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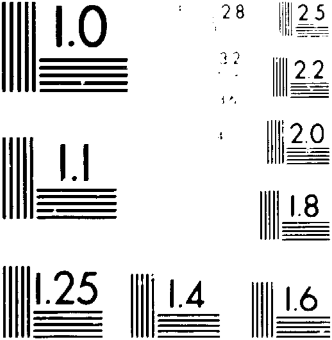

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AN OVERVIEW OF ENGINEERING MATERIALS FOR WELDED STRUCTURES AND METALLURGICAL PROBLEMS IN FABRICATION INDUSTRY - PART I*

by

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1.0 INTRODUCTION

Welding applications are varied and diverse. The applications personnel are often confronted with many welding technological and metallurgical problems, leading to laying down of productive time and energy and increased cost due to wastage of materials and consumables. To avoid or atleast minimise these problems it is necessary to understand or atleast appreciate the metallurgical problems encountered during welding fabrication. For this, one should consider the two aspects of the material's weldability - viz., first, choice of specific materials for any welded component, in terms of the weldment's/material's behaviour in that application; second, choice of fabrication technology, methods and parameters to produce a sound (defect free) joint.

To gain an idea of the former, the core engineering, materials used in the different sectors of fabrication and the logic for their choice are to be considered. Subsequently, the requirements during welding for fabrication of these materials are to be analysed.

2.0 CORE ENGINEERING MATERIALS USED IN FABRICATION INDUSTRIES

Materials used in a specific fabrication industry are numerous and materials, that are welded, form a major part of it today. It is too exhaustive to cover all of them and here, only the core-Engineering materials will be considered. The materials for pressure vessels and boilers, ship building, transport industry (road and rail-road), structures (buildings, and bridges), aircraft and storage tanks will be discussed in order.

2.1 Pressure Vessels and Boilers:

The earlier designs of welded boiler drums and pressure vessels were operated under conditions where plain carbon steels of moderate tensile strength could give satisfactory and economical constructions. Welded pressure vessels of today are designed to operate under conditions which are much more varied and usually more stringent than the past. Pressures upto 204 atmospheres and temperatures upto 540°C, pressure and temperature cycling, environments containing hydrogen and corrosive agents and neutron irradiation have brought into common use a variety of alloys and filler metals heavier sections and new welding processes.

The materials generally employed in boilers and pressure vessels may be grouped as Carbon/Carbon-Mn steels (killed-Si and Al; semi-killed) low alloy steels, quenched and tempered steels, Chromium steels, austentitic steels, clad steels and non-ferrous metals and alloys. The materials used for the core components of a boiler/pressure vessel are given in Table-1.

The materials are often to cater to several of the following requirements in addition to weldability.

01) Improved ambient and/or high temperature

strength (short/long term);

02) Good impact resistance at ambient temperatures;

03) Improved corrosion resistance including sulphur corrosion;

04) Improved oxidation resistance and stability at high temperatures

TABLE-1

MATERIALS FOR PRESSURE VESSELS & BOILERS

Evaporators & Economisers	: 'C' steels
Superheaters and Desuperheaters	: Low alloy Cr-Mo steels Cr-Mo-V steels
Steam pipelines	: Low alloy steels (Cr-Mo, Cr-Mo-V)
Boiler drums	: C and C-Mn steels, low alloy V or Mn-Ni steels
(Sootblowers	: Ferritic stainless steels)
Headers and nipples	: Carbon steel, low alloy Cr-Mo steels

Quenching and tempering treatments are often used in carbon and low alloy steels as a substitute for normalising and as a means of maintaining notch toughness in heavy thicknesses for pressure vessels.

2.2 Ship Building:

The materials for ship building should combine conventional mechanical properties with a suitable level of notch toughness and low hardenability. The notch toughness can be maintained by specifying certain limitations on chemistry and steel making and treating practices. The demand for higher section thicknesses increase the level of control on the notch tough chemistry of the material.

In heavier thicknesses, normalising treatments are required to refine the grains and enhance the low temperature toughness. Certain steels contain low sulphur and phosphorus and a range for vanadium. Q&T C-Mn steels provide yield strengths upto a minimum of 35 Kgf/mm^2 with good notch toughness at -23^oC. Q&T HSLA steels with Ni, Cr, Mo provide upto a minimum YS level of 70 Kgf/mm^2

2.3 Transport Industry:

2.3.1 Railroad Transport:

The Indian Railway system is the largest in Asia, fourth largest in world. The transportation of freight and passenger by railroads in India involves 60,000 Kms. of track, 4 lakh numbers of freight cars, 11,000 locomotives and 38,000 numbers of passenger cars. The trends, in the industty viz., increased carrying capacities, design of cars for carrying specific materials and more passenger-comfort oriented facilities lead to the use of high strength low alloy steels instead of conventional carbon steels and increased use of welding to replace rivetting.

The various components of locomotives, railway cars, commuter cars, freight cars and tank cars are listed in Table-2.

Railroad rails require length build up for making them as continuous rail, which reduces the number of bolted joints reducing cost of maintenance and increasing service life. Normally high or medium carbon steels are used for the rails. Frogs and crossings are made up of 14% Manganese steel, other than the conventional open-hearth steel.

TABLE-2

RAIL-ROAD VEHICLES - COMPONENTS AND MATERIALS

LOCOMOTIVES

Underframe	- Carbon or low alloy steels
Cabs & hoods	- Rimmed steel
Diesel engine:	
Housing	- Forged steel or cast steel with hardfacing for cylinder head valve seat
Oilpan	- Forgings, low 'C' steel plate/sheet
Generator frames & structural attachments	- Low carbon steel with special magnetic properties
Truck frames	- Cast steel (repairs only)
Traction motor frame	- Mild steel rolled and formed sections
Fuel & water tanks	- Rolled plate-semi-killed low 'C' steel
Main air reservoir	- Carbon steel - fire box quality

Pipings - Mild steel (0.26 C Max)

Fuel & lubricating oil lines - Copper tubes for (corrosion resistance)

Exhaust mufflers & manifolds - 'C' steel (firebox quality) or Cr-Mo heat resistant steel

Cylinder heads - Cast iron (repair only)

STAINLESS STEEL CARS

Non-structural areas - Straight chromium ferritic steels

Strucural areas - Austenitic Cr-Ni-Mn steels Cr-Ni cold rolled sheet steels

COMMUTER CARS

Body - Low alloy steels (wrought & cas

Floor sheets - Stainless or low alloy steel (welded with underframe)

Interior panels - Aluminium (commercial purity);

FREIGHT CARS

Body - Rolled steel sections of 'C' or low alloy high strength steels (weather resistant steels with Cu, Cr and Ni)

Others - Cast steel

TANK CARS

Body - Aluminium alloys & Nickel steels for cryogenic fluids stainless steels (austenitic and ferritic)

2.3.2 Road Transport:

The type of service properties expected of a wleded joint of automative parts are given in Table-3.

