/low-manganese weld metal, a few regions with grain boundary carbides were found. With high carbon content, but still low manganese content, isolated grains of retained austenite were found, as well as grain boundary carbides (Fig. 10). With both high carbon and high manganese content, continuous layers of retained austenite were found — Fig. 11.

The impact specimens were extracted from the middle of the plate, and therefore, it cannot be directly assumed that the microphases present in these specimens are of the same kind as those in the

Table 2—Austenite Grain Size of the Weld Metals(a)

Specimen No.	Austenite Grain Size (μm)
1	65
2	55
3	42
4	42
5	71
6	65
7	60
8	48
9	45
10	45
11	45
12	45
13	36
14	36
15	40
16	45

(a) Measured perpendicular to the length axis of the grains.

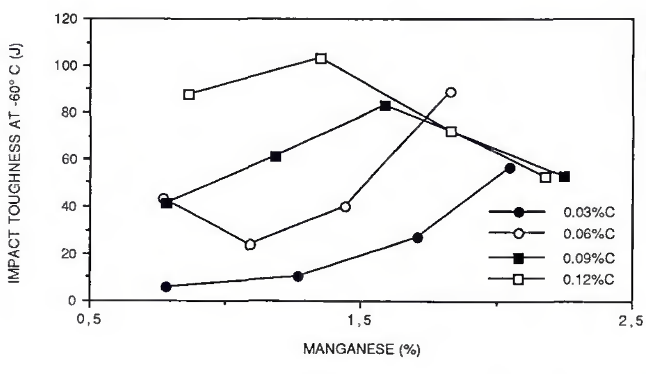


Fig. 3 — Impact toughness at −60°C as a function of manganese content.

