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EFFECT OF WELDING AND POST-WELD HEAT TREATMENT ON DUCOL W30

BY

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SUMMARY

Notch toughness, tensile and hardness properties of a normalised and tempered Mn-Cr-Mo-V steel have been determined after thermal cycling to 1275 °C in simulation of thermal cycles experienced in the coarse grained region of the heat affected zone (HAZ). The metallurgical structure was investigated by means of optical microscopy and electron microscopy of carbon extraction replicas. The coarse grained HAZ was found to have comparable notch toughness, as determined by the Charpy V-notch impact test, to the parent plate except for a decrease in the upper shelf energy.

Post-weld heat treatments for 100 min. in the range $450 - 650^{\circ}C$ resulted in decreased notch toughness of the coarse grained HAZ with maximum embrittlement after heat treatment at $550^{\circ}C$ and $600^{\circ}C$. Heat treatment for 100 min. at $675^{\circ}C$ was necessary to overcome this embrittling effect.

A brief examination was made of HAZ structures produced in multipass welds by subjecting specimens to double weld thermal cycles. A second thermal cycle to a peak temperature of $765^{\circ}C$ on a specimen initially cycled to produce a coarse grained HAZ structure resulted in areas of martensite at the prior austenite grain boundaries with a slight decrease in notch toughness.

Tensile tests at $365^{\circ}C$ were also conducted on the parent plate and some of the thermally cycled specimens. The greatest decreases in proof stress and tensile strength at $365^{\circ}C$ were 11% and 16% respectively for the parent plate.

CONTENTS

Page

1.	INTRODUCTION	1
2.	EXPERIMENTAL.	2
	 2.1 Materials 2.2 Procedure 2.2.1 Simulation of the coarse grained HAZ 2.2.2 Post-cycle heat treatment 2.2.3 Double cycle simulation 2.4 Mechanical testing 2.2.5 Metallographic examination 	2 3 3 3 3 3 3 3 3
3.	RESULTS	4
	 3.1 Mechanical properties 3.2 Metallographic examination 	4 6
4.	DISCUSSION	7
5.	CONCLUSIONS	10
	REFERENCES	11

FIGURES

1. Heat affected zone thermal cycles	used for specimen simulation.
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- 2. Effect of 100 min. post-weld heat treatments on the coarse grained HAZ of Ducol W30 energy/temperature curves.
- 3. Effect of 100 min. post-weld heat treatments on the coarse grained HAZ of Ducol W30 percent crystallinity/temperature curves.
- Effect of a second thermal cycle on the coarse grained HAZ of Ducol W30 - energy/temperature curves.
- 5. Effect of a second thermal cycle on the coarse grained HAZ of Ducol W30 percent crystallinity/temperature curves.
- 6. Parent plate microstructure.
- 7. Microstructure of the coarse grained HAZ.
- Microstructure of the coarse grained HAZ after post-weld heat treatment at 600°C for 100 min.
- Microstructure produced by a double thermal cycle with peak temperatures of 1275°C and 765°C

1. INTRODUCTION

Ducol W30 is a low carbon, low alloy, Mn-Cr-Mo-V steel which was developed by Colvilles Limited to meet the demand for large high-tensile steel plates up to 150 mm. (6 in.) thick for use in pressure vessels and boiler drums operating at temperatures below the creep range, (Ref. 1). It supercedes the use of mild steel plates for many applications where excessive plate thicknesses would be necessary to meet the design requirements of present day vessels. To ensure an adequate level of weldability the carbon content of the steel is restricted to 0.17% maximum and maximum limits imposed on the alloy content.

Ducol W30 is a semi-air-hardening steel and its properties are developed by air cooling from the austenitic range followed by tempering and the same fabrication procedures can therefore be employed as for C-Mn steels. The structure consists of a small amount of proeutectoid ferrite in a matrix of bainite and the steel has a minimum yield strength of 24 tonf./in in plate thicknesses of 75 - 125 mm (3 - 5 in.) and an ultimate tensile strength in the range 34 - 40 tonf./in.

Experience has indicated that butt welds in this material are normally satisfactory although McKenzie (Ref. 1) and Nicholls (Ref. 2) have reported heat affected zone (HAZ) cracking in fillet welds. However, McKenzie has shown that satisfactory fillet welds can be made by employing thoroughly dried basic-coated electrodes with a moderate degree of preheat (100 - 200° C).

