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# Heat-affected zone softening in high-strength low-alloy steels

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**Abstract**

The effect of the chemistry of the steel and the welding process on the softening of the heat affected zone has been investigated. It has been observed that a steel with a high carbon-equivalent exhibited maximum softening. A steel with a low carbon-equivalent with high $M_s$ and $B_s$ temperatures coupled with minimum critical cooling time for nil martensite and full martensite exhibited the least softening in low-heat-input welding (SMAW), whilst a steel with longer critical cooling time for full martensite exhibited more resistance to softening in high-heat-input welding (GMAW). In general, the extent and degree of softening have been observed to be maximum in GTAW and GMAW, which are high-heat-input process. Post-weld heat-treatment in the austenite region eliminated the softened zone. External cooling methods, such as copper backing and argon purging, have been found to be useful in reducing the tendency for softening. © 1999 Elsevier Science S.A. All rights reserved.

*Keywords:* GTAW; GMAW; Heat-affected zone softening; SMAW

## 1. Introduction

The high strength of low-alloy steels is derived from a heat treatment comprising quenching from the austenite region followed by a low-temperature tempering. In other words, these are mainly quenched-and-tempered steels. When these steels are welded they are prone to softening in the heat-affected zone [1,2]. This region will therefore exhibit low hardness and therefore low strength and hence is a weak link in any mechanical testing. Because of the softness this region exhibits low creep and fatigue properties. If these steels are employed for armour application the soft zone exhibits poor ballistic performance [2]. It is therefore necessary to understand the influence of the welding process and the alloy chemistry on heat-affected zone softening in order to find ways to deal with this problem. Keeping this in view, three high-strength low-alloy steels have been selected for investigating the influence of alloy chemistry on heat-affected zone softening in three welding processes namely, shielded metal arc welding (SMAW), Gas Tungusten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW) The effect of external cooling, post-weld heat-treatment, and also the effect of starting base-metal condition, on HAZ softening have also been investigated.

## 2. Experimental

### 2.1. Base metal

Three types of high-strength low-alloy steels with different chemical composition (Table 1) have been selected. The carbon equivalent and hardness of the initial base metal are given in Table 2. One of the steels is studied in its two heat-treatment conditions, namely, medium hardness and high hardness. The microstructures of the parent metals are shown in Fig. 1.

### 2.2. Welding

Bead-on-plate partial-penetration welding was carried with three to welding processes, namely, shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW). In order to maintain similar heat-flow conditions, the weld coupon dimensions were fixed at 60 mm × 40m × 4mm

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Table 1
Compositions (wt%) and hardness details of the steels used in the present study

| | C | Si | Mn | Cr | Ni | Mo | V | S | PP | Zr | | Al | Hv |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P | 0.38 | 0.35 | 0.55 | 3.2 | 1.6 | 0.3 | 0.1 | 0.010 | 0.015 | – | – | – | 570–590 |
| S | 0.305 | 0.175 | 0.5 | 1.4 | 1.6 | 0.425 | 0.1 | 0.015 | 0.015 | – | – | – | 500–520 (High hardness) 320–330 (Medium Hardness) |
| J | 0.325 | 0.65 | 0.875 | 0.875 | – | 0.275 | – | 0.01 | 0.015 | 0.1 | – | | 490–520 |

(Fig. 2) and the electrode diameter fixed at 2 mm. The gas tungsten arc welds were autogenous whilst austenite filler metal was in order welding processes. In order to understand the influence of external cooling, the effectiveness of copper backing as well as back purging with argon, were studied. The steel plate was kept on a 200 mm × 200 mm × 4 mm copper sheet, during welding, thus enabling heat to be extracted by the copper plate. Argon back purging was carried out by keeping the weld coupon on a perforated steel block through which an argon flow was maintained.

### 2.3. Post-weld-heat-treatment

After welding, the weld coupon was heat treated in the austenite region at 900°C for 30 min and quenched in oil.

### 2.4. Mechanical testing

A micro-hardness surey was conducted across the weld beads of all of the weld coupons, a Vickers micro-hardness testing machine was employed for this purpose. All of the hardness readings were obtained at a load of 500 g. A schematic diagram of the hardness survey is shown in Fig. 3.

Table 2
Carbon equivalent of the steels used in this study

| Steel | C.E.(IIW) Ref. [4] $=C+\frac{Mn}{6}+\frac{Cu+Ni}{15}+\frac{CR+Mo+V}{5}$ | C.E.(Graville) Ref. [5] $=C+\frac{Mn}{16}-\frac{Ni}{50}+\frac{CR}{23}+\frac{Mo}{7}+\frac{Nb}{8}+\frac{V}{9}$ |
|---|---|---|
| P | 1.1333 | 0.5051 |
| S | 0.8799 | 0.4369 |
| J | 0.7008 | 0.457 |

### 2.5. Metallography

The microstructures of the welds and the parent metal were examined after conventional polishing and etching with 2% nital solution, a Leitz-make optical microscope and ISI scanning electron microscope were employed for the purpose.

## 3. Results

The data on hardness and microstructure are presented in this section. These are compared, based on the chemistry of the parent metal and welding process, to enable an understanding of the influence of the alloy chemistry in a particular welding process and the effect of different welding processes on the same alloy. The effect of post-weld heat-treatment and external cooling have also been presented in this section.

### 3.1. Hardness

#### 3.1.1. Effect of alloy chemistry

Hardness traverse across the weld beads in the three steels are presented in Figs. 4–6 for the three welding processes, namely SMAW,GTAW and GMAW. It may be noted that all of the steels exhibit a soft region of the HAZ adjacent to the base metal. The degree of softening being observed to be predominant in steel 'P'.