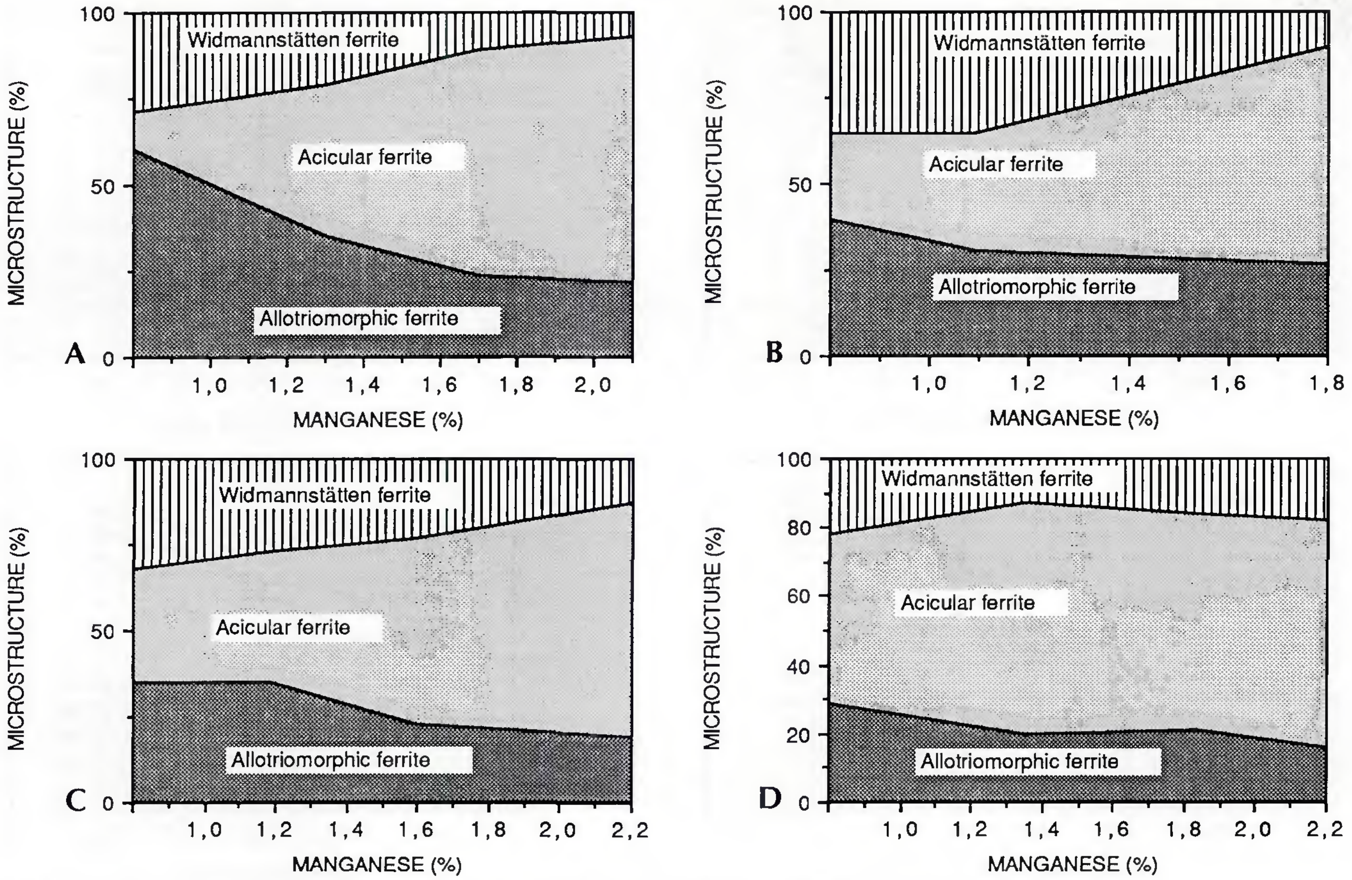


Fig. 4—Quantitative description of the microstructure. A—0.03% C; B—0.06% C; C—0.09% C; D—0.12%C.

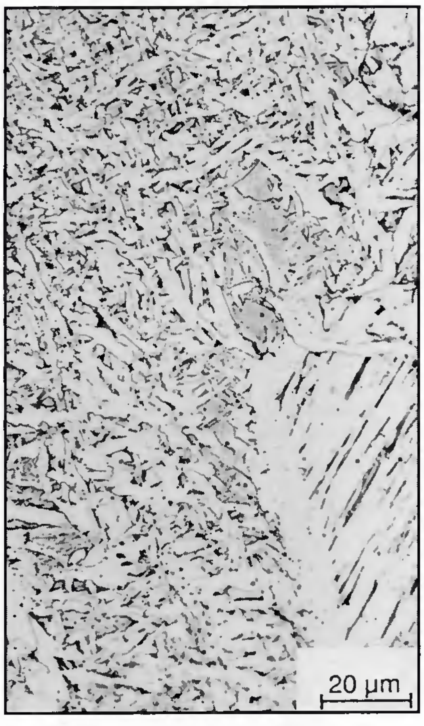


Fig. 5—Optical micrograph of the weld metal with 0.03%C—0.8%Mn. The microstructure consists mainly of a coarse allotriomorphic ferrite, ferrite side plates and coarse acicular ferrite.

last bead. However, since the microphases appear as retained austenite in the as-deposited microstructure, they will be either ferrite + carbide aggregates, untempered martensite or still retained austenite in the reheated material, depending on reheating temperature. All these phases could induce brittleness. Examination of cross-sections of impact specimens containing segregated bands of microphases shows that in areas where the segregation bands are parallel with the notch, the fracture surface has a brittle appearance—Fig. 12. In other cases, in adjacent beads, where the segregation bands are inclined to the notch, the fracture surface has a more ductile appearance—Fig. 13.

These observations cannot be taken as strict evidence for microphase-induced cleavage cracking, but combined with many observations made earlier, we certainly feel confident that the segregated microphases are responsible for the drop in toughness at higher manganese contents.

Discussion

It is commonly assumed that a high amount of acicular ferrite should be present in the microstructure to obtain good impact toughness through the effect of the fine grain size. The increase in acicular ferrite is usually, but not always, accompanied by a decrease in the amount of coarse-grained allotriomorphic ferrite and, thus, as discussed previously, connected to the amounts of carbon and manganese.

In Fig. 14, the impact toughness values at −60°C is plotted as a function of the amount of acicular ferrite. Figure 15 shows similar information extracted from the data of Evans (Ref. 2).

In both investigations, the same general trend is found, that increasing amounts of acicular ferrite improves toughness. Indeed, there is large scatter in the relation between acicular ferrite and toughness, but as a rule of thumb, it can be said that more than 50% acicular ferrite gives acceptable impact toughness. However, in Fig. 14 it can be noted that the weld metals with the lowest C contents give much lower impact toughness values than expected from the acicular ferrite content. This behavior is in contradiction to the results of Evans (Ref. 2), who found a much faster improvement in impact toughness with increasing the amount of acicular ferrite.