In a previous report (Ref. 3) it was shown that the weld HAZ of Ducol W30 consisted of four distinct regions, (a) the region of grain coarsening, (b) the region of grain refinement, (c) the intercritical region, and (d) the spheroidised region. Evaluation of the Charpy V - notch impact properties of these weld HAZ structures produced by a simulation technique employing thermal cycles measured in a submerged arc bead-on-plate weld in 38 mm. (1.5 in.) thick plate at a heat input level of 4.2 KJ/mm. (108KJ/in.) showed that the coarse grained HAZ had the lowest notch-toughness with transition temperatures $50 - 70^{\circ}$ C above parent plate levels. Another Ducol steel supplied to the Babcock and Wilcox specification B.W. 87A, was shown to have similar notch-toughness in the coarse grained HAZ although the transition temperature was only 5 - 10° C above the parent plate level due to the relatively low notch-toughness of the latter which was associated with a coarse grained structure. Watkins et al. (Ref. 4) reported similar levels of notch-toughness in the coarse grained HAZ of a submerged arc weld (in which the heat input was not recorded) in a Ducol W30 steel although in a manual weld the notchtoughness of the coarse grained HAZ was comparable to that of the parent plate. Saunders and Dolby (Ref. 5), using the crack opening displacement (C.O.D.) test, showed reduced resistance to fracture initiation of three Ducol steels in the coarse and fine grained HAZ. The specimens were extracted from single run welds deposited automatically using a heat input of 1 KJ/mm (26 KJ/in.).

Since pressure vessels in Ducol W30 are invariably stress - relieved after welding, the effect of such a treatment on the notch-toughness of the coarse grained HAZ is of interest. The recommended stress-relieving temperature for such structures is in the range $620 - 660^{\circ}$ C such temperature

to be held for 1 hour per inch of thickness of the thickest member. The failure to achieve the desired stress-relieving temperature was a major contributing factor in the catastrophic failure of a pressure vessel at John Thompson (Wolverhampton) Limited, (Ref. 6). Watkins et al. have shown that the notch-toughness of the coarse grained HAZ deteriorates after stress-relieving at 450° C and 550° C for three hours and is not fully recovered even after three hours at 650° C. On the other hand Saunders and Dolby showed that one hour treatments at 450° C and 550° C and 650° C improved the notch toughness of both the coarse and fine grained HAZ as measured by the C.O.D. test, although only the 650° C treatment restored the notch-toughness to parent plate levels. Less improvement was observed after the 550° C treatment than after the 450° C treatment and this effect was associated with the precipitation of vanadium carbide.

The main objects of the present work was to examine the effects of post-weld heat treatments in the temperature range $450^{\circ}C - 675^{\circ}C$ on the coarse grained HAZ in order to ascertain the treatments which produced maximum embrittlement and those which restored notch-toughness to parent plate levels. A brief examination was also made of the effect of a second thermal cycle to peak temperatures of $1275^{\circ}C$ and $765^{\circ}C$ on the initial coarse grained HAZ structure such as may occur in multi-pass weldments.

2. EXPERIMENTAL

2.1 Materials

The Ducol W30 used for this investigation was in the form of 57 mm (2.25 in.) thick plate. The chemical analysis and mechanical properties of material taken from the mid-thickness of the plate are shown below. The mechanical test specimens were taken along the rolling direction.

Composition	C	Si	Mn	S	Р	Ni	Cr	Mo	V	Cu
	0.11	0.25	1.48	0.018	0.013	0.07	0.58	0.27	0.11	0.009
Specification maximum	0.17	0.30	1.50	0.050	0.050	0.30	0.70	0.28	0.10	-
Mechanical	0.2% proof stress (MN/m ²)		0.2% proof stress (tonf/in ²)		U. T. S.		U. T. S.		Reduction of	
properties					(MN/m^2)		$(tonf/in^2)$		Area (%)	
Longitudinal	478		31	.1	626		40.7		69	
Specification (transverse)	346 at	: 120 ⁰ C	22.5 at	: 120 ⁰ C	553/646		36/42		-	

