Shielding Gas Mixtures for High Quality Mechanized GMA Welding of Q&T Steel

Effect of various mixtures on penetration characteristics is exploited to find a helium rich mixture suitable for welding HY130 steel

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ABSTRACT. Reported here is a development program to establish the gas mixtures for mechanized GMA welding of HY80, HY100 and HY 130 steels which give improved performance in terms of deposit mechanical properties and welding procedure characteristics.

The program studied first the effect of inert gas rich mixtures upon welding characteristics to establish the most promising mixtures from a consideration of bead shape and defect incidence for mechanized, flat position, GMA welding. The best of these mixtures, together with Ar-2%O_2, were used in the second part to make welds in HY130 steel. Tensile, Charpy impact and crack opening displacement (COD) tests were carried out and the properties from the selected gas mixtures compared with those for Ar-2%O_2.

This investigation demonstrates the advantages of alternative gas shields over the Ar-2%O_2 mixture currently used for high quality mechanized GMA welding of quenched and tempered steels. The He-rich mixtures can be expected to give equivalent mechanical properties to those with Ar-2%O_2 while reducing the risk of welding defects. It is considered that these developments will be of advantage primarily to those involved in the fabrication of quenched and tempered steels but there are, nonetheless, other areas of steel fabrication where they are likely to be of benefit.

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Introduction

With the continuing rise in labor costs, there has been a growing need for the development of manual welding processes that are more economical than shielded metal arc and for the introduction of mechanized processes to replace manual operations. In developments to meet these needs, the gas metal arc (GMA) welding process has attracted considerable attention both in the semiautomatic and mechanized forms because of the advantages it offers.

The particular merits of the process are its ability to deposit more metal in a given period of time than that deposited by the shielded metal-arc process and the ease by which it can be mechanized for flat and out of position welding. A further major advantage is its potential to deposit very clean welds of high quality and excellent fracture toughness. This last feature has led to its consideration and use for joining high quality quenched and tempered steels, such as HY80, HY100 and HY130. However, while very clean sound welds may be made in the laboratory with better fracture toughness properties than deposits made by any other welding process, apart from gas tungsten-arc, this is not so readily achieved in a shipyard where these materials have been most widely fabricated in practice. This arises because the arc shielding gas is readily blown away without there being any visible indications to warn when it is occurring. Furthermore, the argon-oxygen gas mixtures developed to provide the high toughness deposits have sacrificed some of the good welding characteristics achieved with the more oxidizing mixtures and soundness is far more difficult to guarantee.

With Ar-2/5% O_2 gas shielding, the most serious welding defects are porosity and lack of side-wall and inter-run fusion. These occur not only through loss of gas shielding but also because of the deep finger penetration encountered in beads deposited with this gas mixture.

The porosity risk can be minimized by ensuring that shielding is not lost and the incomplete fusion risk reduced by careful attention to welding practice. In a shipyard, however, where thick sections are welded, these are difficult conditions to achieve. Therefore, any improvement in gas shielding efficiency or weldability is not just desirable but a most essential feature if the full potential of the process is to be achieved and the risk of brittle fracture in service kept to an acceptable level.

At the HY80 strength level, various metal-arc processes may be used,

Table 1 — Chemical Analyses of 25 mm (1 in.) Thick HY 130 Plate and 1.6 mm (1/16 in.) Electrode "Wire T", wt%

	C	S	P	Si	Mn	Ni	Cr	Mo	V	Cu	Nb	Ti	Al
Plate	0.11	<0.005	0.006	0.33	0.84	4.98	0.59	0.52	0.10	0.04	<0.005	<0.01	0.04
Wire T	0.08	0.006	0.011	0.35	1.82	2.30	1.04	0.61	0.04	0.08	<0.005	0.01	0.01

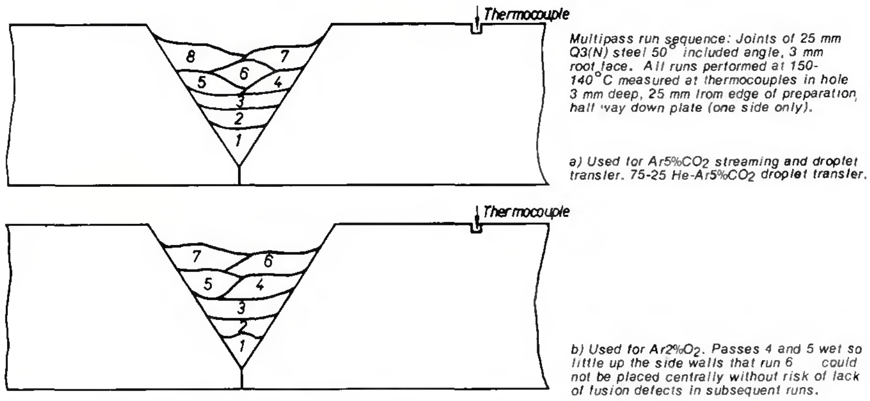


Fig. 1 — Welding sequence — multipass tests. The first pass was made at reduced current in each case and is not representative

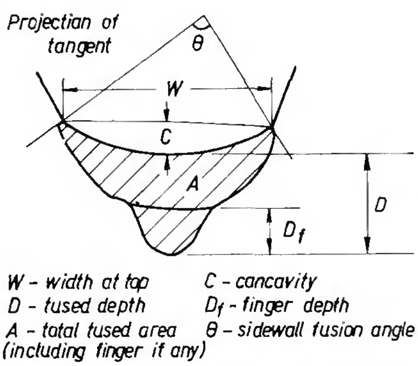


Fig. 2 — Measurements taken from sections. Bead in groove

permitting the GMA welding process to be limited to the less critical areas where its higher deposition rate offers production advantages. However, with the higher strength HY100 and HY130 steels, it may be necessary to use GMA welding in the more critical areas because the shielded metal arc and submerged arc processes cannot achieve sufficient toughness. With this in mind, a development program has been started to establish GMA shielding mixtures that give improved performance in terms of deposit mechanical properties and welding procedure characteristics. The program, which has dealt with mechanized welding of HY130 steel in the flat position, incorporates an examination of the influence on welding characteristics of various inert gas rich mixtures. These mixtures were based on the Ar-O_2, Ar-CO_2, Ar-He-O_2 and Ar-He-CO_2 systems. Finally, butt welds were made using the gas mixtures with the best welding characteristics to compare the mechanical properties with Ar-2%O_2.

Materials

Shielding Gas Influence on Welding Characteristics

The tests were carried out using HY80 and HY130 steels and 1.6 mm (1/16 in.) diam electrode designated "wire T". The chemical analyses of the HY130 steel and wire T are given in Table 1. The shielding gas mixtures were laboratory prepared using welding grade helium, argon, oxygen and CO_2.

Ar-CO_2 and He-Ar-CO_2 Mechanical Tests

25 mm (1 in.) thick HY130 plate was welded with 1.6 mm diam wire T. Shielding gas mixtures were laboratory prepared with welding grade gases.

Shielding Gas Influence

The optimum GMA gas shield for welding HY130 steel as regards yield strength and toughness is considered to be Ar-2%O_2. This mixture, therefore, formed the basis for the study of the influence of gas mixture upon metal transfer and bead shape. The shielding gases examined were selected from the following combinations: AR-O_2, Ar-CO_2, Ar-He-O_2 and Ar-He-CO_2. The welding parameters (current, voltage, wire feed speed) were established for the different metal transfer modes, and, subsequently, a number of shielding gas mixtures were selected for bead-in-groove and multipass tests. The specimens were examined to establish the effect of the different shielding gas mixtures upon bead profile, wetting and incidence of defects.