The only element which clearly is different between the low-carbon welds and the other welds in this study is nitrogen; being much higher in the low-carbon welds. Nitrogen is well known to embrit-

Fig. 6 — Optical micrograph of the weld metal with 0.03 – 2.1% Mn. Mainly acicular ferrite and thin rims of allotriomorphic ferrite.

Fig. 7 — Optical micrograph of the weld metal with 0.12%C – 0.8%Mn. The rim of allotriomorphic ferrite is quite thin. The amount of ferrite side plates is quite high.

Fig. 8 — Optical micrograph of the weld metal with 0.12%C – 2.2%Mn. Shown is the extremely fine microstructure with a high amount of acicular ferrite.

tle weld metals, although the values found here would not be considered as dangerous. Unfortunately, Evans did not give values of nitrogen content in his report. The agreement for low values of acicular ferrite is not surprising, since this is determined by the overall brittle microstructure. The deviation at the high amounts of acicular ferrite is, for lack of a better explanation, assumed to be due to nitrogen. However, this is purely speculative and needs more investigation.

Another observation that can be made from both Figs. 14 and 15 is that the impact toughness shows a slight decrease for the highest amounts of acicular ferrite. This decrease in toughness seems to occur for acicular ferrite contents in excess of about 70%. Comparison with Fig. 12 shows that the lower toughness is due to increased amounts of brittle cleavage fracture.

Evans (Ref. 2) argued that the decreasing toughness of high alloying content welds was due to increasing yield strength without a corresponding decrease in grain size. As explained in the background section, the mechanical properties are a function of a mixture of microstructures. To assess the influence of each type of microstructure on the properties is a complex task. Even if it is a great oversimplification to relate the mechanical properties to the as-deposited microstructures, this approach should give guidance to the operating mechanisms.

However, as noted above, the highest alloyed welds contained higher amounts of acicular ferrite than the lower alloyed welds. The yield strength of these alloys also was higher than the lower alloyed metals. If the above way of reasoning is accepted, then a higher amount of acicular ferrite is equivalent to a decreasing grain size in the whole weld metal. The higher yield strength is, thus, partly a grain size effect. Finer grains should also lead to better toughness, contrary to what is observed.

The classical model of cleavage fracture is that this occurs at a temperature where the yield strength exceeds the fracture stress. However, both the yield strength and the fracture stress are grain-size dependent in such a way that finer grains lead to both higher yield and fracture strength. Thus, the amount of cleavage fracture is not expected to increase in the highest alloyed weld metals, but this is obviously what happens when the toughness falls. Obviously, something in the microstructure offsets the beneficial effect of finer grains. The most likely factor responsible for this is the segregated microphases, which is in line with the observations in Figs. 12 and 13.

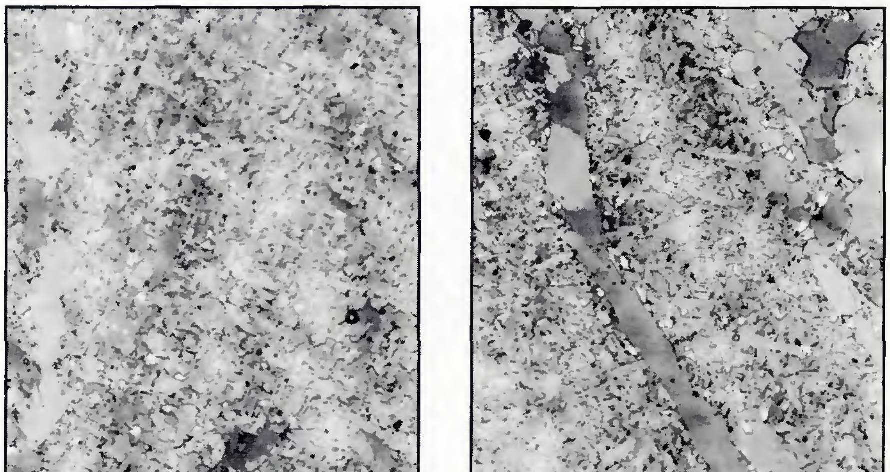


Fig. 9 — A — Optical micrograph showing how the microphases (white small grains) are randomly dispersed; B — with higher alloying content, the microphases are becoming more segregated. Etching was made, using Klemms reagent (Ref. 21), to more easily distinguish the microphases.