Chemical composition and mechanical properties of Ducol W30

- 2 -

2.2 Procedure

2.2.1 Simulation of the coarse grained HAZ

Specimen blanks 83 mm x 10.7 mm x 10.7 mm (3.25 in. x 0.42 in. x 0.42 in), machined from the mid-thickness of the plate and along the rolling direction, were subjected to a weld thermal cycle with a peak temperature of 1275° C in a weld thermal cycle simulator. The thermal cycle, Fig. 1, was measured in the coarse grained HAZ of a bead-on-plate weld in 38 mm (1.5 in.) thick plate (Ref. 7) with a heat input of 2.1 KJ/mm (54 KJ/in.) and a preheat of 120 C using the techniques described by Coward (Ref. 8). The weld thermal cycle simulator has been described in detail elsewhere (Ref. 9). Briefly, this utilises resistance heating of the specimen blank and water cooling via hollow brass clamping blocks to achieve the desired thermal cycle.

2.2.2 Post-cycle heat treatment

After simulation some of the specimens were given furnace treatments at 450, 500, 550, 600, 620, 650 and 675 C for 100 min. and additionally at 620 C for 30 and 60 min. to simulate the effect of post-weld heat treatment.

2.2.3 Double cycle simulation

Some of the simulated specimens were given a second thermal cycle to peak temperatures of 1275°C of 765°C using the thermal cycles shown in Fig. 1 in order to examine the HAZ in multipass weldments.

2.2.4 Mechanical testing

Seventeen simulated blanks were prepared for mechanical testing for each condition described above. Ten of these were machined into standard Charpy V-notch impact test pieces with the notch positioned in the throughthickness direction with respect to the parent plate, and a transition curve determined by testing over a wide range of temperature. Six simulated blanks were machined into No. 13 Hounsfield tensile test pieces with a modified gauge length of 7.6 mm (0.3 in.) so that the gauge length was contained within the heat treated zone at the centre of the blanks. Three of these were tested at room temperature in a Universal Instron testing machine at a strain rate of approximately 2.8 x 10⁻³ sec. ⁻¹. The other three tensile test pieces were tested at 365^oC in a Hounsfield tensometer using a similar strain rate. The values of 0.2% proof stress, tensile strength, and reduction of area were recorded. The remaining simulated blank was sectioned transversely across the centre and the hardness determined using a Zwick hardness testing machine and a load of 5 kg.

2.2.5 Metallorgaphic examination

The section used for hardness testing was reground and polished to remove the hardness indentations and an optical metallographic examination carried out using a Reichert 'MeF' projection microscope. Etching was carried out in 2% nital. Carbon extraction replicas were then prepared and examined in a Siemens Elmiskop (model 1A) electron microscope.

3. RESULTS

3.1 Mechanical properties

The Charpy results for the parent plate and the coarse grained HAZ before and after various post-weld heat treatments for 100 minutes are shown in Figs. 2 and 3 respectively for the energy and crystallinity transitions. Apart from a drop in upper shelf energy from 134 to 88J (98 to 65 ft. lbf.) the coarse grained HAZ had comparable notch-toughness to the parent plate. Post-weld heat treatment in the range 450° C - 620° C resulted in a reduction in notch-toughness with maximum embrittlement at 550 C and 600 C. At 650 C the notch-toughness was almost back to parent plate levels, while at 675° C the notch-toughness was above the parent plate level. The most embrittled structure had a transition temperature about 55 C above the parent plate level. The three structures produced by post-weld heat treatment at 620° C for 30, 60, and 100 min. had similar notch-toughness properties so the curves are not shown.

The Charpy results for the coarse grained HAZ structures after a second thermal cycle to peak temperatures of $1275^{\circ}C$ or $765^{\circ}C$ are shown in Figs. 4 and 5 respectively for the energy and crystallinity transitions. The second thermal cycle to a peak temperature of $1275^{\circ}C$ produced comparable notch-toughness properties to the single cycled condition but with a slightly higher upper shelf energy. The second thermal cycle to a peak temperature of $765^{\circ}C$ raised the transition temperature by about $20^{\circ}C$ although the upper shelf energy was improved.