#### 3.1.2. Effect of welding process

Softening tendencies based on process are presented in Tables 3–5, the data being derived from Figs. 4–6. These data comprise of quantities such as the location of the soft zone, the width of the soft zone, and the minimum hardness and maximum hardness. The location of soft zone is the distance of the least-hardness region from the weld centre. For the purpose of the width of the soft zone, a hardness value below 450 VPN is treated as soft. In general, it is observed that the widths of the soft zone are maximum in the high heat-input welding processes (GTAW). The location of the soft zone is also farther in respect of these processes, with the exceptional of steel 'J'.

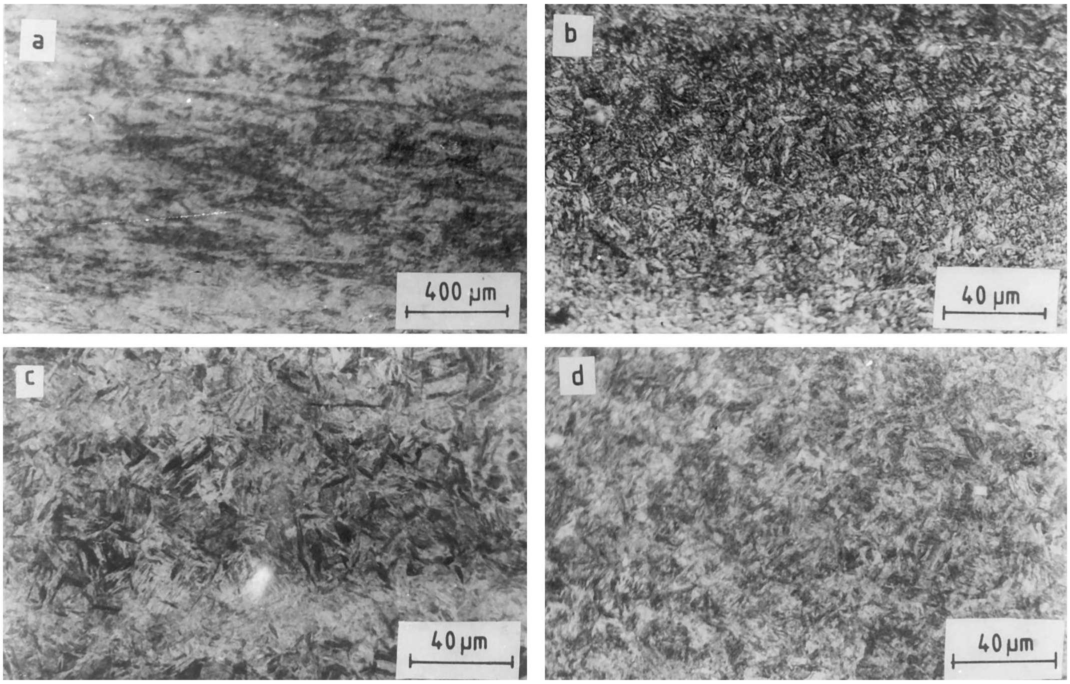


Fig. 1. Microstructures of the three HSLA steels: (a) Steel P;(b) Steel S (MH); (c) Steel S (HH); (d) Steel J.

*3.1.3. Effect of external cooling*

The effect of external cooling on the hardness distribution across the weld bead (SMAW) of steel 'J' is shown in Fig. 7. It is observed that Cu backing, as well as argon purging, resulted in reducing the degree of softening. It is also to be noted that the soft zone has shifted towards the weld in respect of the Cu backing: data presented in Table 6 substantiated this view. Additional information that can be drawn from this data is that the width of the soft zone is also reduced for both of the external cooling techniques. However, the width of the soft zones is the least in the case of argon purging.

*3.1.4. Post-weld heat-treatment*

The influence of post-weld heat-treatment on the hardness distribution across the weld beads of steel 'P' in the SMAW and the GMAW process is shown in Fig. 8. It may be observed from this figure that the soft region in the HAZ has been eliminated and a generally uniform hardness has been attained.

*3.1.5. Effect of the condition of the initial parent metal*

Hardness profiles across the weld beads of steel 'S' in its two heat-treatment conditions in the three welding processes are presented in Fig. 9. Medium-hardness steel 'S' exhibited hardening in the coarse HAZ and softening in the HAZ near to the base metal. Hardening in the coarse HAZ can be attributed to exposure to high temperatures above $AC_3$, followed by quenching, whilst softening is due to exposure at temperatures greater than 600°C (the tempering temperature for the steel). Steel in the high-hardness condition exhibited a softening effect similar to that of quenched and tempered steels.

*3.2. Metallography*

The microstructures of the coarse HAZ and the soft HAZ of the three steels in the three welding processes

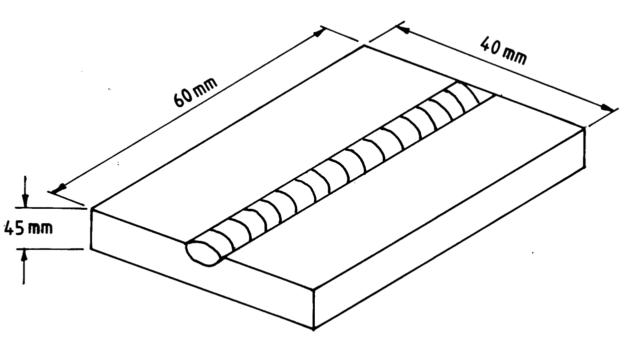


Fig. 2. Schematic sketch of the weld coupon.