Fig. 10 — TEM micrograph showing isolated islands of retained austenite (arrowed) and some grain boundary carbides.

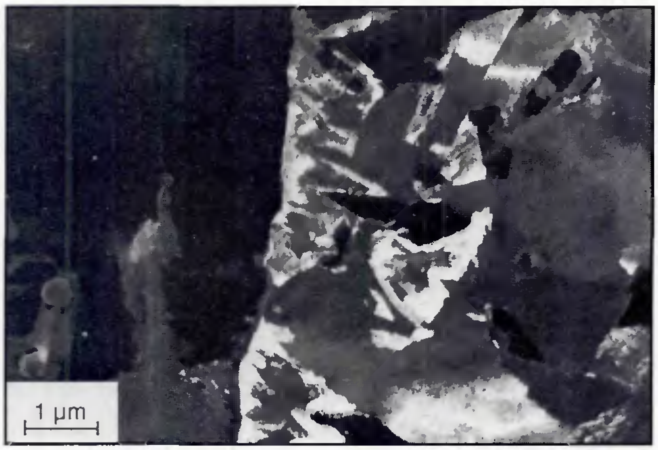


Fig. 11 — Centered dark field TEM micrograph of weld metal 0.12%C — 2.2%Mn, showing an almost continuous layer of retained austenite.

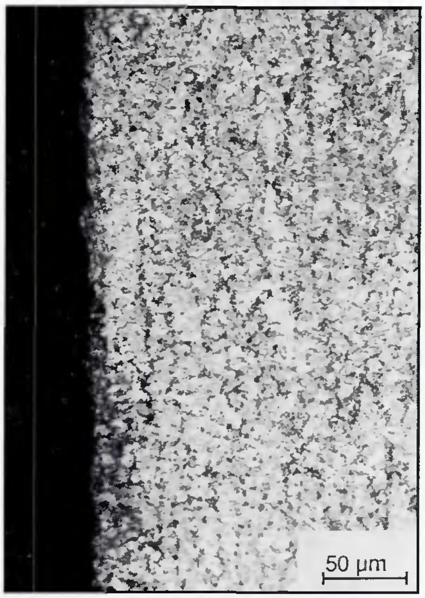
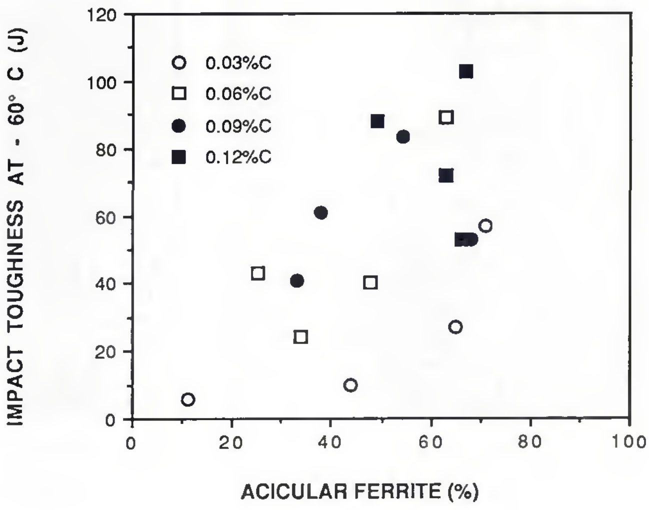


Fig. 12 — Optical micrograph of a polished cross-section through an impact specimen, showing that the brittle appearance of the fracture surface is parallel with the segregation band of microphases.

Fig. 13 — Optical micrograph showing a ductile appearance of the fracture surface in an area where the bands of microphases appear at an angle to the fracture surface.

Fig. 14 — Impact toughness at −60°C as a function of acicular ferrite content, from this investigation.



Garland and Kirkwood (Ref. 22) have pointed out the detrimental effect to toughness of segregated microphases in the form of martensite. On the other hand, if the microphases appear as grain boundary carbides, they may facilitate propagation of cleavage cracks across grain boundaries, as suggested by Knott (Ref. 17). Also, if they appear as small, randomly dispersed regions of martensite or retained austenite, they may act as starting points of cleavage cracks, in a manner similar as suggested for oxide inclusions. Thus, the microphase generally has a negative effect on toughness, by faciliating the nucleation of cleavage cracks.