TABLE-3

SERVICE REQUIREMENTS OF AUTOMATIVE PARTS

1. Mechanical strength
2. Fatigue Resistance
3. Rigidity
4. Corrosion resistance (weather resistance)
5. Leak tightness
6, Aesthetics

Many types of metals and alloys are used in welded fabrication of automative products, as given in Table-4.

TABLE-4

TYPICAL MATERIALS FOR AUTOMATIVE PARTS

PARTS	METALS USED
Engine blocks and heads	: Alloy cast iron and Aluminium
Door hinges, chassis brackets	: Malleable iron
Frames, propeller shafts	: Low carbon steel
Body components	: Cold rolled/hot rolled low 'C' steel, galvanised cold rolled sheet steel, Zinc-rich painted sheet steel low alloy high tensile sheet steels.
Rear axle housing	: Low or medium carbon steel stampings, cast steel or malleable iron
Wheels	: Low 'C rimmed or semi-killed steel, dualphase steel
Fuel tanks	: Terne plate
Trim & hardware	: Stainless steel, Aluminium & Zinc dye-cast
Commercial trailers	: Aluminium sheets, angles, extrusions

In India, efforts have been put in for development of 'dual phase steel' for the wheel drums, requiring high formability as well as high YS with good weldability.

Passenger carrying components, whether truck-cab or automative body, are made of cold rolled sheets. Freight handling trailors are constructed of spot welded carbon steel or low carbon high strength steel. In setting the material for the rotating components of the automative products fatigue is an important factor in design.

2.4 Structures:

2.4.1 Buildings:

Welding has become a major method of joining in building structures. Advantages of welding are now started to be recognised by designers as well as fabricators.

These structures are subjected to static loading or a low frequency dynamic stress. Table-5 below gives the materials used in these structures. While impact property requirements are not a part of these steel specifications today, they may have to be taken as a job-requirement in terms of the welded joints constructed at North-Indian regions where brittle fracture behaviour below the transition temperature could always be exhibited.

TABLE-5

MATERIALS WELDED FOR BUILDING AND BRIDGE APPLICATIONS

* Carbon/carbon-Manganese structural steels (Hot rolled)
* High strength low alloy steels (Mn-V steels and Cb-V steels)
* High yield strength Q&T alloy steel plates.

2.4.2 Bridges:

Structural elements of bridges are normally exposed to atmosphere while that of the buildings are normally protected from such exposure. Also, bridges (and crane runway girders etc) are subjected to dynamic and repetitive live loads unlike buildings. The different types of materials used are also given in Table-5. Dead-weight reduction is achieved by HSLA steels providing economic advantage. Weather resistant steels have also been indigenously developed in India for this application. In using Weather Resistant steels, special investigations are necessary to evaluate their weldability.

2.5 Aircraft industry:

Materials with high strength to weight ratio are of utmost importance to the aircraft industry. Aluminium and Magnesium alloys meet this requirement for structural materials in aircraft. Low alloy steels, corrosion-resistant steels, cobalt, nickel and titanium based alloys are also employed where temperature level demand their use. Precipitation hardening stainless steels, improved nickel and cobalt base alloys, new iron base alloys and refractory metals are being increasingly used. Composite materials (such as honeycomb or sandwich structures) are now quite common.

The range of alloys are given in Table-6. In solid propellant rocket motor cases, use is made of new alloy Ti-13V-11Cr-3Al.

TABLE-6

MATERIALS USED IN AIRCRAFT INDUSTRY

Aluminium and its alloys	- Commercial purity Non-heat treatable 'Al' alloys Heat-treatable alloys Cold rolled sheets/forms
Magnesium & its alloys	- Different varieties of Magnesium alloys
Titanium and its alloys	- Commercial purity Alpha alloys (Al-Sn, Al-Mo-V, Al-Cb-Ta) Alpha-Beta(6Al-4V) alloys Beta alloys(13V-11Cr-3Al) Alpha-Beta newly developed alloys (8Mn, 4Al-3Mo-1V, 2.5Al-16V etc)
Austenitic stainless Steel	- Stabilised grades (Ti or Nb)
Precipitation hardening corrosion resistant steels	- Non air-hardenable alloys 17-4PH, 17-7PH, 350, 355. PH15-7Mo, PH 14-8Mo
Ni base alloys	- Ni-Cr-Mo-Fe solid solution hardened. (Inconel & Hastellsy B,W, X, C) For moderate high temperature strength and

- excellent oxidation resistance and corrosion resistance

Superalloys - Agehardenable Ni base, Fe base, Co base materials for fatigue, stress-rupture and strength at high temperature.

2.6 Storage Tanks:

Growth of cities and towns has increased the demand for the consumablex like water, oil, cooking gas and the petroleum products, necessitating medium and large storage tanks for them. Also, scientific and industrial developments have emphasized the need for storage of cryogenic fluids like liquid nitrogen, oxygen, and hydrogen. Refrigerated ammonia and acid for fertilizer industries requires storage tanks. The materials for the field placed tanks, exposed to weather conditions should be weather-proof. Tank material should withstand corrosion at ambient low or elevated temperatures. These tanks are not pressurised inside. The various materials used for storage tanks fabrication are given in Table-7.