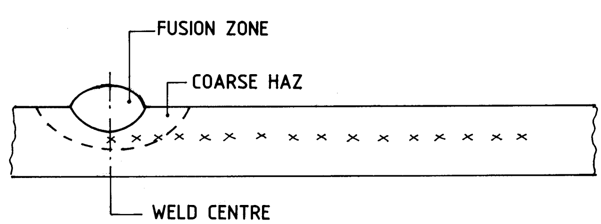


Fig. 3. Schematic sketch of the hardness traverse across the heat-affected zone.

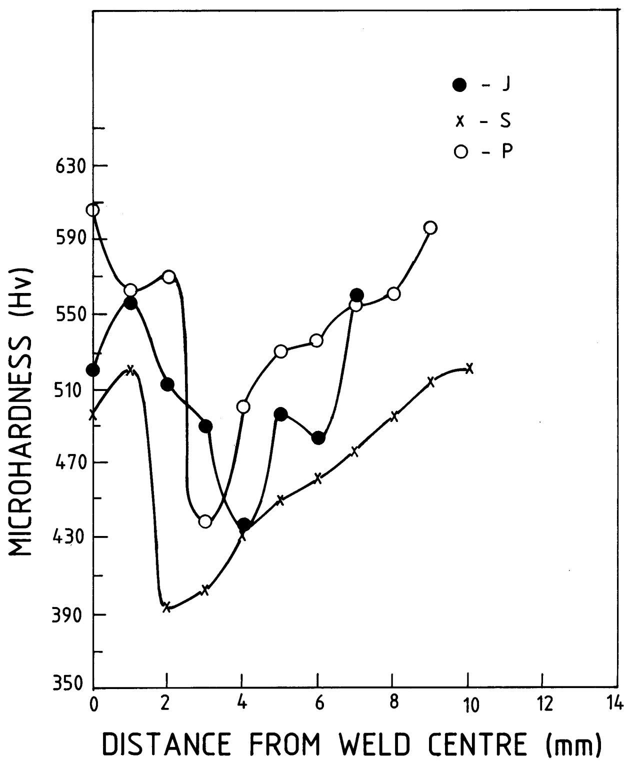


Fig. 4. Comparison of the hardness profiles in the heat-affected zones of the three HSLA with respect to the SMAW process.

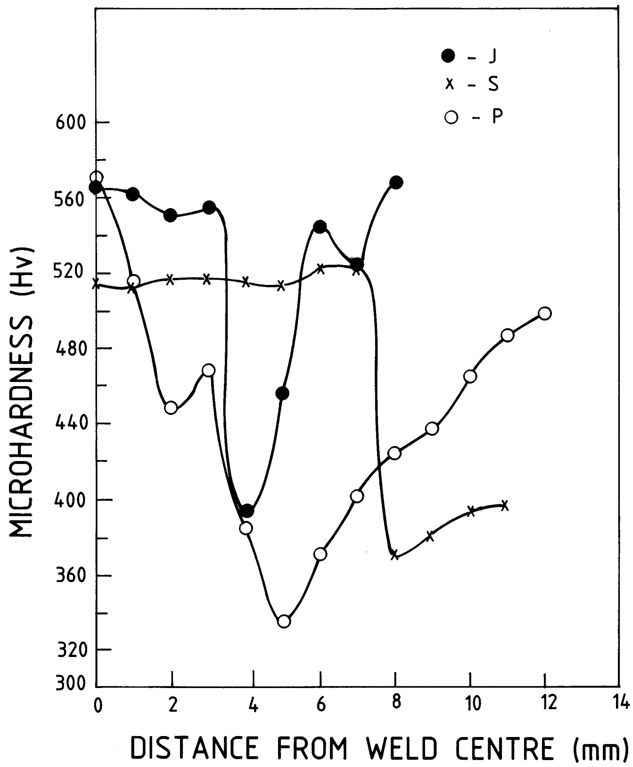


Fig. 5. Comparison of the hardness profiles in the heat-affected zones of the three HSLA steels with respect to the GTAW process.

are presented in Figs. 10–12. The coarse HAZ in all of the cases contains predominantly martensitic microstructures whilst the soft HAZ contains high-temperature transformation products in addition to martensite. The course HAZ in high heat-input welding processes (GTAW and GMAW) showed coarse austenite grains and also grain-boundary ferrite in some cases (Figs. 10 and 11). The microstructure after post-weld heat-treatment consist of predominantly martensite (Fig. 13).

## 4. Discussion

In order to understand and explain the trends observed in HAZ softening in the three steels, data on full

Table 3
Location and width of the soft zone of steel P with respect to the three different welding processes

| Process | Distance of the soft zone from the weld centre (mm) | Width of the soft zone ($H_v$) | Minimum micro-hardness | Maximum Microhardness($H_v$) |
|---|---|---|---|---|
| SMAW | 3.0 | 1.1 | 438 | 606 |
| GTAW | 5.0 | 6.4 | 350 | 570 |
| GMAW | 6.0 | 11.8 | 310 | 400 |

Table 4
Location and width of the soft zone of steel S with respect to three different welding processes

| Process | Distance of the soft zone from the weld centre (mm) | Width of the soft zone (mm) | Minimum hardness ($H_v$) | Maximum hardness ($H_v$) |
|---|---|---|---|---|
| SMAW | 2.0 | 3.7 | 394 | 520 |
| GTAW | 8.0 | 3.5 | 394 | 520 |
| GMAW | 4.0 | 3.4 | 394 | 546 |