If the microphases are martensitic or retained austenite, they will have a high carbon content, since carbon is diffusing into these areas, away from the ferrite during the austenite to ferrite transformation. Martensitic regions would be very brittle, if they are not tempered. However, most of the martensite appearing under the notch in an impact specimen from a multipass weld metal would have been tempered and, thus, should not be detrimental to toughness. The work of Garland and Kirkwood (Ref. 21) is related to a two-pass welding procedure, and the impact testing was made on solely as-deposited microstructure, where no tempering of the martensitic regions could occur. Retained austenite microphases in multipass weld metal must, on the other hand, be considered as a more unreliable component in terms of toughness, since it is likely to be unstable and transform to brittle martensite during the impact testing. If the microphases appear as segregated bands, as in the high-carbon, high-manganese welds, the situation is even worse, since cleavage cracks should then be able to both nucleate and propagate easily.

The observation of the microphases in the high-carbon, high-manganese specimen being only retained austenite and not martensite can be understood by considering the enrichment of carbon in the remaining austenite. From average composition data, the M_s temperature is so high that no retained austenite is expected. However, with increasing carbon content, the M_s temperature falls below room temperature and, consequently, the austenite is retained.

As noted previously, the highest impact toughness in the present work was obtained with the combination 0.12 C - 1.35 Mn, but several other combinations had almost the same toughness. This shows that a proper microstructure, and hence good toughness, can be obtained balancing carbon and manganese in several combinations. What is obviously essential is to achieve high enough proportion of acicular ferrite, but then not alloy the welds further, since this causes segregated bands of microphases. This observation is somewhat at variance with the work of Evans (Refs. 2-9), where mainly the combination 1.4 Mn-0.07 C gave optimum toughness.

Thus, to summarize, the impact toughness values found can mainly be understood by considering the general microstructure and, for high manganese contents, the detrimental effect of microphases. Nitrogen may have caused low impact toughness values in some specimens.

We would further like to point out, that:

1) The positive effect of only 50% acicular ferrite is something seldom noticed, in fact it is more common to believe that 80-90% acicular ferrite is necessary to obtain satisfactory impact toughness at −60°C.

2) An increasing yield strength of the alloys did not negatively influence the impact toughness. The increase in yield strength was mainly achieved by a decreasing grain size and naturally, this improves the impact toughness.

3) The positive effects of decreasing grain size by increasing alloying content can be offset by the formation of segregated bands of brittle microphases.

We believe that these points are important to note for future developments in this field.

Conclusions

1) Several combinations of carbon and manganese produced impact toughness of the level of 100 J (74 ft-lb) at −60°C (−76°F).
2) The most important factor seemed to be an acicular ferrite content of more than 50%.
3) With excessive alloying, the segregation pattern of microphases caused decreasing toughness.
4) Although only a limited variation in oxygen content was studied, no influence of oxygen could be found on impact toughness.
5) With low carbon content, surprisingly low impact toughness was found. The nitrogen content of these specimens was higher than in the other specimens and this may lead to embrittlement.
6) The nature of the microphases varied from grain boundary carbides at low alloying content to more or less continuous layers of retained austenite at the higher alloying contents.

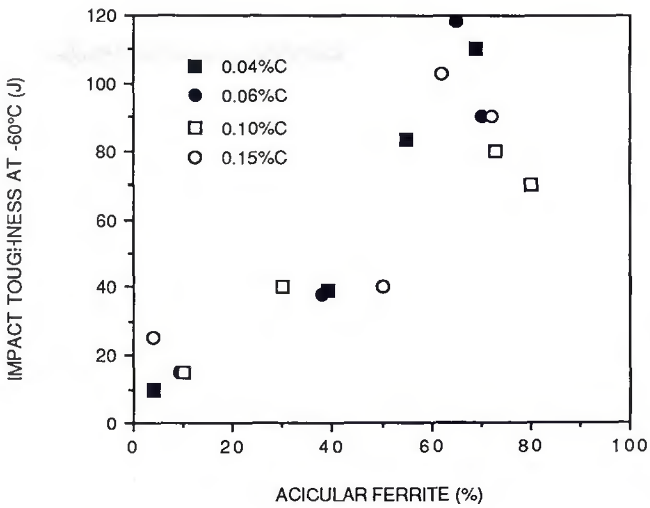


Fig. 15 — Impact toughness at −60°C as a function of acicular ferrite content, from the work of Evans (Ref. 2).

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