TABLE-7

MATERIALS FOR STORAGE TANK FABRICATION

* Deoxidised carbon steels, C-Mn steels with good notch-toughness in normalised or Q&T condition
* Copper bearing steels with 'Cu' upto 0.2%
* Nickel containing steels - 2.25 or 3.5% Ni
* Wrought iron forms/shapes

- Aluminium and its alloys
- Austenitic stainless steels
- Low alloy Q&T Cr-Ni-Mo-V-B-Cu steel

3.0 WELDABILITY PROBLEMS IN FABRICATION

Weldability is a complex and not a well-defined term. However, one popular definition for weldability is 'the capacity of a material or a combination of materials to be welded under fabrication conditions, imposed into a specific suitably designed structure and to perform satisfactorily in the intended serv

Two different aspects of the three branches of weldability viz., the fabrication weldability and the design (or service) weldability are included in the above definition. The fabrication weldability problems to a larger extent, can be considered without consideration of the service aspects. The problems of service weldability necessiates discussions along with the relevant application.

3.1 Fabrication weldability:

The term 'fabrication weldability' covers the metallurgical problems associated with the soundness of a joint. The various types of cracking problems in weldments and porosities in welds are covered under this.

The cracking problems are the bug-bear of the fabrication industry today. An onlook into the various types of cracking would enable one to have a better understanding in eliminating or minimising the problem.

3.1.1 Hot Cracking:

This occurs at high temperature nearer to the solidification temperature range of the alloy. When the alloy contains large amounts of impurities or tramp elements, the solidification temperature range is widened. When sufficient restraint is present during welding, which hinders the weldmetal from shrinking/contracting during cooling, the weldmetal hot cracks occur, mostly along the centreline of weld. Conditions for cracking are more conducive at the weld-end-crater.

These cracks also appear at the Heat Affected Zone (HAZ) of the material, where high temperatures are experienced near to the melting points of any low melting eutectics formed. HAZ hot cracks are called 'liquation cracks'.

Both types of hot cracks are intergranular in nature and normally medium and high carbon steels or steels with larger impurities than restricted levels are more prone to this type of cracking. Mild steels and low alloys steels are not much prone if proper heat input and weld pool geometry are maintained. In case of austenitic stainless steels, weldmetal should have a composition balance to avoid cracking so as produce 3 to 5% delta ferrite in the otherwise fully austenitic weld. Aluminium alloys are prone to hot cracking which are to be guarded against by a proper control of chemistry of the weldment - especially with reference to the 'Mg' and 'Si' contents.

Factors responsible for hot cracking:

i) Impurities, widening solidification range;
ii) Restraint;
iii) Weld pool geometry

Today mathematical models have been developed to predict hot cracking tendency of steels, based on which, to a large extent, one can decide and achieve the required acceptable weld metal composition, resistant to hot cracking.

One of the models for hot cracking index is,

$$HCS = \frac{C\left(S + P + \frac{Si}{25} + \frac{Ni}{100}\right) \cdot 10^3}{3Mn + Cr + Mo + V}$$

The higher this index, the more is the hot cracking susceptibility of the material.

Of the various weldability tests for evaluation of hot cracking susceptibility, the Varestraint test and Murex test are the widely used tests.

3.1.2 Cold Cracking:

This cracking occurs at or near the ambient temperatures usually below 150°C. The combined effects of diffusible hydrogen (which enters weld from many sources, diffuses out mostly through the HAZ of weldment), the hardening at HAZ and the residual stresses, cause a coldcrack. The cracks are mostly transgranular but intergranular cracks also are observed. Precautions to avoid cold cracks are:

a) Proper level of preheat and post heat;
b) Reduced moisture in coating or welding atmosphere
c) Choice of low hardenability materials

Mild steels in heavy sections, low alloy steels and martensitic stainless steels are much prone to cold cracking. There is a lot of work put in to exactly predict the cold cracking behaviour and to suggest the combination of precautions to avoid crack (preheat, postheat, heat input, diffusible hydrogen etc) for a specific thickness and type of steel for any construction. Limits have been imposed on the moisture content of SMAW electrodes for various strength levels of base materials to avoid cracking.

One of the mathematical models available to predict cold cracking is given below:

$$Pcm = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B$$

(Ito - Bessyo's Carbon equivalent)

$PW(\%) = Pcm + HD/60 + R_{FY}/40{,}000$ where HD is Diffusible hydrogen in deposited metal - ml/100 gm (JIS method)

R_{FY}: Intensity of Restraint of a joint (Kgf/mm.mm)

Preheat To (^{O}C) = 1440PW - 392 (for oblique Ygroove)

The various widely used weldability tests for evaluation of cold cracking susceptibility are -

i) Implant test
ii) Tekken test
iii) CTS (Controlled Thermal Severity) test

All these tests use actual welding and hence are called the direct weldability tests.

For a proper prediction of the cold cracking behaviour of a steel the steel's hardenability indices as well as its' CCT (continuous cooling transformation) diagram are very helpful. The normal 'CCT' diagrams are not really useful in welding applications due to the peculiarities of the weld thermal cycle. Hence, there is a need to plot the 'Weld-CCT' diagrams for the materials.

In welding Research Institute, Tiruchirapalli, Weld-CCT diagrams for several materials have already been plotted. A typical weld-CCT diagram plotted at WRI for a 1Cr-1Mo- 0.25V steel has been shown in Fig.1.

This diagram differs from the conventional CCT diagram with respect to the X-axis legend, where the time taken for cooling from 800°C to 500°C (tr8/5) is represented.