Welding Procedure

Throughout the project the arc lengths were set as short as possible without short-circuiting occurring. This was to ensure the best directional stability for the arc in the single and multipass deposits.

Initial tests to establish the process characteristics in the various shielding gases were conducted as bead-on-plate tests, using bright mild steel. Mild steel was used because properties of the plate material were unlikely to affect either the arc or the transfer characteristics associated with the electrode wire, and the behavior of subsequent tests on HY80 and HY130 plate supported this assumption.

For the bead shape tests, bead-in-groove deposits were made in HY80 plate. Composite specimens were constructed but only the bead-in-groove results are considered because the welding parameters chosen did not give a good condition for the other deposits. The testplates were 150 × 150 × 25 mm (6 × 6 × in.) with a 50 deg included angle groove 20 mm (0.79 in.) deep and a 6 mm (0.24 in.) root radius. These were preheated to 200 C (390 F) in a furnace and then allowed to cool to between 140 and 150 C (285 and 300 F) before each deposit was made.

The order and positions in which the multipass runs were made are shown in Fig. 1. The tests were made at preheat and interpass temperatures of 140-150 C, followed by a postweld heat treatment for 25 h at 150 C to remove hydrogen.

Metallographic sections were taken from three points in each weld at a quarter, a half and three-quarters along the length of the weld.

The weld bead profile was determined metallographically from the section taken at the middle of each weld run. The pertinent measurements, used to define the bead profile, penetration characteristic and degree of wetting are shown in Fig. 2.

Metal Transfer Characteristics

In this investigation of free flight metal transfer characteristics, three modes of transfer were observed for the range of welding current investigated, sub-threshold, droplet and streaming, these being defined as follows:

Sub-Threshold — The droplets grow in size at low currents to several times the wire diameter and transfer under the force of gravity to the workpiece. This mode is not normally usable due to the low transfer frequency and, therefore, is not considered further.

Droplet — At higher currents than sub-threshold transfer, the wire end becomes rounded and spherical droplets, approximately the same size as the wire, detach at moderate velocity and a rate dependent upon the wire feed speed. The detachment forces are principally electromagnetic in origin and the detachment rate is approximately 40/s.

Streaming — At still higher currents there is a transition to streaming transfer. This mode is associated with a self-induced magnetic field which exerts a strong radially constrictive force. This force suppresses the normal droplet mode and constricts the molten tip into a taper from which small droplets transfer at high frequency and velocity across the arc.

The droplet transfer mode is preferred owing to the avoidance of the finger penetration into the plate produced with streaming transfer. However, with the Ar-O_2 mixtures used in the high quality GMA welding of steel, the deposition rates of the droplet mode of transfer are very low and are generally uneconomic to adopt in production. Because of this, GMA welding with Ar-O_2 mixtures normally operates in the streaming transfer mode with an inherently greater risk of porosity and lack of fusion defects occuring.

Figure 3 shows the transition currents from droplet to streaming transfer for the Ar-He, Ar-HeO_2 and Ar-He-CO_2 mixtures examined. Increasing the proportion of He above about 75% in the Ar-He system increases the transition current markedly, so much so that at 95% He only droplet transfer is obtained at welding currents up to 400 A. The addition of oxygen to Ar-He mixtures reduces the transition current by 25-50 A. Moreover, the value of this transition, for any particular Ar-He mixture is further reduced as the oxygen content is increased from ½ to 5%. In contrast, the addition of 5%CO_2 to an inert Ar-He mixture containing more than 20% He raises the transition current. It has also been found that higher voltages were required with He rich mixtures than Ar-rich mixtures to avoid short-circuiting.

Welding Parameters

The currents and voltages at which the droplet-streaming transitions occur have been determined for all the gas mixtures investigated and are

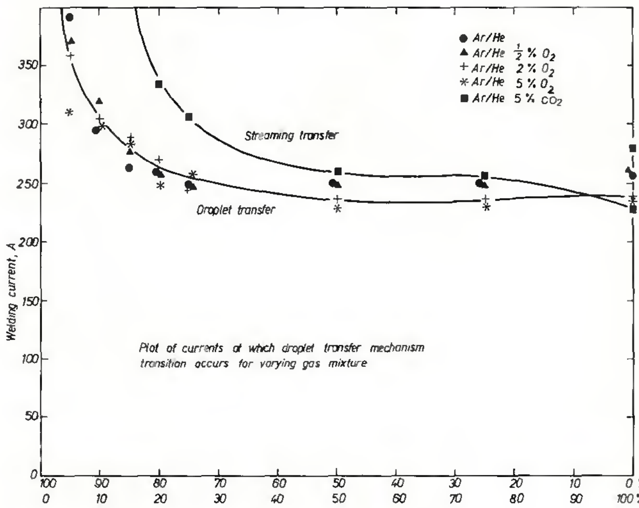
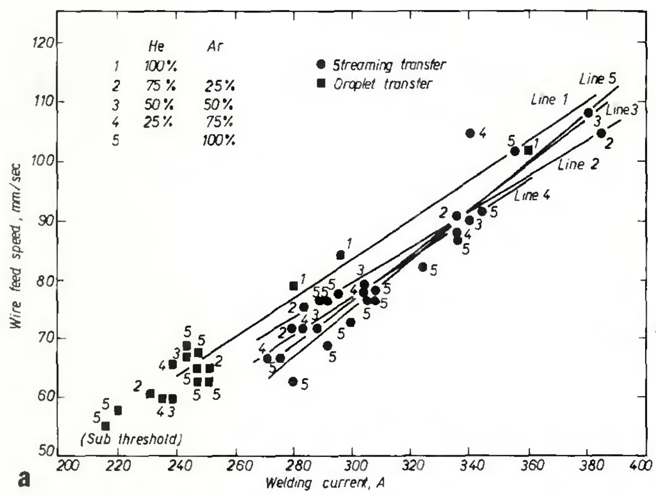


Fig. 3 — Transfer mode transition currents



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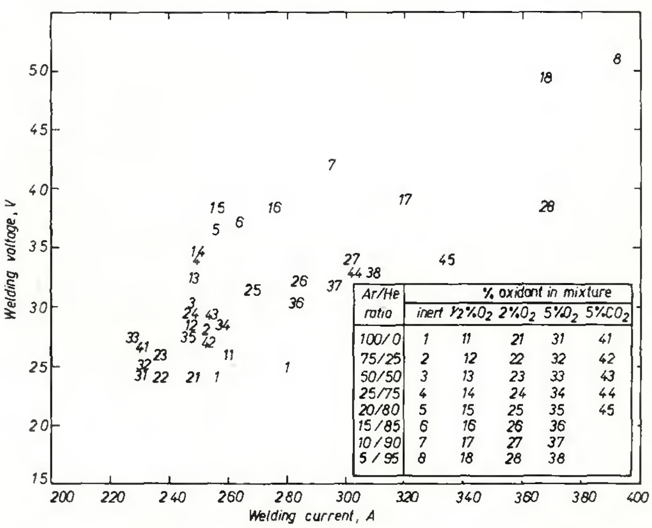

Fig. 4 — Currents and voltages at transfer mode transitions. Transition points (droplet-streaming transfer) for shielding gas mixtures Ar-He-O_2-CO_2