The hardness and room temperature tensile properties of all the structures are shown in Table 1 together with transition temperatures and upper shelf energies taken from the Charpy tests. The tensile properties at 365° C are shown in Table 2. The hardness results show a secondary hardening peak after post-weld heat treatment at 600° C. This treatment also produced the highest value of proof stress and coincided with the maximum embrittlement in the Charpy test. The tensile test results at 365° C, Table 2, showed that little loss in proof stress and tensile stress occurs at normal service temperatures. The average drop in proof stress was 6% with a maximum of 11% for the parent plate. The corresponding figures for the tensile strength were 12% and 16%.

- 4 -

Heat Treatment			0.2% Proof Stress		U.T.S.		Reduc-	Transition Temp.		Upper Shelf		Hard-	
							tion	C		Energy		ness	
							of						
	1							Area				r	
1st	2nd	Post-weld	Treatment	2	2	2	2	~	20ft.	50%		Ft.	
Cycle	Cycle	heat Temp.	Time	MN/m	tonf/in	MN/m	tonf/in	%	lbî.	Fibrous	J	lbi.	HV5
-	-		100 min.	479	31.1	627	40.7	69	-16	+37	134	98	214
1275 [°] C	-	-	-	848	55.1	1063	69.1	61	-28	+13	92	67	352
1275 [°] C	-	450 [°] C	100 min	820	53.3	936	60.8	66	+ 5	+42	109	80	291
1275 [°] C	-	500 ⁰ C	100 min.	818	53.2	920	59.7	61	+10	+46	92	67	306
1275 [°] C	-	550 [°] C	100 min.	839	54.5	941	61.1	61	+38	+67	98	72	296
1275 ⁰ C	-	600 ⁰ C	100 min.	882	57.4	993	64.5	65	+27	+75	94	69	333
1275 [°] C	-	620 ⁰ C	100 min.	816	53.0	922	59.9	68	+12	+58	109	80	318
1275 ⁰ C	-	650 ⁰ C	100 min.	829	53.9	900	58.4	67	0	+37	116	85	308
1275 [°] C	-	675 ⁰ C	100 min.	778	50.6	860	55.8	70	-28	+ 7	126	93	295
1275 ⁰ C	-	620 ⁰ C	30 min.	855	55.6	945	61.4	62	+12	+58	102	75	304
1275 ⁰ C	-	620 ⁰ C	60 min.	838	54.4	944	61.3	65	+12	+58	100	74	312
1275 [°] C	1275 ⁰	C -	-	836	54.3	982	63.9	68	-20	+21	107	79	321
1275 [°] C	765 ⁰	ç _ ·	-	804	52.2	1000	65.4	64	0	+40	120	88	325

Table 1. Room temperature tensile, hardness, and Charpy properties of Ducol W30 specimens.

5

Heat Treatment					Proof	U.T.	S.	Reduction of
				St	ress			Area
1st	2nd	2nd Post- Treat-		MN/	tonf/	MN/	tonf/	
Cycle	Cycle	weld heat Temp.	ment Time	m ²	in. ²	m ²	in. ²	%
-	-	-	-	428	27.8	527	34.2	69
1275 ⁰ C	-	-		845	54.9	948	61.6	52
1275 [°] C	-	600 ⁰ C	100 min.	820	53.3	872	56.6	64
1275 [°] C	-	620 ⁰ C	100 min.	777	50.5	832	54.0	65
1275 [°] C	-	650 [°] C	100 min.	772	50.1	795	51.6	65
1275 [°] C	-	675 ⁰ C	100 min.	717	46.6	747	48.5	67
1275 [°] C	-	620 ⁰ C	30 min.	745	48.4	818	53.1	65
1275 [°] C	-	620 [°] C	60 min.	812	52.7	832	54.0	64
1275 [°] C	1275 [°] C	-		763	49.6	915	59.4	53
1275 [°] C	765 ⁰ C	-	-	772	50.1	892	57.9	67

Table 2. Tensile properties at 365 °C of Ducol W30 specimens

3.2 Metallographic examination

The parent plate had a coarse grained structure of ferrite and tempered bainite, Fig. 6. The coarse grained HAZ produced by thermal cycling to a peak temperature of 1275°C, Figs. 7a and 7b, had a large prior austenite grain size and the structure resembled upper bainite. As described above the notch-toughness of this structure was comparable to that of the parent plate and this was probably due to the relatively coarse grain size of the latter which would give inherently poor notch-toughness. All the post-weld heat treatments produced structures consisting of temper carbides in a ferritic matrix. These structures were very similar so that only one of these is shown, Figs. 8a and 8b. Because of the significant differences in mechanical properties it seems likely that structural variations do exist between the different post-weld heat treatments and this is probably due to the presence of very fine vanadium carbides precipitates, as shown by Saunders and Dolby, which have not been extracted in the present work.