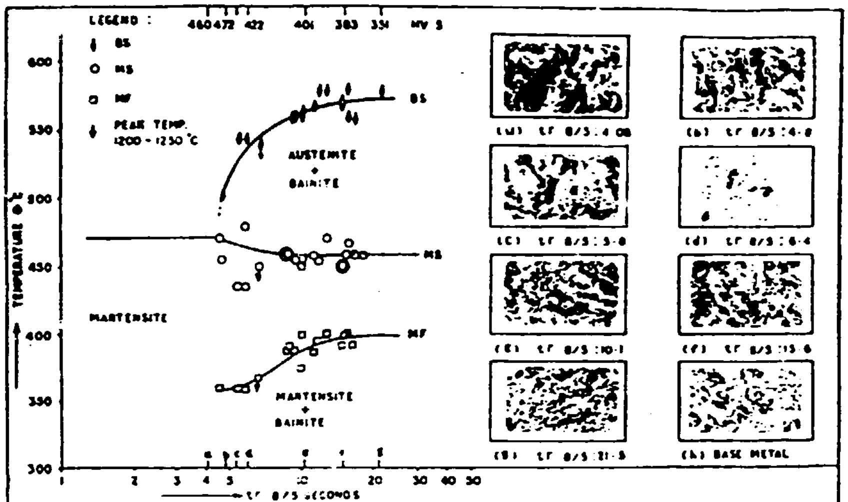


FIG:1 .MODIFIED WELD-CCT DIAGRAM OF FOV (1Cr-1Mo-0.25V) GENERATED BY IN-SITU WELD THERMAL CYCLE ANALYSIS

This tr8/5 determines the resulting microstructure and properties of the material at the HAZ of a weldment. The time of cooling from 800°C to 500°C (tr8/5) depends upon the thickness of the weldment the heat input and the welding process used.

3.1.3 Restraint Cracking:

When restraint of a member being welded is quite high, and beyond a critical value this cracking can occur due to high weld reactive stresses developed. The initiation of a crack may be due to restraint alone or due to cold or hot cracking. Solution to avoid this type of cracking is to lower the restraint level by proper sequencing etc, below the critical level (as found by experiments - Restraint cracking tests) which depends on welding parameters. The evaluation of the critical restraint intensities are carried out for any combination of welding conditions using tests such as:

i) Rigid Restraint Cracking (RRC) tests
ii) Elastic Restraint Cracking (ERC) tests
iii) Tensile Restraint Cracking (TRC) tests

Of these, the ERC tests are preferable due to

i) less sophisticated instruments and equipments required; and

ii) less volume of material consumed for testing

3.1.4 Reheat Cracking:

This type of cracking observed only in Cr-Mo or Cr-Mo-V steels, also takes place at elevated temperatures at or near the stress-relief temperature for the material, especially at the coarse-grained region of the HAZ of weldment. Factors responsible are -

i) lowered ductility of grain boundary due to presence of segregated impurities like sulphur etc;

ii) stress-relieving temperatures nearer to creep-relaxation;

iii) grain body strengthening due to submicroscopic precipitations of specific alloy carbides; and

iv) high level of residual stresses in as welded condition.

The reheat cracking susceptibility predicted based on the chemical composition, is given by -

$$P_{SR} = Cr + Cu + 2Mo + 7Nb - 5Ti - 2.0$$

If $P_{SR} > 0$, the steel will be prone to reheat cracking problems.

3.1.5 Lamellar Tearing:

This type of tearing occurs on welding of rolled structural materials with large amounts of elongated inclusions (Manganese Sulphide or Silicate type) When material is unclean, the through thickness direction ductility suffers. When through thickness (Z-direction) stresses are created during welding of a member (say a 'T' fillet weld), the elongated inclusions decoheses from matrix, join together by vertical jumps and cause a lamellar tear. Sometimes, the tear may run to several feet, starting from underneath the weld. Manytimes the tear is initiated by a cold crack.

Factors responsible are -

i) large number of elongated inclusions with sharper ends causing a low Z-direction ductility;
ii) existence of Z-direction stresses during welding.

Precautions against lamellar tearing are -

a) Selection of good materials having better Z-direction ductility
Inclusion shape control by rare earth additions;
b) Weld design modification to avoid/minimise Z-direction stresses;
c) Buttering of horizontal plates (in-T fillets) before fillet welding using a ductile weld deposit, which absorbs Z-direction strains;
d) More ductile weldmetal (with lower strength if design permits & other ways are not possible)

3.1.6 Porosities:

Weld porosities are due to any one or combination of several factors -

i) Large amounts of absorbed/dissolved gases in materials;
ii) Non-deoxidised materials containing oxides and oxygen;
iii) Improperly protected arc (insufficient shielding of arc)

Due to improved material production technologies, the problem due to the first factor is becoming reduced especially in case of vacuum degassed or vacuum arc melted materials.

In case of welding of rimmed steels, where second factor is the cause, deoxidizers are to be added in the filler materials in more quantity to compensate for dilution from rimmed steel parent metal. Third factor is to be taken care of through adjustment of technological parameters.

3.2 Fabrication Weldability Tests - A WRI PACKAGE:

Although several indirect test methods are available to evaluate weldability, it is widely recognised that the thermal cycles unique to welding result in behaviours that cannot be simulated otherwise.

Direct weldability tests have more promise of meeting the requirement for evaluation of weldability since they measure the effect of welding directly by welding process. There is a need to evaluate weldability of any material newly developed for a set of fabrication weldability problems such as hot cracking, cold cracking, restraint cracking etc.

"THE WELDABILITY PACKAGE" developed at WRI consists of raw material testing (conventional chemical and mechanical tests, and micro examination as required by relevant standards), hot cracking tests, cold cracking tests and restraint cracking tests. If the material is prone to reheat cracking, this susceptibility also is evaluated.

WRI PACKAGE OF WELDABILITY TESTS

a) Raw material Tests
b) Hot cracking test - Transvarestraint test
c) Cold cracking tests -

  - Bead on plate
  - Direct rate in-situ thermal analysis and plotting weld - cct
  - Inplant weldability test
  - Modified Tekken test or controlled thermal severity test (CTS)
  - Restraint/Reheat cracking tests if needed

d) Procedure qualification tests -

  - Evaluation of strength and toughness of weld and HAZ.
  - Based on above tests, a master weldability diagram for any steel can be developed by WRI.

With these tests, one can establish for any material a master weldability diagram which could be of direct use for the fabricator in selection of welding process and parameters to avoid the various cracking problems and to achieve the desired properties of the weldment.

3.3 Service Weldability:

3.3.1 Fabrication of Pressure Vessels and Boilers:

These applications call for matching filler materials resulting in weldment with matching properties.