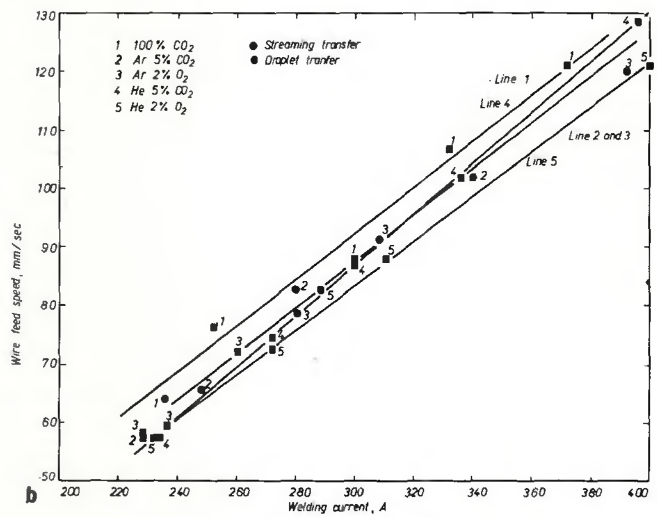

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Fig. 5 — Melting rate characteristics, (a) inert gas mixture, (b) oxidizing gas mixtures

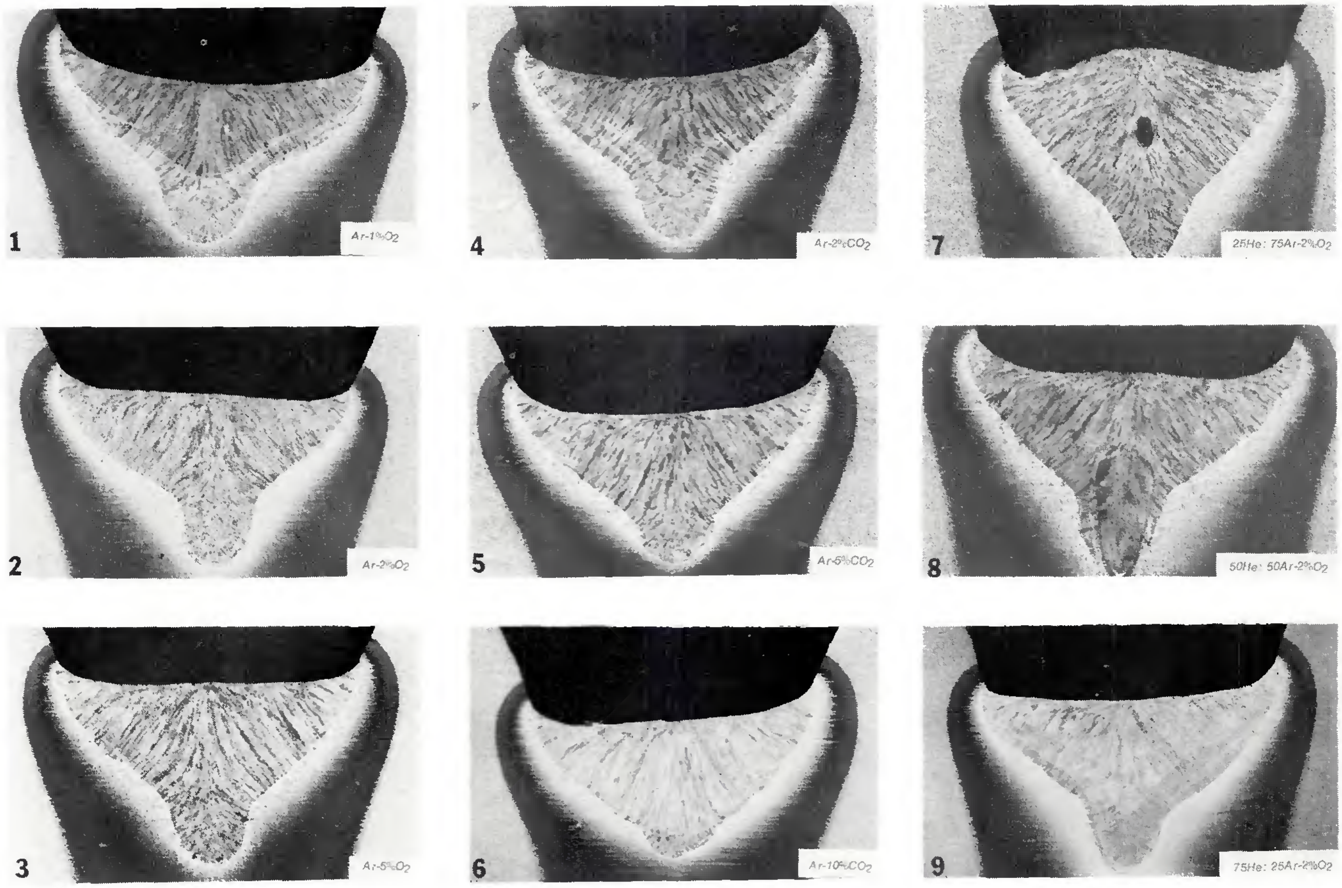


Fig. 6 — Sections of single pass deposits showing effect of shielding gas mixtures on finger depth (central penetration) and sidewall fusion (Numbers 1-11) streaming transfer mode; (12-18) droplet transfer mode. x5 (approx.), reduced 46%

shown in Fig. 4. It was found that the usable arc voltages (V) and arc currents (I) over the range 200-400 A were given approximately by the following relationship, where V_t and I_t are the transition voltage and current respectively.

$$V = \frac{V_t - 15}{I_t} \times I + 15$$

This relationship is valid only for bead-on-plate welds and must be treated with caution for other situations.

With a self-adjusting arc system it is not possible to set the operating current, per se, but only the wire feed speed as the independent variable. Accordingly, the relationships between wire feed speed and welding current for various mixtures have been determined as shown in Fig. 5.

Using the data in Figs. 3-5 and the above equation, welding current, voltage and wire feed speed can be determined for either droplet or streaming transfer with the gas mixtures studied. Travel speed can subsequently be determined from knowledge of the energy input required.

Arc and Weld Pool Behavior

With an inert gas which is not oxidizing and electrode positive, the arc cathode mechanism is unstable, metal transfer is erratic and the weld bead deposited is peaky and poorly wetted into the base metal. This instability and the associated problems are eliminated by the addition of a small quantity of an oxidizing gas (e.g., 1.5%O_2 or 1-10%CO_2).

Process Behavior of Bead-in-Groove Tests

Tests were carried out for Ar-½%O_2, Ar-1%O_2, Ar-2%O_2, Ar-1%CO_2, Ar-2%CO_2, Ar-5%CO_2, Ar-10%CO_2, (75Ar:25He)-2%O_2, (75Ar:25He)-5%CO_2, (50Ar:50He)-2%O_2, (50Ar:50He)-5%CO_2, (25Ar:75He)-2%O_2 and (25Ar:75He)-5%CO_2. These mixtures were examined using welding parameters established by the procedure described previously. It was found necessary to trim these parameters only slightly in any run to obtain good groove welding conditions for the particular gas shielding and current level chosen.

For many of the gas mixtures and current settings investigated, the welding voltage for operation in the groove was critical, on occasions to less than ± ½ V. Too low a voltage caused heavy short-circuiting, disruption of the gas shield and serious agitation of the weld pool. Conversely, too high a voltage allowed the lengthened, but still short, arc to wander about the preparation thus seriously affecting the position, profile and wetting of the deposit.