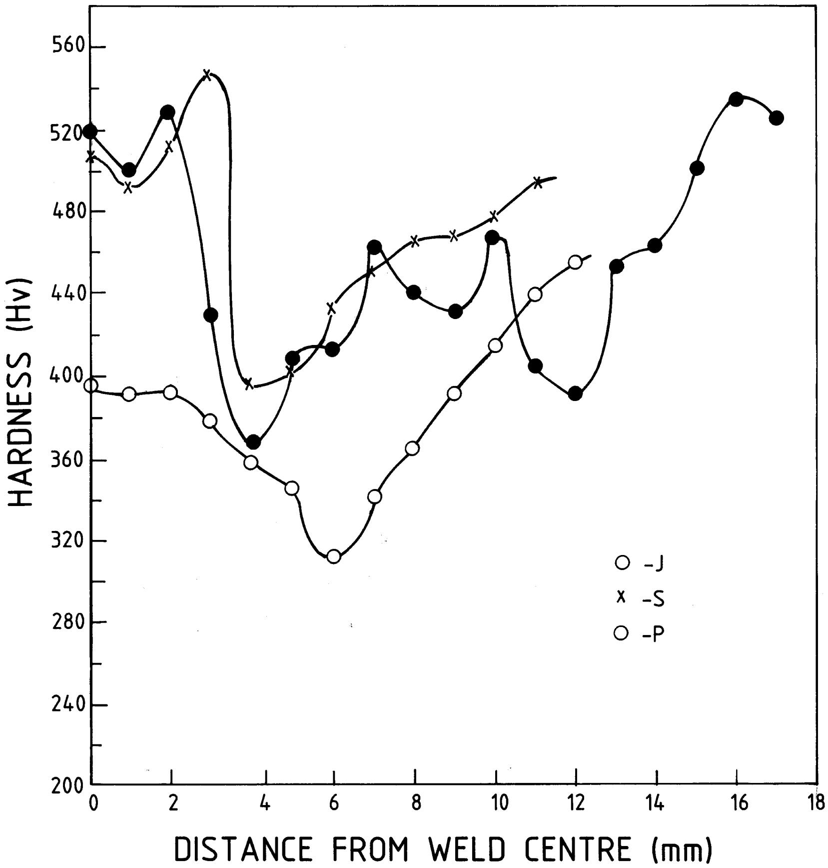


Fig. 6. Comparison of the hardness profiles in the heat -affected zones of the three HSLA steels with respect to the GMAW process.

martensite hardness, nil martensite hardness, critical cooling time for full martensite, critical cooling time for nil martensite, and $M_s$ and $B_s$ temperatures, have been calculated, being presented in Tables 7 and 8: these are based on the equation in the paper by Yurioka [3].

From Table 7 it is observed that steel 'P' has the greatest hardness of full martensite followed by steel 'J'. The hardness of the nil-martensite structure is the least in steel 'J', whilst steels P and S have a similar hardness of the nil-martensite microstructure. These steels also exhibit longer critical cooling times for nil martensite and full martensite. Steel 'S', which displayed the least maximum hardness, showed intermediate Ms and Bs temperatures. Steel 'J', which showed the least nil martensite hardness, exhibited the highest $M_s$ and $B_s$ temperatures (Table 8).

Based on the maximum hardness of the full martensite and minimum hardness of the nil-martensitic structure, the degree of the softening has been obtained for the three steels in the three different welding processes. For this purpose the hardness difference between full martensite and nil martensite has been taken as an index for 100% softening. The data on the degree of the softening are given in Table 9. From the data it may be observed that steel 'J' exhibited least softening in the SMAW process, which can be attributed to the highest $M_s$ and $B_s$ temperatures for this steel. This would aid in the formation of hard microstructures in the short thermal cycle of the

Table 5
Location and width of the soft zone of steel J with respect to three different welding processes

| Process | Distance of the soft zone from the weld centre (mm) | Width of the soft zone (mm) | Minimum microhardness ($H_v$) | Maximum microhardness ($H_v$) |
|---|---|---|---|---|
| SMAW | 4.0 | 1.2 | 436 | 560 |
| GTAW | 4.0 | 1.5 | 373 | 564 |
| GMAW | 4.0 | 10.2 | 367 | 540 |

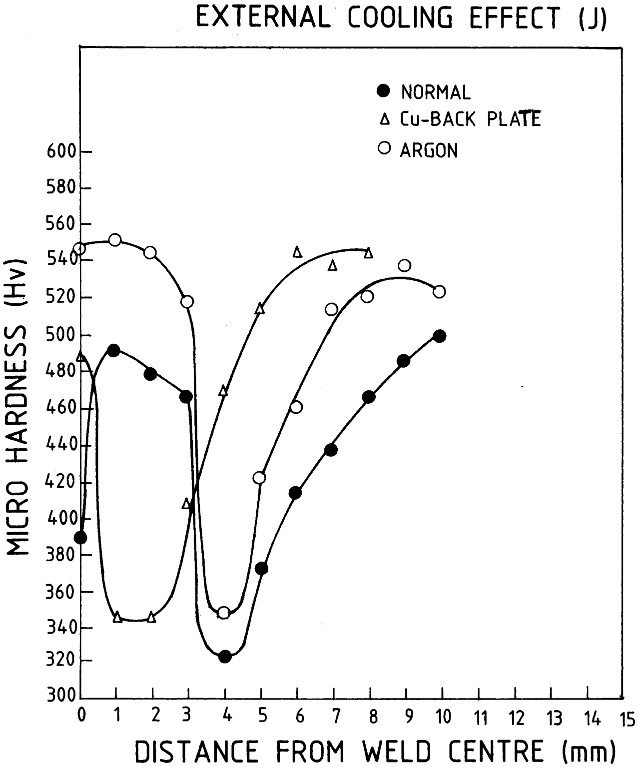


Fig. 7. Hardness traverse across the HAZ of a steel J weldment subjected to external cooling.