The thicker sections of carbon steels and all section thicknesses of low alloy steels will require a thermal stress-relief which also tempers the HAZ of weldments. Quenched and tempered steels require carefully controlled procedures different from that of N&T materials to maintain the advantages of the Q&T treatment. In particular, the Heat Input, and level of preheat should be balanced to avoid degradation of HAZ properties - especially strength and toughness.

Ferritic and chromium iron alloys will have structures as duplex to avoid grain-growth and brittleness problems, associated with fully ferritic alloys or the intense HAZ hardening of fully martensitic alloys. For welding austenitic stainless steels for heat resistance, higher carbon (0.20%C) grade electrodes/fillers are to be used.

Due to high quality requirements for pressure vessels, often GTA welding is recommended for root welding of pipes and tubes.

3.3.2 Ship building Applications:

Processes and fillet metal used should result in properties (strength and minimum notch-toughness) expected of base metal at the lowest design temperature. For welding of HSLA steels, tempering bead must be used (covering pass). Stress relieving generally should not be performed on low alloy steels especially prohibited on certain types of electrodes.

3.3.3 Transport Industry:

3.3.3.1 Rail Road:

Fusion and Resistance welding processes are extensively used. When welding stainless steels for corrosion or for high temperature operation, columbium stabilised stainless weldmetal is used. Large amounts of repair welds are made on railway components. Reclamation of cylinder heads of cast iron material is done with high preheats ($700^{o}C$) using preheat furnaces. Welding is done by oxy-acetylene process using flux and a cast iron rod. Slow cooling after repair is ensured. The wornout cam shafts are repaired by 'Hot Arc' process developed by Welding Research Institute, Tiruchirapalli.

In addition to welding, many non-ferrous alloys (copper base), malleable cast iron etc are being brazed. Fuel and lubricating oil lines are generally made of copper to counteract corrosion and are brazed with a silver brazing alloy. In kitchens of passenger trains, soldering or brazing repairs done should use filler metals free of cadmium to avoid food-poisoning. Dissimilar joints between malleable iron and copper tubing also are done with a silver brazing alloy. As a permanent repair for eddy current clutches, copper overlay is built up on steel bore of clutch.

3.3.3.2 Automative Industry:

The materials for automative joints to achieve greater corrosion protection have been metallic coated or painted. This has a definite effect on the welding process, dictating a modification in technology to be followed.

For repair welding of cast iron engine blocks and heads, SMAW process using a pure 'Ni' or 55% Ni electrode is employed. The weld deposit is machinable, though of course, HAZ of cast iron will always exhibit poorer machinability due to hardening. Judicious peening of weld bead made in short lengths reduces the residual stresses or alters the stress pattern to produce harmless compressive stresses. For avoiding hot cracks, Ferronickel electrodes would be better compared to 'Ni' electrodes.

Welding of passenger car or truck wheels was made possible by extensive R&D in wheel design and welding techniques. Careful wheel design, shape of weld nugget, weld location, control of process parameters are required to be taken care of. The wheel rim is made from a strip of low carbon steel by flash welding to make a band, forming into the shape by various pressing and rolling operations and expanding to size. The weld must be free from defects and must be uniform in its properties, throughout circumference to withstand the subsequent die forming operations. A new steel, being developed in India too, viz., 'Dual phase steel' is being evaluated for its weldability for this application by Welding Research Institute.

3.3.4 Bridges:

When welding of high YS Q&T steels (ASTM A514) high heat input processes like Electroslag and Electrogas are not to be used. Proprietory steels and steels to specifications, providing atmospheric corrosion resistance are available and while welding such steels, the finishing passes of multipass welds must have a chemical composition that will have a similar atmospheric corrosion resistance.

3.3.5 Aircraft Industry:

Since some of the welded magnesium alloys are prone to stress-corrosion cracking, it is essential that a thermal treatment be employed to remove the welding residual stresses. Welded joints made between magnesium and other metals are not generally recommended because of the resulting galvanic corrosion which is rapid.

Since Titanium and its alloys are reactive with air and other foreign materials while welding, greater care must be exercised in preventing contamination. Also, normally the weldmetal will consist of very large grains.

Though welding of precipitation hardening corrosion resistant steel in annealed condition will result in higher weldmetal tensile strengths, this is not always the best sequence to secure the required joint properties. The welding process applied is a major factor in planning a welding and hardening procedure but same heat treating steps and temperatures are employed irrespective of the thickness of the material. Aluminium containing precipitation hardening steels should not be welded using processes other than gas shielded processes, since 'Al' is lost by oxidation in weldmetal. For a dissimilar weld, of course with this steel, any process can be applied.

When welding Nickel-base alloys (matrix strengthened) the following are the points to be considered -

a) Filler metal at least equal to base-metal in corrosion property;

b) High cleanliness (free from grease, paint, etc, causing 'S' pick up);

c) Multipass welds in stringer-bead to avoid cracking through, interpass cleaning;

d) With GTA process, inert gas backing is necessary when possible;

e) No root gap necessary in GTA process since penetration is achieved.

3.3.6 Storage Tanks:

Like the materials for field placed tanks, the weld metal also should possess the weather-proof property, withstanding corrosion at ambient, low or elevated temperatures.

4.0 WELDABILITY EVALUATION OF AN INDIGENOUS HSLA STEEL - A CASE STUDY

The microalloyed steels have definite advantages over the conventional low alloy steels for structural applications. Cost of alloying is lower with microalloying elements like 'Nitrogen' and 'Al', 'Cb', 'V', or 'Ti' which raise the yield point by precipitation hardening as well as by fine-grain development in the steel. There is an improvement in the weldability as well as impact and fracture properties due to lowered carbon levels.

A micro alloyed steel developed in India, was required to be evaluated for the weldability aspects. Thin sections of 10mm thickness supplied by the steel makers, were taken up for following tests -

i) Hydrogen cracking susceptibility tests;

ii) Solidification cracking tests;

iii) Loss of toughness of weld/HAZ

Though in addition to the above, lamellar tearing is one of the major problems in arc welding, the tests for lamellar tearing was not taken up since the tearing problems will be absent in thin materials such as 10 mm plates.