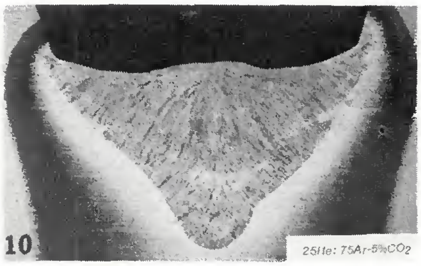
None of the test welds exhibited undercutting. This was attributed to the combination of low heat input and the short arc length used throughout.

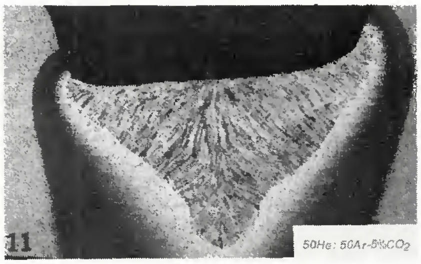
Transfer Mode Vs. Fusion in Single Pass Tests

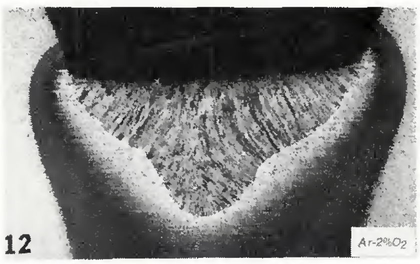
Streaming transfer, which is the most commonly used mechanism of free flight metal transfer in GMA welding, was found to lead to distinct finger penetration in the deposit. The resultant weld beads were deeply penetrated at their centerline, but to either side of the finger, the fusion of the base metal was very much reduced in comparison. The deposits formed by a droplet transfer mechanism exhibited little or no finger, and base metal fusion was moderate and more uniformly distributed over the full width of the weld.

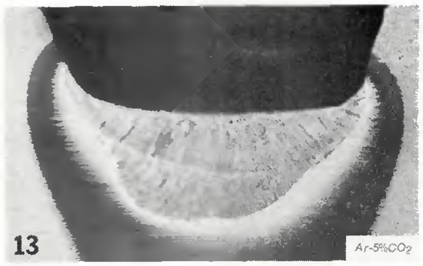
Gas Mixture Vs. Weld Form in Single Pass Tests

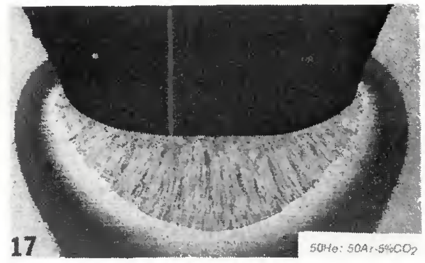
The results are given in Table 2. Because of arc blow effects at the ends of the plate, sections taken from these regions were not considered

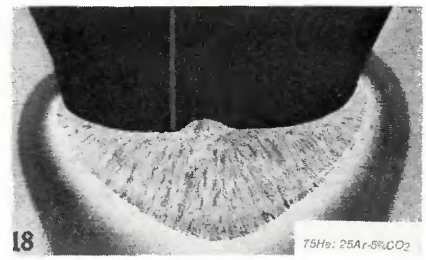












representative of the welds as a whole. For this reason, the data which are presented are taken from the mid-position sections of the welds. Selected profiles of the welds are shown in Fig. 6.

Measurements of the single pass welds in the base of a groove show that, within the probable limits of scatter due to arc length criticality, for a given current the total fused area was approximately constant for all gas mixtures. A reduction of 25% in welding current reduced the fused area by approximately 20%.

Within the limits investigated (½-5%O_2 and 1-10%CO_2), the proportion of oxidant in the shielding gas did not influence significantly the finger depth for streaming transfer. However, there is a slight tendency for the finger to be less pronounced when using a 5%CO_2 mixture compared with the 2%O_2 mixture, particularly if there is He present. In general the finger is reduced as the He content is increased.

For welds employing the droplet transfer mechanism the differences in central penetration are more pronounced. The 5%CO_2 mixtures show a rounded penetration profile but the 2%O_2 mixtures still display some finger penetration which He enrichment reduces.

Increased He content was found to increase the depth of sidewall fusion and general wetting into the plate. This latter aspect was assessed from measurements of the 'sidewall fusion angle'. For an increase in He content from Ar-2%O_2 to 75He:25Ar-2%O_2, the sidewall fusion angle increased from 45 to 73 deg.

Mixtures containing 5%CO_2 were found to fuse the sidewalls better than those containing 2%O_2. This is also shown clearly in the multipass test sections where Ar-5%CO_2 and Ar-2%O_2 were both used with a streaming transfer mechanism.

Gas Mixture on Weld Form in Multipass Tests

Multipass welds were made in 25 mm thick HY130 using the joint configuration shown in Fig. 1 to assess the performance of the gas mixtures in a joint. Only three gas mixtures were used, these being selected from those giving the best performance in the single pass tests. The gas mixtures examined were: Ar-2%O_2, Ar-5%CO_2 and 75He:25Ar-5%CO_2. Macrostructures of the multipass welds are shown in Fig. 7.

Multipass welds using 75He:25Ar-5%CO_2 with high current droplet transfer showed no incipient defects, either slag entrainment between passes, or incomplete of side wall fusion. By comparison, Ar-5%CO_2 and Ar-2%O_2 using streaming transfer, although reasonably satisfactory, were less attractive. Of these the CO_2 mixture was preferred, producing deeper sidewall fusion and being less susceptible than the O_2 mixture to heavy short circuiting when the arc voltage was slightly (0.5 V) below the optimum value. Ar-5%CO_2 also gave satisfactory interpass and sidewall fusion in the droplet transfer mode but not as good as that for the 75He:25Ar-5%CO_2 mixture.

Mechanical Tests — Ar-CO_2 and He-Ar-CO_2

To conclude this program of work, a series of welds was made in 25mm thick HY130 using the best of the shielding gas mixtures developed in the preceding part, to compare the mechanical properties with those of welds made with Ar-2%O_2 shielding. The welds were deposited at two energy inputs, 1.2 and 2.0 kJ/mm (30 and 51 kJ/in.), with 75He:25Ar-5%CO_2 in the droplet transfer mode and Ar-5%CO_2 in the streaming mode of transfer.

For comparison, welds were made with Ar-2%O_2 using a streaming transfer mode at the same energy inputs.

Welding Procedure

The welds were made mechanized in the flat position with wire T between two 150 × 400 × 25 mm (6 × 16 × 1 in.) plates along the 400 mm dimension. A single V preparation was used as detailed in Fig. 8. The plates were preset at an angle of 4 deg and preheated to 150 C. When

Table 2 — Single Pass Bead in Groove Results for (A) Helium-Free and (B) Argon-Helium Mixtures

(A) Helium free:
Streaming mode transfer

Gas	V	A	Depth, mm	Width, mm	Fused area, mm²	Con-cavity, mm	Finger depth, mm	Sidewall fusion angle, deg	Bead-on-plate angle of rein-forcement, deg	Com-ments
Ar-½%O_2	23	292	6.2	12.7	40.3	2.0	2.1	−19	44	
Ar-1%O_2	23	296	6.7	12.7	43.2	1.7	2.9	26	33	
Ar-2%O_2	23	290	7.1	12.0	42.1	0.8	3.0	45	34	
Ar-5%CO_2	23	304	7.6	12.5	47.4	0.8	2.9	50	35	
Ar-1%CO_2	23	284	6.7	12.5	45.8	1.7	3.1	−1	45	
Ar-2%CO_2	23.5	288	6.7	12.0	43.3	1.4	2.7	78	37	
Ar-5%CO_2	24	296	6.2	12.5	43.2	1.6	2.2	85	30	
Ar-10%CO_2	25	300	8.5	11.6	54.9	0.2	2.5	67	31	(a)
Ar-10%CO_2	26	290	6.0	12.6	46.8	1.2	1.1	87	—	(a)
Droplet mode transfer										
Ar-2%O_2	21.5	232	5.7	12.1	38.1	0.6	2.3	43	34	
Ar-5%CO_2	23	232	4.5	12.1	37.8	0.7	1.1	55	30	