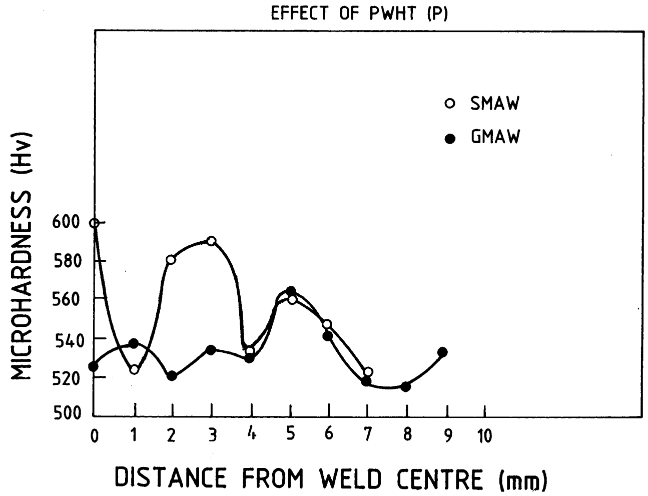


Fig. 8. Effect of post-weld heat-treatment on the hardness distribution across the heat-affected zone of steel P.

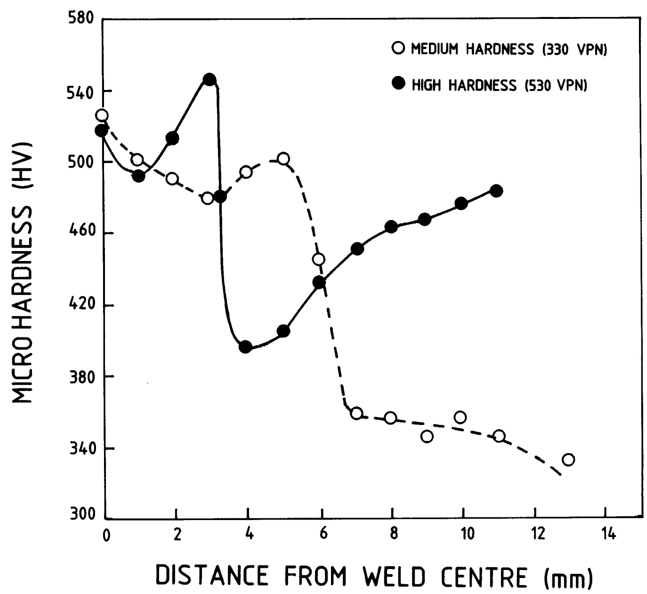


Fig. 9. Comparison of the hardness profiles in the heat-affected zones of the high and medium steel S with respect to the GMAW process.

SMAW process (a low heat-input process). It may be observed however, that the degree of softening is maximum in high heat-input welding processes (GTAW and GMAW). This is due to the exposure of the material to higher temperatures for longer duration, leading to the decomposition of the hard low-temperature transformation products to high-temperature equilibrium products. Thus it is imperative to keep the heat input in a welding process as minimum as possible, to avoid excessive softening.

It is also to be seen that steel 'S', which has the highest critical cooling time for full martensite, exhibited the least softening tendency in high heat-input welding (Table 4). This can only be attributed to the slow transformation kinetics for this steel, which would enable it to resist transformation to soft high-temperature products.

Thus the high $M_s$ and $B_s$ temperature as well as the short critical cooling times for full martensite and nil martensite for steel 'J' make it least prone to softening in low heat-input welding. However, in high heat-input welding, steel 'S' has an edge over other steels

Table 6
Effect of external cooling on the location and width of the soft zone of steel J

| Type of cooling | Distance of soft zone from the weld centre (mm) | Width of the soft zone (mm) | Minimum microhardness ($H_v$) | Maximum microhardness ($H_v$) |
|---|---|---|---|---|
| Normal | 4.0 | 4.4 | 324 | 492 |
| Copper backed plate | 1.0 | 3.2 | 344 | 490 |
| Argon | 4.0 | 2.3 | 346 | 552 |