The structure produced by a second thermal cycle to a peak temperature of $1275^{\circ}C$ was very similar to the single cycled condition, Figs. 7a and 7b, and the mechanical properties were also similar. A second thermal cycle to a peak temperature of $765^{\circ}C$ produced partial transformation of the coarse grained HAZ structure, Fig. 8. Transformation occurred at the prior austenite grain boundaries and these transformed areas had a microhardness of 420 - 460 V. P. N. indicating

the presence of martensite, which would account for the small increase of 25° C in the transition temperature.

4. DISCUSSION

Previous work has shown that the weld HAZ of Ducol W30 steel can be divided into four regions (Ref. 3) viz. coarse grained, fine grained, intercritical, and spheroidised regions. Notch-toughness measurements on simulated specimens representative of these regions showed that the lowest notch-toughness was associated with the coarse grained HAZ. In addition this region was the most severely embrittled on subsequent post-weld heat treatment due to reprecipitation of molybdenum and vanadium carbides taken into solution during the weld thermal cycle. For this reason the present work was devoted entirely to an examination of the coarse grained HAZ and in particular to the effects of various post-weld heat treatments on notchtoughness.

The work reported herein shows that in the coarse grained HAZ of a submerged arc bead-on-plate weld made with a heat input of 2.1 KJ/mm (54 KJ/in.) and a 120°C preheat the notch-impact properties are comparable to those of the parent plate although there is some reduction in upper shelf energy. In comparing these results with other published information on the weld HAZ properties of Ducol W30 steel it is first of all necessary to compare the variations in parent plate properties that exist. In this respect the Ducol W30 steels appear to fall into two categories viz. those with fine grained structures with comparatively low transition temperatures, and those with coarse grained structures and comparatively high transition temperatures. The differences in transition temperature between these two categories can be as much as 60°C as shown by McKenzie (Ref. 1) who published a range of impact/temperature curves for 125 mm (5 in.) plates of Ducol W30 steel. In addition Smith et al. (Ref. 3) found a difference of 35 - 60°C in the transition temperature between a coarse and a fine grained Ducol W30 steel although the simulated coarse grained HAZ of both steels had similar transition temperatures. Since these steels also had similar compositions the variations in parent plate properties are most likely due to variations in heat treatment procedures. The steel used in this work was typical of the coarse grained variety of Ducol W30. Although these steels are basically for use at elevated temperatures where there should be no danger of brittle fracture, the coarse grained steel could well suffer brittle failure during construction when potential stressraisers are numerous or possibly even during the periods between high temperature service. It is suggested, therefore, that heat treatment requirements should be modified to allow the sale of fine grained steel to the fabricators.

An examination of published information on the notch-toughness of the coarse grained HAZ of Ducol W30 steel shows that this is very dependent upon the welding conditions used and this may be rationalised in terms of the cooling rate through the transformation range (i.e. 700° C to 300° C). In order to use a common criterion for comparison the 50% crystallinity transition temperature in the Charpy V-notch impact test will be used as this value is quoted in most of the papers. Smith et al. (Ref. 3) using a fine grained Ducol W30 steel and a coarse grained one to the Babcock and Wilcox specification BW87A measured a transition temperature of 56°C in the coarse grained HAZ of both steels using