(B) Argon-Helium mixtures
Streaming mode transfer

Gas	V	A	Depth, mm	Width, mm	Fused area, mm²	Con-cavity, mm	Finger depth, mm	Sidewall fusion angle, deg	Bead-on-plate angle of rein-forcement, deg	Com-ments
100Ar:0He-2%O_2	23	290	7.1	12.0	42.0	0.6	3.0	45	34	
75Ar:25He-2%O_2	24.5	312	8.9	11.8	54.2	−0.8	2.2	50	35	(a)
50Ar:50He-2%O_2	26	308	8.3	13.5	54.4	1.2	3.5	110	26	(a)
25Ar:75He-2%O_2	27	300	7.2	12.2	46.8	1.0	2.8	73	21	
100Ar:0He-5%CO_2	24	296	6.2	12.5	43.2	1.6	2.2	85	30	
75Ar:25He-5%CO_2	26	308	7.7	13.3	55.5	1.1	2.4	109	30	
50Ar:50He-5%CO_2	27	304	6.9	12.7	48.0	1.1	2.1	95	29	
Droplet mode transfer										
25Ar:75He-5%CO_2	29	284	5.3	12.7	44.2	1.4	0.6	91	26	(b)
100Ar:0He-2%O_2	21.5	232	5.7	12.1	38.1	0.6	2.3	43	34	
75Ar:25He-2%O_2	23	232	5.5	12.3	37.9	1.2	2.0	81	33	
50Ar:50He-2%O_2	24	232	5.0	12.3	38.1	1.9	1.5	52	27	
25Ar:75He-2%O_2	26	232	4.5	13.0	37.6	1.7	0.8	69	23	
100Ar:0He-5%CO_2	23	232	4.5	12.2	37.8	1.7	1.1	55	30	
75Ar:25He-5%CO_2	—	—	—	—	—	—	—	—	—	(c)
50Ar:50He-5%CO_2	26.5	232	4.0	12.5	34.8	1.8	0	86	24	
25Ar:75He-5%CO_2	28	244	4.7	12.6	41.4	1.7	0.4	73	22	

(a) Test spoiled by full penetration.
(b) High current droplet transfer.
(c) Would not run.

Table 3 — Welding Conditions for HY130 Welds

Weld no.	Shield gas	Arc energy, kJ/mm	Cur-rent, A	Vol-tage, V	No. of runs	Shield gas flow l/min	Travel speed, mm/min
BF 586	Ar-2%O_2	1.2	330	25	18	26	415
BF 587	Ar-2%O_2	2.0	330	25	15	26	290
BF 588	Ar-5%CO_2	1.2	330	25	18	26	415
BF 589	Ar-5%CO_2	2.0	330	25	12	26	290
BF 590	71He-24Ar-5%CO_2	1.2	290	31	20	59	440
BF 591	71He-24Ar-5%CO_2	2.0	250	32	14	59	240

welding was completed on the first side, the reverse side was arc air gouged to a depth of 13 mm (½ in.) and the weld finished. The interpass temperature was kept in the range 100-150 C and, on completion, the weld was heat treated for 20 h at 150 C to remove hydrogen. The welding conditions for each weld are summarized in Table 3.

Mechanical Tests

The following tests were carried out on welds made with each shielding gas-energy input combination. Specimen extraction is shown in Fig. 9.

(a) Two Hounsfield No 14 tensile specimens tested at room temperature.

(b) Seven Charpy-V notch impact specimens tested at temperatures in the range −60 to +20 C (−76 to +68 F).

(c) Six COD specimens were extracted and notched (0.15 mm wide slots) in the through-thickness direction. Two specimens were tested at each of the following temperatures: −5 C, −25 C and −40 C (23, −13 and 40 F) using three point bending and a cross head speed of approximately 2 mm/min (0.08 in./min).

Mechanical Test Results

Charpy-V Notch Impact Tests — Absorbed energies at +20, 0 and −40 C derived from mean Charpy energy transition curves are summarized in Table 4.

With each gas mixture, the Charpy

Table 4 — Summary of Fracture Toughness and Strength Data for HY 130 Welds

Weld no.	Shield gas	Energy input, kJ/mm	Mean Charpy energy, J at +20 C	0 C	−40 C	Avg yield str, N/mm² @+20 C	Yield strain eγ (x10⁶) @+20 C	Lower bound values(a) of COD, δc, in mm@ 0 C	−40 C	Defect tolerance(b) parameter, δc/eγ, in mm at 0 C	−40 C
BF 586	Ar -2%O_2	1.2	155	143	80	927	4480	0.36	0.27	80	60
BF 587	Ar-2%O_2	2.0	135	121	77	845	4080	0.37	0.18	91	44
BF 588	Ar-5%CO_2	1.2	121	105	67	966	4670	0.24	0.24	51	51
BF 589	Ar-5%CO_2	2.0	80	76	54	958	4630	0.28	0.23	60	50
BF 590	71% He' 24% Ar-	1.2	145	126	89	898	4340	0.33	0.29	76	67
BF 591	5% CO_2	2.0	115	98	55	864	4170	0.31	0.23	74	55

(a) The lower of (1) Mean COD from plotted curve
(2) Level of COD above which fracture initiation was by tearing.
(b) The yield strain at +20 C has been used for calculation.

properties are better in the deposit made at the lower energy input. Furthermore, at each energy input, the Charpy properties are best with Ar-2%O_2 and worst in the Ar-5%CO_2 deposit with the 75He:25Ar-5%CO_2 mixture falling about midway between the two.

Tensile Tests — Table 5 summarizes the results of the tensile tests on the HY130 welds. As was to be expected, the yield strength of the welds made at the lower energy input for each gas mixture were highest. Only with the Ar-5%CO_2 mixture, however, was the yield strength greater than 895 N/mm² at both energy inputs.

COD Tests — The results of these tests are plotted in Fig. 10. For each gas mixture, the COD values for fracture initiation, δc, are better at the lower energy input. Comparing the effect of shielding mixtures shows that the COD values are similar for the Ar-2%O_2 and 75He:25Ar-5%CO_2 welds these being slightly better than the Ar-5%CO_2 welds.