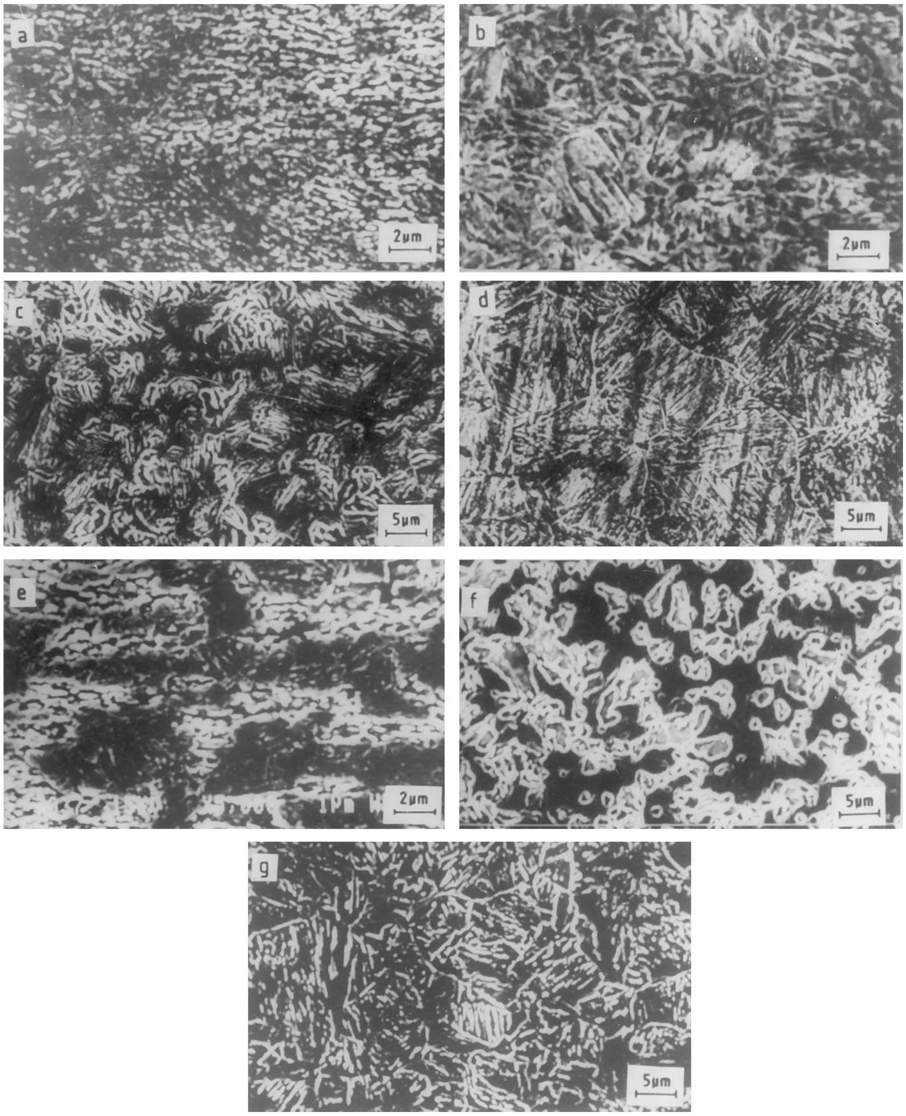


Fig. 10. Microstructural features of the metal and of the heat-affected zones of steel P with respect to the three different welding processes: (a) base metal; J (b) hard HAZ-SMAW; (c) hard HAZ-SMAW; (d) hard HAZ-GMAW; (e) soft HAZ-SMAW; (f) soft HAZ-GTAW; (g) soft HAZ-GMAW.

Table 7
Hardness and critical cooling times based on the empirical equations[a]

| Steel | Vickers hardness of the full martensite $H_m$ ($H_v$) | Vickers hardness of the nil martensite $H_B$ ($H_v$) | Critical cooling time for the full martensite (s) | Critical time for the nil martensite (s) |
|---|---|---|---|---|
| P | 615 | 271 | 25.33 | 3615.43 |
| S | 556 | 269 | 27.83 | 1049.73 |
| J | 572 | 261 | 7.131 | 280.71 |

[a] $H_m$ ($H_v$) $= 884C(1-0.3C^2)+294$

[3,6] where C(wt%) < 0.8%. Critical cooling time for full martensite, $T_m$ is given by log $T_m = (4.6$ CEI $- 2.08.)$

[3] CEI (%) = Cp + Si/26 + Mn/6 + Cu/15 + Ni/12 + Cr(1 − 0.16 Cr)/8 + Mo/4 + H Steel $H_B(H_v) = 145 + 130$ tanh (2.65 CEII − 0.69)

[7] where CEII = C + Si/4 + Mn/5 + Cu/10 + Ni/18 + Cr/5 + Mo/2.5 + V/5 + Nb/3 [3,6].