thermal cycles measured in a submerged arc bead-on-plate weld with a heat input of 4.2 KJ/mm (108 KJ(in.) and a cooling rate through the transformation range of $5\frac{1}{2}\%$ C/sec. Watkins et al. (Ref. 4), using a fine grained Ducol W30 steel reported a transition temperature of 48 C after a thermal cycle measured in the coarse grained HAZ of a submerged arc weld. The welding conditions were not reported but the thermal cycle shown had a cooling rate through the transformation range of $6^{\circ}C/sec$. On the same steel, using a thermal cycle measured in a manual weld with a cooling rate through the transformation range of $27^{\circ}C/sec$. the transition temperature for the coarse grained HAZ was $-10^{\circ}C$. The present work, which utilised a thermal cycle measured in a submerged arc bead-on plate weld with a heat input of 2.1 KJ/mm (54 KJ(in.) and a preheat of 120 °C with a cooling rate through the transformation range of $10\frac{1}{2}$ °C/sec. showed a transition temperature of 13 °C in the coarse grained HAZ. Thus it would appear that the lowest notch-toughness in the coarse grained HAZ is associated with the higher heat inputs and hence slower cooling rates. The improvement with lower heat inputs and faster cooling rates may be explained by changes in metallurgical structure from coarse upper bainite through fine upper bainite and lower bainite to low carbon martensite. Smith showed a predominantly upper bainitic structure associated with a heat input of 4.2 KJ/mm (108KJ/in.), while Saunders and Dolby showed a structure of autotempered martensite and lower bainite associated with single run welds deposited automatically using a heat input of 1 KJ/mm (26 KJ/in. The low notch-toughness of upper bainite compared to lower bainite and auto-tempered martensite has been shown by Irvine and Pickering (Ref. 10) and supports the above discussion.

There are a number of references in the literature to post-weld heat treatment embrittlement in the coarse grained HAZ of Ducol W30 steel. Smith et al. reported an increase in the 50% crystallinity transition temperature from 56°C to 110°C after a post-weld heat treatment in the range 600°C -645°C for 100 min. with an increase in hardness from 281 to 295 HV5. This was for a submerged arc weld with a heat input of 4.2 KJ/mm (108 KJ/in.) and a cooling rate through the transformation range of $5\frac{1}{2}$ C/sec. Watkins who carried out 3 hour post-weld heat treatments at 450°C, 550°C, and 650°C on the coarse grained HAZ, found that the 550°C treatment produced the most embrittlement. In the submerged arc weld (cooling rate 6°C/sec.) the transition temperature increased from 48°C to 108°C while in the manual weld (cooling rate 27°C/sec) the increase was from -10°C to 100°C. Embrittlement occurred also after the 450°C treatment with increases in transition temperature from 48°C to 98°C for the submerged arc weld, and -10°C to 55°C for the manual weld. After the 650°C treatment there was evidence of recovery in both welds although the transition temperatures were still higher than before post-weld heat treatment, the transition temperatures being 74°C and 26°C respectively for the submerged arc and manual welds. Saunders and Dolby, using the C.O.D. test on specimens extracted from single run welds deposited automatically using a heat input of 1 KJ/mm (26 KJ/in.), found a secondary hardening peak after a 1 hour post-weld heat treatment at 550°C although the C.O.D. values were higher than before the post-weld heat treatment, but lower than parent plate values. A 1 hour post-weld heat treatment at 650 °C restored notch-toughness to parent plate levels. The lower degree of embrittlement reported by Saunders and Dolby may be due to the different technique used in assessing notch-toughness or to the lower molybdenum and vanadium contents of their steel.

In the present work, which examined 100 min. post-weld heat treatments in the range 450° C to 675° C the maximum embrittlement occurred after the 550 °C and 600 °C treatments and was thus in general agreement with the findings of other workers discussed above. The highest value of the 50% crystallinity transition temperature occurred after the 600 °C treatment where the value increased from 13 ° to 75 °C. This structure also had the highest proof stress and hardness and the lowest upper shelf energy (see Table 1). On the other hand the 550 °C treatment gave the highest 20 ft. lbf. temperature so that the maximum embrittlement was deduced to occur between these two temperatures, i.e. 550 °C and 600 °C. However a substantial degree of embrittlement occurred after all post-weld heat treatments in the range 450 °C to 620 °C and only the 675 °C treatment brought about complete recovery of notch-toughness.