Table 5 — Results of Tensile Tests on HY 130 Welds

Weld no.	Shield gas	Arc energy, kJ/mm	Yield stress, N/mm²	Tensile stress, N/mm²	Elongation, %	Red. of area, %
BF 586	Ar-2%O_2	1.2	930	976	22	70
BF 586	Ar-2%O_2	1.2	924	970	23	68
BF 587	Ar-2%O_2	2.0	837	919	25	69
BF 587	Ar-2%O_2	2.0	852	920	20	67
BF 588	Ar-5%CO_2	1.2	942	1001	20	63
BF 588	Ar-5%CO_2	1.2	989	1030	20	64
BF 589	Ar-5%CO_2	2.0	962	1035	20	62
BF 589	Ar-5%CO_2	2.0	954	1016	18	63
BF 590	71He-24Ar	1.2	880	935	23	68
BF 590	−5%CO_2	1.2	915	955	19	65
BF 591	71He-24Ar	2.0	844	978	23	67
BF 591	−5%CO_2	2.0	883	999	19	63

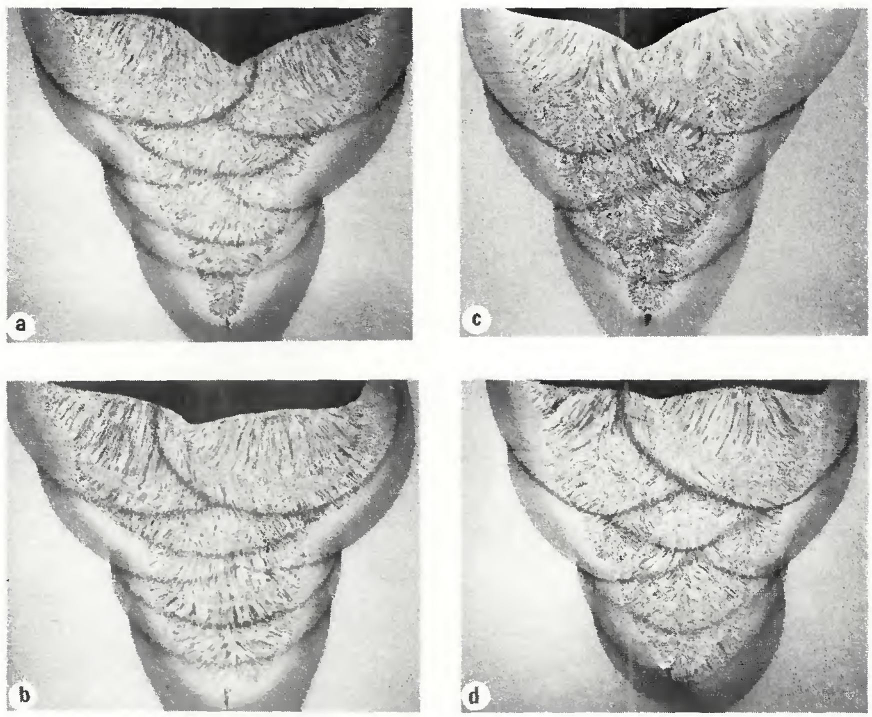


Fig. 7 — Multipass weld deposits. (a) Ar-5%CO_2 Droplet transfer mode; (b) 75He:25Ar-5%CO_2. Droplet transfer mode; (c) Ar-2%O_2. Streaming transfer mode; (d) Ar-5%CO_2. Streaming transfer mode

Discussion of Fracture Tests

The Charpy V-notch energies, yield strength and defect tolerance values ($\delta c/e\gamma$), are summarized in Table 4. The lower bound COD values have been used in the derivation of the defect tolerance parameters when initiation is by tearing. The temperatures were chosen to correspond to tests where microvoid coalescence (0 C) or cleavage (−40 C) were the dominant mechanisms of fracture initiation.

The defect tolerance values at 0 C are similar for both energy inputs with the 75He:25Ar-5%CO_2 shielding mixture and slightly better at the higher energy inputs with the other two mixtures. The reason for the better performance at the high energy input with these two mixtures is because of the lower yield strength which results in a higher $\delta c/e\gamma$ value.

In contrast, the defect tolerance levels at −40 C decrease with the Ar-2%O_2 and 75He:25Ar-5%CO_2 mixtures as the energy input is raised from 1.2 to 2.0 kJ/mm. With the Ar-5%CO_2 mixture there is no change. The fall in the other cases is because the measured fracture toughness, δc, is lower and the effect of this reduction is not compensated by the lower yield strength.

The best defect tolerance values at 0 and −40 C are given by the Ar-2%O_2 and 75He:25Ar-5%CO_2 mixtures at 1.2 kJ/mm. At the higher energy input, the 75He:25Ar-5%CO_2 mixture is still good and is better than the Ar-5%CO_2 mixture at both energy inputs. However, notice must be taken of the yield strengths since, in certain instances, including the 75He:25Ar-5%CO_2 mixture at the higher energy input, the values are below the minimum levels which would be considered acceptable for HY130 steel.

The observations made concerning the defect tolerance parameters are completely in accord with the trends evident in the Charpy impact results.

Chemical Analysis

Spectrographic analyses were carried out on transverse sections taken from the weld deposits. The chemical analyses are given in Table 6. Oxygen analyses were made on drillings taken from the weld deposits and the values obtained are included in Table 6.

The carbon equivalent values are tabulated also and these are similar for the Ar:2%O_2 and Ar-5%CO_2 welds but lower for the 75He:25Ar-5%CO_2 welds. The oxygen values are very low. They are consistent, however, with separate unpublished Welding Institute data for GMA welds made with Ar-2%O_2 shielding. The 75He:25Ar-5%CO_2 and Ar-2%O_2 mixtures give equivalent values indicating that oxygen pickup from these gases is similar. The Ar-5%CO_2 mixture gives a marginally higher oxygen value than is given by the other two mixtures.

Soundness

Macrosections of the joints are shown in Fig. 11. In the welds made with Ar-5%CO_2 shielding a number of small pores are visible. The presence of pores in the welds made with Ar-5%CO_2 shielding was confirmed by x-ray examination. The level of these was not high and no evidence was obtained during mechanical testing to indicate they were influencing fracture. No defects were detected in the welds made with the other two shielding mixtures.

General Discussion

The work carried out in this program was undertaken to establish whether alternative shielding mixtures to Ar-2%O_2 are available or could be developed for GMA welding in the flat position which gave similar or better mechanical properties than Ar-2%O_2 but are easier to use and result in lower defect levels in the deposits. The program was directed at the GMA welding of the high strength quenched and tempered steels because for certain applications of these, the alternative flux shielded metal-arc processes are unlikely to achieve the high levels of fracture toughness required. As a result, HY130 steel has been used and the mechanical test values obtained have been assessed in terms of their suitability for welding this material. For this reason, yield strengths below 895 N/mm² (130 ksi) and toughness properties below those of Ar-2%O_2 have been considered unacceptable.

Attempts to develop gas mixtures in such cases as this have concentrated, in the past, almost exclusively on the short circuiting transfer mode in order to provide positional ability (Ref. 1). Because of this, little attempt has been made to develop alternatives to the Ar-2%O_2 mixture for high deposition rate welding, whether mechanized or semiautomatic, and it is for this reason that the present work was undertaken.

The particular problem with Ar-2%O_2 shielding in the flat position, as described previously, is the risk of porosity and lack of side-wall and inter-run fusion. Examination of the results obtained in this program demonstrates that improvements in the welding characteristics can be obtained with He-rich mixtures without causing a deterioration in the mechanical performance. Furthermore, the developments reported go much of the way towards providing a shielding mixture with the desired features.

The 75He:25Ar-5%CO_2 mixture examined is particularly promising. The reason why its performance is better is threefold. First, its oxygen potential, as evident from the oxygen analyses reported in Table 6, is the same as Ar-2%O_2. Second, a droplet transfer mechanism can be used at the current levels required for acceptable welding and deposition rates resulting in a rounder, more evenly penetrated bead being produced.