4.1 Loss of Weld Metal/HAZ Toughness:

In wrought steels, the influence of microalloying elements on austenite transformation is often obscured by carbide formation, which retards grain coarsening of the austenite and removes carbon from solution. This results in a loss of hardenability which offsets the positive effects of the microalloying elements. Hence the effect of titanium and columbium on hardenability is highly dependent on the prior thermal history of the material. Both titanium and columbium suppress the formation of proeutectoid ferrite in weld metals and HAZ's more effectively than in wrought materials. Toughness can be significantly improved by alloying additions which promote the formation of fine interlocking microstructures, such as acicular ferrite.

On the other hand, while grain refinement results in improved cleavage resistance, precipitation strengthening always result in loss of toughness. Columbium, vanadium and titanium are powerful precipitation strengtheners, and the magnitude of their effect will depend upon the weld thermal cycle. In addition, in steels where only columbium is present, there is the possibility of the formation of lath type martensite which can reduce the toughness significantly. In the foregoing test, presentation has been made on the result of the weldability and associated metallurgical investigations on three different heats of a HSLA 'I' section developed by the research and development department of one of the major steel plants in India.

DETAILS OF EXPERIMENTS

Three different heats of an 'I' section of high strength low alloy steel developed by the R & D division of a major steel manufacturer were investigated for their weldability.

The chemical composition and mechanical properties of the different heats are given in Tables 1 and 2 respectively.

TABLE 1

CHEMICAL COMPOSITION

Element	Percent Content		
	Heat-I	Heat-II	Heat-III
Carbon	0.15	0.16	0.18
Manganese	1.18	0.82	1.44
Silicon	0.12	<0.10	0.17
Niobium	0.03—0.05	0.04	0.03—0.05
Vanadium	<0.05	<0.05	<0.03
Sulphur	0.02	0.028	0.024
Phosphorous	0.017	0.016	0.013
Aluminium	0.3—0.5	<0.02	0.03
Chromium	0.096	<0.10	0.10
Nickel	<0.10	<0.10	0.10
Molybdenum	<0.10	<0.10	0.10

TABLE 2

MECHANICAL PROPERTIES

Property	Heat-I	Heat-II	Heat-III
UTS kg/mm^2	(i) 56.8 (ii) 56.4 (iii) 58.5	(i) 52.5 (ii) 51.2	(i) 62.8 (ii) 61.9
Yield Strength kg/mm^2	(i) 44.0 (ii) 44.9 (iii) 45.6	(i) 40.6 (ii) 39.4	(i) 45.9 (ii) 46.3
% Elongation	(i) 28.5 (ii) * (iii) 28.3	(i) 21 (ii) *	(i) 25.6 (ii) 27.4
% Reduction in Area	(i) 54.4 (ii) 50.9 (iii) 56.0	(i) 61.3 (ii) 61.1	(i) 53.3 (ii) 54.8

*Broken at shoulder.

TABLE 3

RESULTS OF TRANSVARESTRAINT TEST

Sl. No.	Die Block Radius (mm)	Strain %	Observation (CCL)		
			I	II	III
1	1000	0.3	X	—	—
2	500	0.6	X	X	—
3	333	0.9	X	—	—
4	300	1.0	—	1.2	X
5	250	1.2	Cracks in isolated regions	8.7	X
6	200	1.5	—	—	—
7	150	2.0	—	15.7	Small Cracks seen

X—No Cracks Observed

CCL—Cumulative Crack Length (mm)

The transvarestraint test was conducted on the three different heats at different strain levels as indicated in Table 3, to determine the hot cracking tendency. (A sketch of the test set-up is shown in Fig. 1) and the test is described elsewhere (10). The results of the test are given in Table 3.

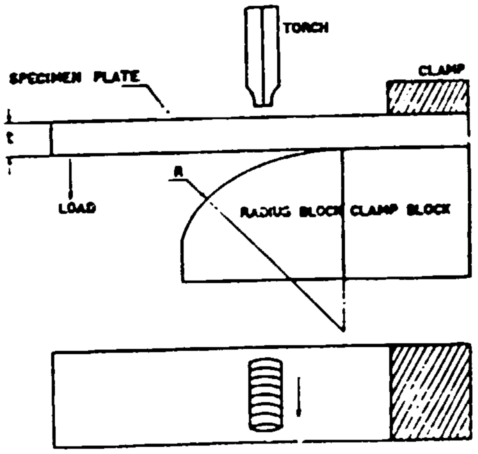
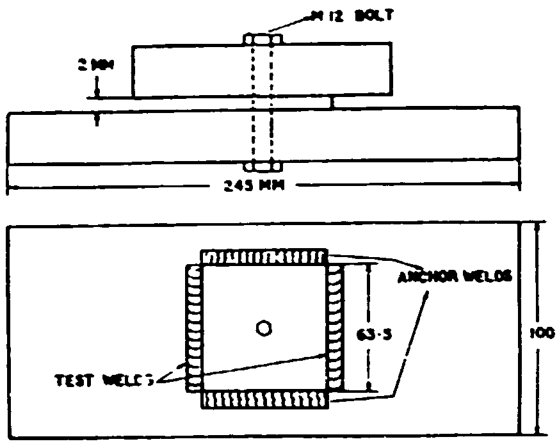


FIGURE 1 SCHEMATIC DIAGRAM FOR TRANSVARESTRAINT TEST

The susceptibility to cold cracking was assessed using the Controlled Thermal Severity (C.T.S.) test (Fig. 2). The test was conducted without preheat using AWS E-7018 electrodes under properly redried as well as in the as-supplied conditions. The redrying temperature employed was 400 C and the duration of redrying was 1 hour. The results of the test are given in Table 4.