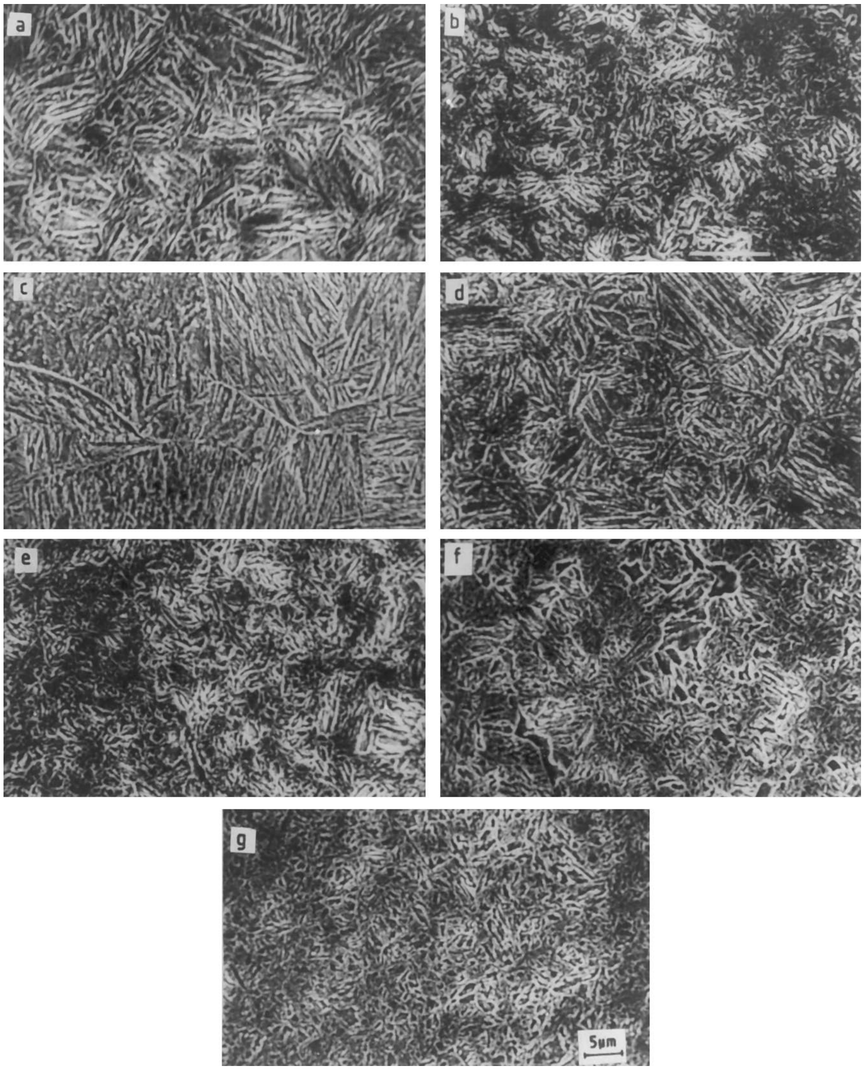

Fig. 11. Microstructural features of the base metal and of the heat-affected zones of steel S with respect to the three different welding processes: (a) base metal; (b) hard HAZ-SMAW; (c) hard HAZ-GTAW; (d) hard HAZ-GMAW; (e) soft HAZ-SMAW; (f) soft HAZ-GTAW; (g) soft HAZ-GMAW.

because of its, highest critical cooling time for full martensite transformation. Steel 'S' would therefore be more forgiving when the heat input is on the higher side. The least softening tendency of steel 'J' can also be attributed to its higher silicon content. Silicon is known to delay the temper martensite embrittlement, implying retardation in tempering [8,9].Course grain structure coupled with occasional grain boundary ferrite formation in high heat-input welding explains the reason for the maximum softening observed in these welding processes (GTAW and GMAW). Hardening of medium hardness steel 'S' in the coarse HAZ and the elimination of soft HAZ after PWHT shows that the general HAZ softening in the steels is due to decomposition of martensite to high-temperature soft products due to over-tempering.

The effectiveness of external cooling on softening can be seen from the data on degree of softening presented in Table 10. The degree of softening becomes reduced with Cu backing as well as with back purging with argon. Extraction of heat will shorten the duration of

Table 8
$M_s$ and $B_s$ temperatures of the three steels based on empirical equation[a]

| Steel | $M_s$ temperature (°C) | $B_s$ temperature (C°) |
|---|---|---|
| P | 323.97 | 431.225 |
| S | 344.17 | 510.175 |
| J | 358.17 | 579.425 |

[a] $M_s = 512 - 453C - 16.9Ni + 15Cr - 9.5Mo + 217(C)^2 - 71.5(C)(Mn) - 67.6(C)(Cr)$; $B_s = 830 - 270(\%C) - 90Mn - 37Ni - 70Cr - 83Mo$

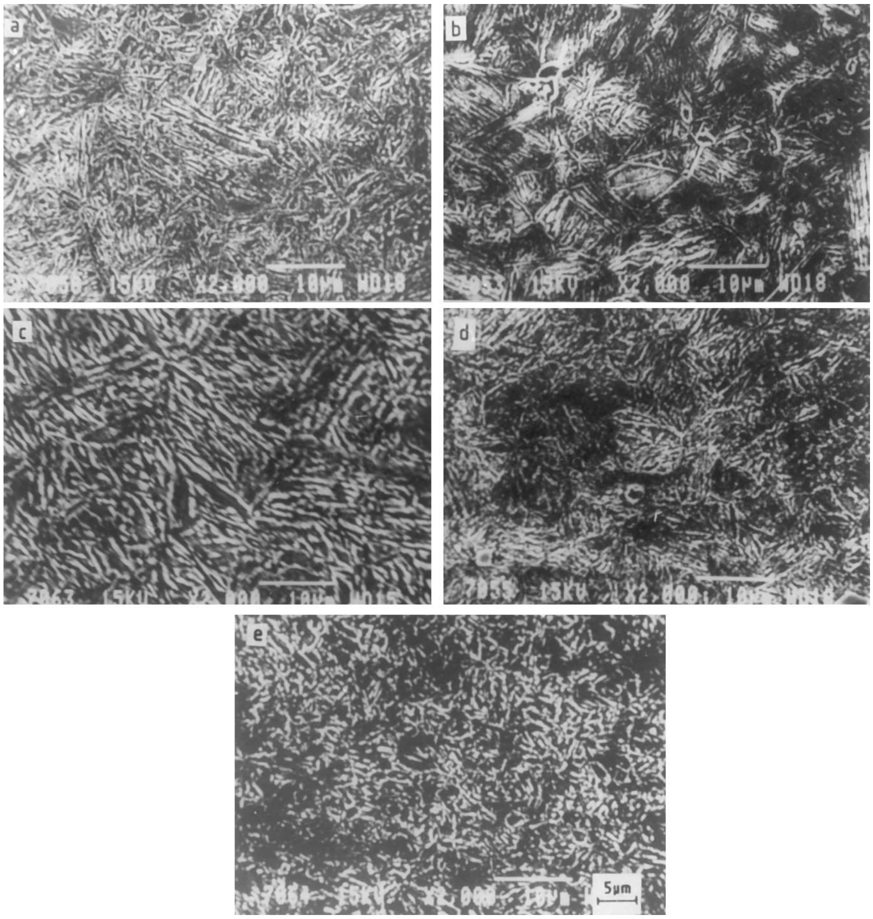

Fig. 12. Microstructural features of the base metal and of the heat affected zones of steel J with respect to the three different welding processes: (a) base metal; (b) hard HAZ-SMAW; (c) hard HAZ-GMAW; (d) hard HAZ-SMAW; (e) soft HAZ-GMAW.