Third, the He-rich mixture offers better process stability. In this work, the major process stability problem experienced was associated with volt-

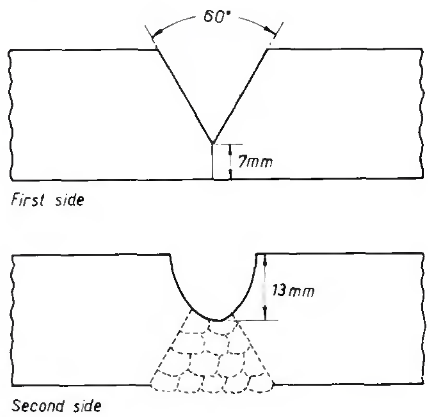
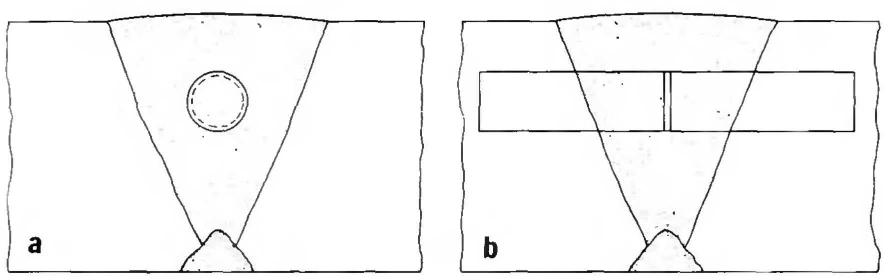


Fig. 8 — Joint dimensions for welds in HY130 steel



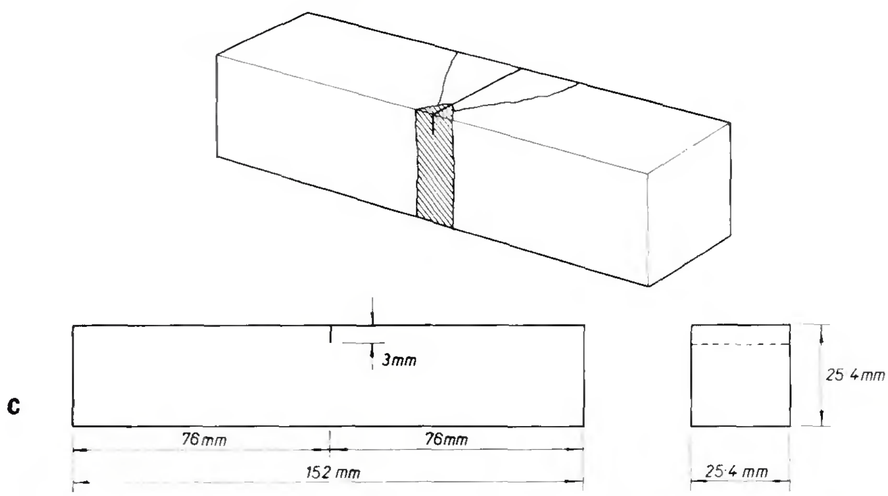


Fig. 9 — Specimen extraction: (a) Hounsfield no. 14 tensile specimens; (b) Charpy V-notch specimens; (c) COD specimens