SET-UP FOR C·T·S·TEST

FIGURE : 2

TABLE 4

RESULTS OF CTS TEST

Sl. No.	No. of Trials	Electrode Conditions	Pre-heat	Observations		
				Heat-I	Heat-II	Heat-III
1	3	Improperly baked	None	LPI-Revealed Micro-porosity at start and end of weld	No Cracks observed	No Cracks observed
2	3	Properly baked	None	No Cracks observed	No Cracks observed	No Cracks observed

From the results of the cracking tests, it was inferred that only properly redried electrodes could be employed for producing welds without defects. Hence, a procedure qualification trial was carried out using only electrodes redried at 400°C for 1 hour.

The test carried out for qualifying the procedure included :—

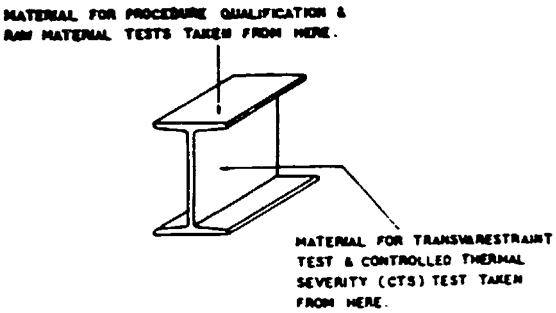
Two transverse tensile tests.

Two root bend tests.

Two face bend tests.

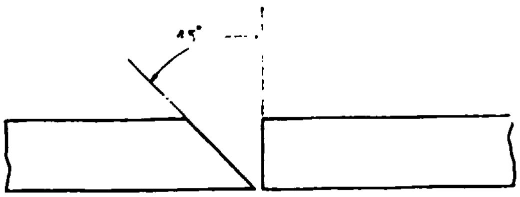
Charpy-V impact tests with the notch located in (a) the centre of the weld (b) the region exposed to temperatures greater than A_3 (Coarse grained region of the HAZ but below the melting point) (c) the fine grained region and (d) the unaffected base material. Metallographic investigations which included analysis of weld. heat-affected zone and parent material structures and hardness survey across these three regions.

The web portion of the 'I' section was used for the transvarestraint test and C.T.S. test and the flange portions for the procedure qualification trials using single 'V' edge portions. The relevant cutting plans and joint geometry for the cracking tests and procedure qualification are shown in fig. 3 and fig. 4.



CUTTING PLAN FOR WELDABILITY TESTS & W
PROCEDURE QUALIFICATION

FIGURE : 3

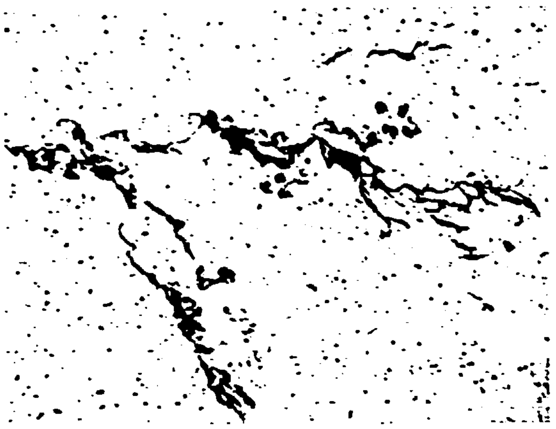


EDGE PREPARATION FOR WELDING PROC
QUALIFICATION

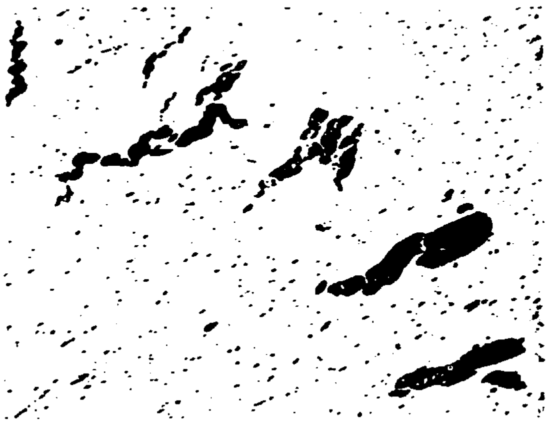
FIGURE : 4

RESULTS AND DISCUSSION

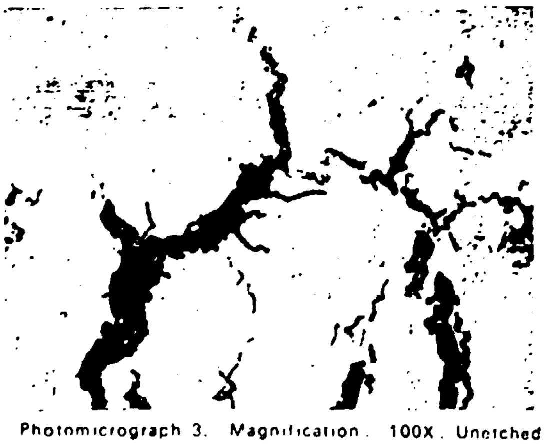
The transvarestraint test was mainly conducted in order to determine the critical cracking strain for the various heats. While for the first and third heats, incidence of micro hot cracking was noted at strains greater than 1.2% and 2.0% respectively, the second heat exhibited significant hot cracking at strains over 1.0%. The cumulative crack length for the second heat at 2.0% strain level was 15.7 mm. The difference in the hot cracking tendency of the second heat as compared with the other two heats could be attributed chiefly to the low Mn S ratio of 29.3 in the second heat. The first and third heats has Mn S ratios of 59.0 and 60 respectively. Photomicrographs 1, 2 and 3 show the hot cracks in the transvarestraint test on the three heats.



Photomicrograph 1. Magnification : 100X ; Unetched. Structure showing hot cracks formed in the transvarestraint test at 1.2% strain in the heat No. 1. Inclusions, probably oxides are seen in the background



Photomicrograph 2. Magnification : 100X ; Unetched A metallographic cross-section of the transvarestraint test specimen of heat No. 2 tested at a strain level of 1.2%. Microfissuring is seen in the structure



Photomicrograph 3. Magnification : 100X . Unetched Photo showing hot cracks in the transvarestraint test specimen of heat No. 3. The cracks were observed at a strain level of 2%

The controlled thermal severity test demonstrated incidence of micropores in the test weld when the test was conducted with AWS E-7018 electrodes in the as-supplied condition. While porosity could be acceptable according to some codes, it is preferable to do the actual welding of components with properly dried electrodes (at 400 C for 1 hour) in order to avoid cold cracks even though the C.T.S. test did not reveal any cracks with both redried and as-supplied electrodes. Photomicrograph 4 shows the micro-structure of the weld, HAZ and base material in the C.T.S. test conducted on the first heat which is representative of the other two heats as well.