These results emphasise the potential dangers from secondary hardening embrittlement which may occur in the coarse grained HAZ of welds in Ducol W30 steel as a result of post-weld heat treatment and this effect can still be quite marked in the normally recommended range for post-weld heat treatment of such structures, i.e. 620 C - 660 C. The failure to reach even the recommended post-weld heat treatment temperature can lead to more severe embrittlement as was shown in the report on the failure of a pressure vessel in Ducol W30 steel at John Thompson's (Wolverhampton) Limited. The effectiveness of increasing the time of post-weld heat treatment to overcome the secondary hardening embrittlement has not been resolved in the present work. Post weld heat treatments at 620°C for 30, 60, and 100 min. produced no significant variation in notch-toughness although there was a slight increase in hardness with increasing time which would suggest that the secondary hardening peak had not been reached after 100 min. The only safe way of ensuring freedom from post-weld heat treatment embrittlement at the moment appears to be to use a temperature at the top or slightly above the recommended range, i.e. $660^{\circ}C - 675^{\circ}C$ with a time of 5 hours. This would at least ensure that the peak of embrittlement was passed and that the HAZ would be well on the way to recovery if not actually fully recovered. Mechanical properties would then be adequate in the coarse grained HAZ but the effect of such a treatment on the parent steel has not been determined.

The effect of recycling the coarse grained HAZ structure to another 1275^OC peak temperature cycle, which may occur in multi-pass weldments was to produce a structure of comparable notch-toughness to the single-cycled condition but with a slightly improved upper shelf energy and a slight drop in proof stress, tensile strength, and hardness. The metallurgical structure produced by the single and double cycles were very similar so that no serious consequences were apparent as a result of the second thermal cycle.

A second thermal cycle to a peak temperature of $765^{\circ}C$ on the coarse grained HAZ structure produced areas of martensite at the prior austenite grain boundaries of the initial structure. These areas could constitute a danger from the point of view of brittle fracture but, since post-weld heat treatment would subsequently be carried out, such areas would be tempered.

It should be noted that this martensite was formed for a cooling rate

obtained with a preheat and interpass temperature of $120^{\circ}C$, which is within the 100 - 200 $^{\circ}C$ preheat range recommended by McKenzie in order to avoid cold cracking. It is, therefore, suggested that McKenzie's recommendation should be modified, possibly to a minimum of $165^{\circ}C$ since cracking has not been reported to occur above this temperature.

The tensile tests at $365^{\circ}C$ (Table 2) substantiated the claims that Ducol W30 maintains a high proportion of its room temperature proof stress and tensile strength at this temperature. The reductions in proof stress and tensile strength for the parent plate were 11% and 16% respectively. A C - Mn steel on the other hand was shown by McKenzie to lose about 40% of its room temperature proof stress at this temperature. The weld HAZ structures examined in the present work suffered similar small strength losses at 365°C but this was considered not to be significant because of the high strength levels of these structures. Low reduction of area values were recorded for the specimens cycled once and twice through the 1275°C peak temperature cycle which may be indicative of low ductility. However, such structures would be tempered by a post-weld heat treatment in the practical situation.

5. CONCLUSIONS

1. The coarse grained HAZ of a submerged arc weld in Ducol W30 made with a heat input of 2.1 KJ/mm (54 KJ(in.) and a preheat of 120° C was shown to have comparable notch-toughness to coarse grained parent plate except for a slight reduction in the upper shelf energy.

2. Post-weld heat treatments for 100 min. in the range 450° C - 650° C resulted in embrittlement of the coarse grained HAZ. Maximum embrittlement occurred at 550°C and 600°C where the transition temperatures were raised by about 60°C.

3. Post-weld heat treatment for 100 min. at $675^{\circ}C$ restored notchtoughness to better than parent plate levels.

4. A double cycle to a peak temperature of $1275^{\circ}C$ produced a structure comparable to the single cycled condition.

5. A second thermal cycle to a peak temperature of 765°C on the coarse grained HAZ structure resulted in the formation of areas of martensite at the prior austenite grain boundaries and these areas may provide potential sites for cold cracks in multi-pass welds unless the necessary precautions are taken.

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Fig 2. Effect of 100min. post-weld heat treatments on the coarse grained HAZ of Ducol W30 -energy/temperature curves.







it crystatinity / temperata



optical (a)

x 500.



(b) carbon extraction replica x 9000.

Fig. 6 Parent plate microstructure.





Fig. 7 Microstructure of the coarse grained HAZ.



(a) optical x 500.



(b) carbon extraction replica x 9000.

Fig. 8 Microstructure of the coarse grained HAZ after post-weld heat treatment at 600 °C for 100 min.



optical

x 500.

Fig. 9 Microstructure produced by a double thermal cycle with peak temperatures of 1275 °C and 765 °C.