Table 9
Degree of softening in the three HSLA steels with respect to the different welding processes

| Steel | $\Delta H_{th}$ $(H_m - H_B)$ $(H_v)$ | $\Delta H$ expt $(H_v)$ | | | Degree of softening (%) | | |
|---|---|---|---|---|---|---|---|
| | | SMAW | GTAW | GMAW | SMAW | GTAW | GTAW |
| P | 344 | 177 | 265 | 305 | 51.45 | 77.48 | 89.18 |
| S | 287 | 162 | 186 | 162 | 56.44 | 64.48 | 56.44 |
| J | 311 | 136 | 199 | 205 | 43.72 | 64.00 | 66.00 |

time of retention at high temperature and afford less chance for reversion to high temperature transformation products. This method can therefore be used as a tool in minimising softening tendencies.

## 5. Conclusion

(1) Steel 'J' which has low-carbon equivalent as well as high silicon, showed the least softening tendency in low heat-input welding. The high $M_s$ and $B_s$ temperatures of this steel are also responsible for this behaviour.

(2) Steel 'S', which has longer critical cooling time for full martensitic transformation, exhibited greater resistance for softening in high heat-input welding (GMAW).

(3) External cooling has been found to be beneficial in minimising HAZ softening.

(4) A post-weld heat-treatment above AC3 eliminated the soft zone.

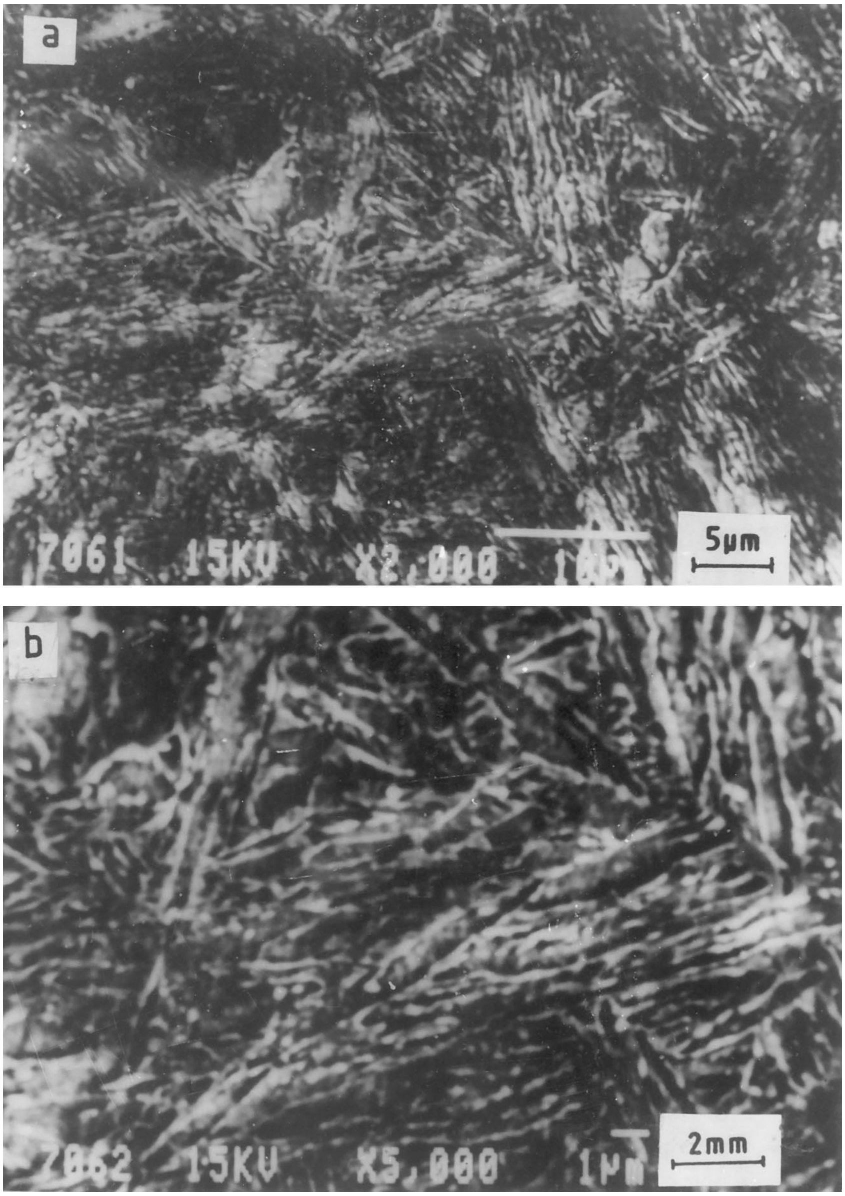


Fig. 13. Microstructural features of the heat-affected zone of post-weld heat-treated steel P.

Table 10
Degree of softening in an externally cooled steel J weldment (with respect to the SMAW process)

| Steel | Normal | | Back-plate (Cu) | | Argon | |
|---|---|---|---|---|---|---|
| | Coarse HAZ | Soft HAZ | Coarse HAZ | Soft HAZ | Coarse HAZ | Soft HAZ |
| J | 86 | 56.64 | 85.66 | 60.13 | 96.5 | 60.49 |

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