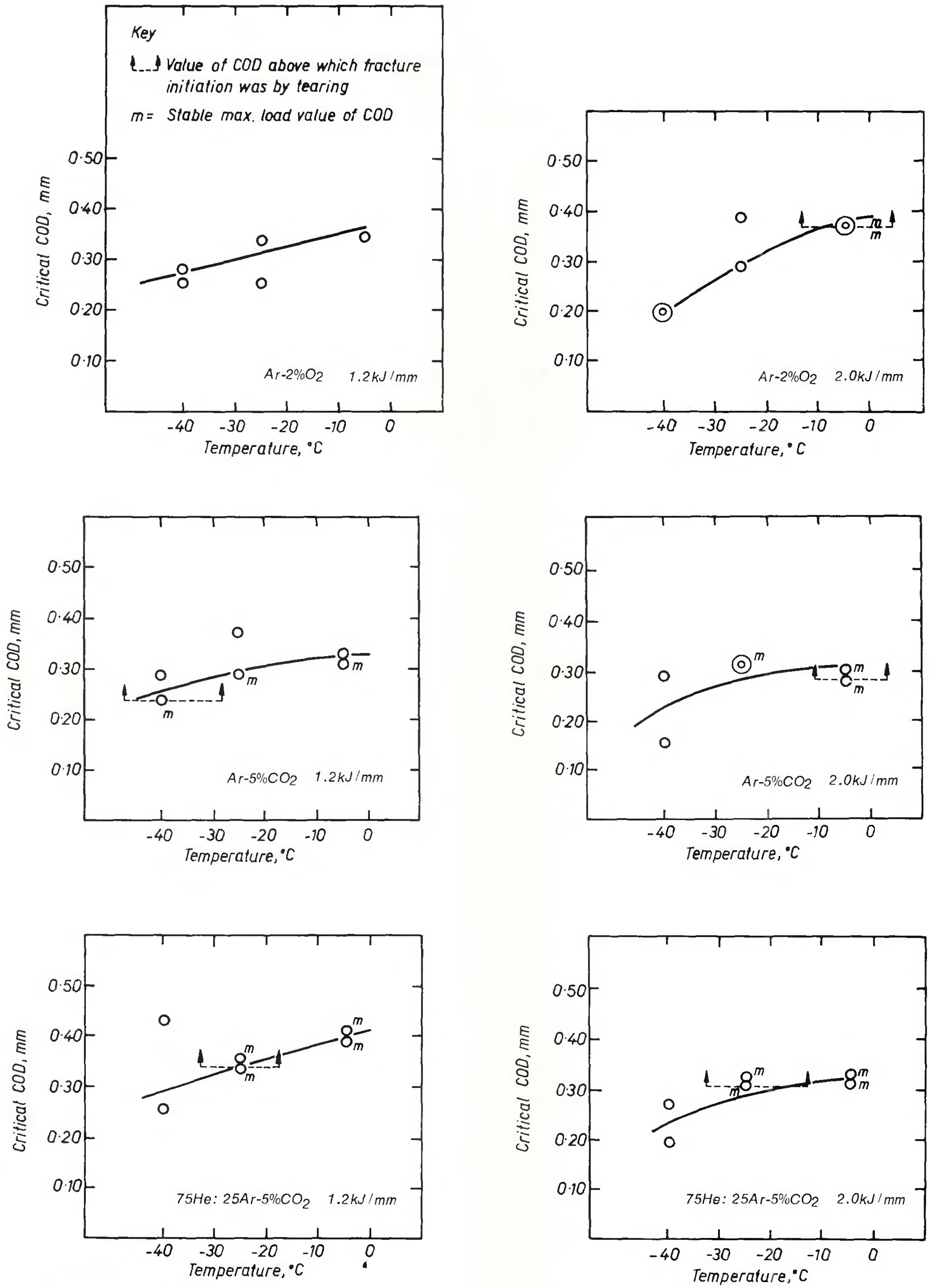


Fig. 10 — COD test results

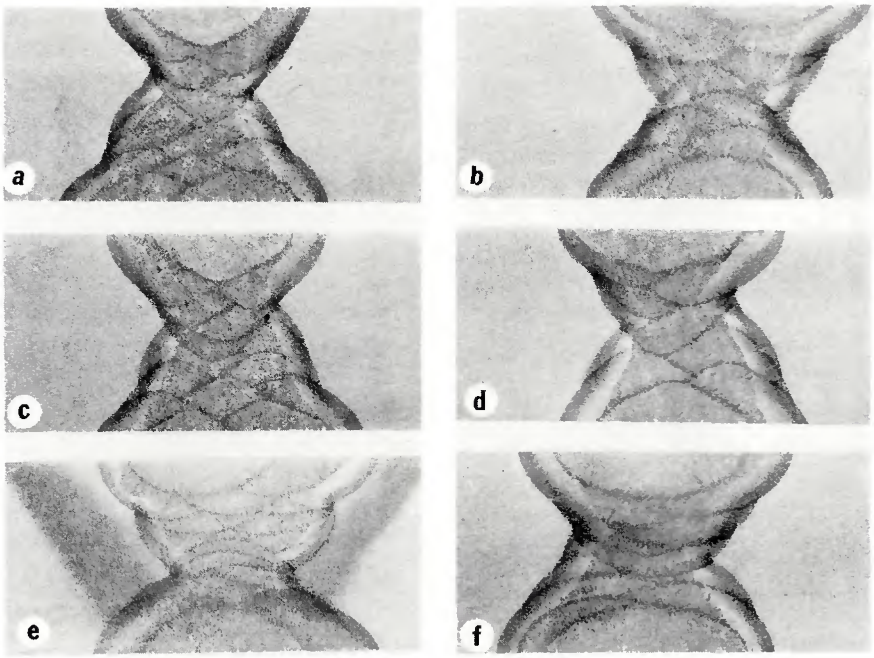


Fig. 11 — Macrosections of HY130 welds. (a) Ar-2%O_2-1.2 kJ/mm; (b) Ar-2%O_2 2.0kJ/mm; (c) Ar-5%CO_2-1.2kJ/mm; (d) Ar-5%CO_2-2.0 kJ/mm; (e) 75He:25Ar-5%CO_2-1.2 kJ/mm; (f) 75He:25Ar-5%CO_2-2.0 kJ/mm

age control. Too long an arc length caused excessive arc wander when welding in a groove, and too short an arc length gave excessive shortcircuiting. Streaming transfer was the less tolerant mode and the optimum arc length was very sensitive to the voltage setting. This tolerance was improved by replacing the O_2 by CO_2. The tolerance with droplet transfer was greater and arc voltage could be set to within 2 V for all gases. Of the gases chosen for the multipass deposits, Ar-2%O_2 was least tolerant to changes in arc length as the voltage required a minor adjustment for each pass, whereas 75He:25Ar-5%CO_2 and Ar-5%CO_2 required only one or two adjustments throughout the welding sequence.

While it has not been possible to demonstrate conclusively that the risk of defects being formed is reduced with the He-rich mixture it does appear that there is no greater risk than with Ar-2%O_2 shielding.

Turning to fracture toughness and tensile properties, the 75He:25Ar-5%CO_2 mixture produced a deposit which was softer than Ar-2%O_2 at the same energy input. This result is consistent with the carbon equivalent values which were higher in the Ar-2%O_2 deposits. These higher values arose mainly because Mn and Si were lower in the He-rich welds.

The 0 C fracture toughness of the 75He:25Ar-5%CO_2 weld made at 1.2 kJ/mm where fracture initiation is by microvoid coalescence is almost as good in terms of defect tolerance values as the Ar-2%O_2 weld. At −40 C, where fracture initiation is by cleavage, it is better.

The fracture toughness results at −40 C and 0 C taken together show that the 75He:25Ar-5%CO_2 mixture is every bit as good as Ar-2%O_2 However, when yield strength is taken into account Ar-2%O_2 has the advantage since the yield strength with the He-rich mixture only just meets the minimum levels for HY130.

The potential of the Ar-5%CO_2 mixture is not as good as the He-rich mixture. In the tests carried out in this program, the Ar-5%CO_2 mixture provided only a minor improvement in the welding characteristics, primarily because streaming metal transfer has to be used at the current levels of interest. In terms of the tensile and fracture toughness properties the performance of the Ar-5%CO_2 mixture is inferior to Ar-2%O_2, although one advantage is that the yield strengths of the deposits made at the two energy inputs were similar and were both higher than the low energy input Ar-2%O_2 weld.

Conclusions

The tensile, fracture toughness and welding behavior properties of GMA deposits made in HY130 steel in the flat position with different shielding mixtures have been determined. The following conclusions have been drawn.

1. The finger penetration encountered with Ar-2%O_2 shielding is associated with a streaming metal transfer mechanism and can be avoided by reverting to a droplet transfer mechanism. The current

Table 6 — Analyses of Welds in HY 130 Steel, wt %

Weld no.	Shield gas	Energy input kJ/mm	C	S	P	Si	Mn	Ni	Cr	Mo	V	Cu	Nb	Ti	Al	B	Pb	Sn	Co	O	CE
BF 586	Ar-2%O_2	1.2	0.08	<0.005	0.006	0.36	1.57	2.95	0.97	0.61	0.03	0.07	<0.005	<0.01	0.005	<0.001	<0.01	<0.01	<0.01	0.011	0.87
BF 587	Ar-2%O_2	2.0	0.08	<0.005	0.006	0.35	1.59	2.74	0.97	0.61	0.03	0.07	<0.005	<0.01	0.005	<0.001	<0.01	<0.01	<0.01	0.012	0.87
BF 588	Ar-5%CO_2	1.2	0.09	<0.005	0.005	0.36	1.52	3.02	0.92	0.60	0.04	0.07	<0.005	<0.01	0.008	<0.001	<0.01	<0.01	<0.01	0.015	0.86
BF 589	Ar-5%CO_2	2.0	0.09	<0.005	0.005	0.36	1.50	3.11	0.92	0.60	0.04	0.07	<0.005	<0.01	0.009	<0.001	<0.01	<0.01	<0.01	0.012	0.86
BF 590	71He-24Ar	1.2	0.08	<0.005	0.005	0.32	1.43	2.83	0.96	0.61	0.03	0.07	<0.005	<0.01	0.005	<0.001	<0.01	<0.01	<0.01	0.011	0.83
BF 591	-5%CO_2	2.0	0.08	<0.005	0.005	0.32	1.34	2.96	0.93	0.61	0.04	0.07	<0.005	<0.01	0.005	<0.001	<0.01	<0.01	<0.01	0.011	0.82

levels needed for the droplet transfer mechanism with Ar-2%0_2 are low and would be rejected on economic considerations in practice.

2. Addition of He to shielding mixtures raises the transition current from droplet to streaming transfer. With 75He:25Ar-5%CO_2, droplet transfer can be achieved at current levels equivalent to those used with Ar-2%0_2 mixtures for welding HY130 steel.
3. The fracture toughness of 75He:25Ar-5%CO_2 welds is similar to that of welds made with Ar-2%0_2. The yield strength is slightly lower but at 1.2 kJ/mm exceeds 895 N/mm^2.
4. Argon-rich gas mixtures containing CO_2 in place of 0_2 produced less finger penetration and deeper sidewall fusion when used with a streaming transfer mechanism. The yield strengths of welds made with Ar-5%CO_2 were higher than those made with Ar-2%0_2 but the fracture toughness was slightly inferior. Little benefit would be obtained by replacing Ar-2%0_2 by Ar-5%CO_2.
5. The 75He:Ar-5%CO_2 mixture can be used in the flat position to make weld deposits having similar mechanical properties and soundness to those made with Ar-2%0_2.

In larger scale tests, it is expected that the benefits of the droplet transfer mechanism will result in sounder welds being obtained with the He-rich mixture.

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