Photomicrograph 4. Magnification : 100X ; Etchant : 3% Nital. Structure showing the weld (top right) the coarsegrained bainite of the HAZ (middle) and the refined ferrite and pearlite structure (bottom left)

The results of the transverse tensile test conducted on the welded plates of procedure qualification tests indicated a matching strength and ductility in the weld metal as compared with that of the base metal.

The face and root bend tests passed the 180° bend angle without openings in the third heat while in the first heat there were some minor openings in the base materials in one root and one face bend test. One of the root bend specimens revealed a small opening in the second heat However, the openings were all within the permissible limits.

The Charpy-V impact tests carried out with the notch in the four zones of the weldment, namely, the unaffected parent material weld, coarse-grained HAZ and fine-grained HAZ revealed very high impact toughness values of over 20 kgfm cm² in the grain-refined HAZ even at temperatures below — 50 C. The impact toughness of the grain-coarsened region was lower and the ductile-brittle transition temperature (50% ductility) was between — 30 C and — 50 C. The base material impact toughness was also quite high even at sub-zero temperatures except in the case of the second heat which had relatively lower impact toughness, probably due to the presence of inclusions. The average impact strength vs. testing temperature curves for the three heats with the notch located in the four different zones are given in Fig. 5, 6 and 7 respectively.

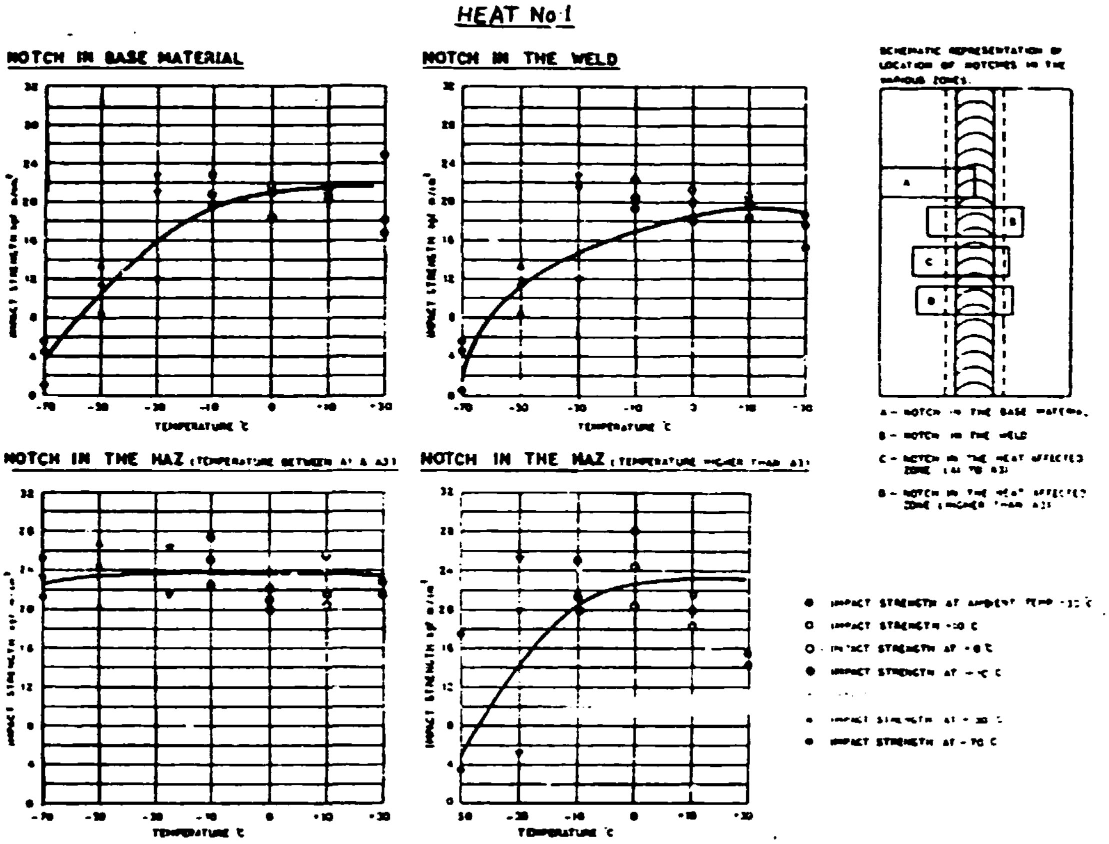


FIG-5 IMPACT STRENGTH VS TEMPERATURE CURVES (DUCTILE BRITTLE TRANSITION CURVES).

HEAT No:2

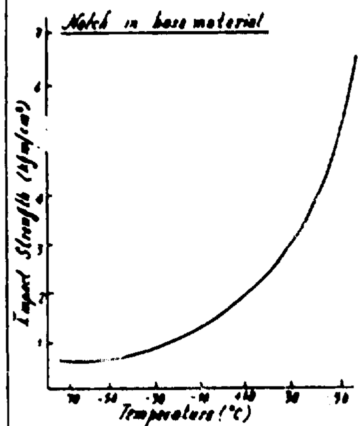


Fig - 6(a)

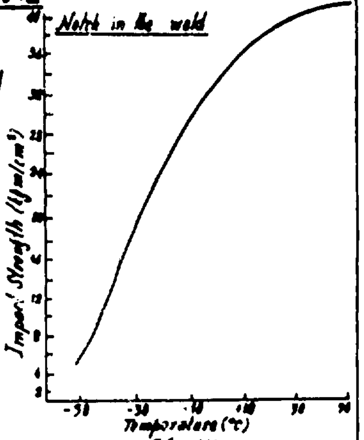


Fig - 6(b)

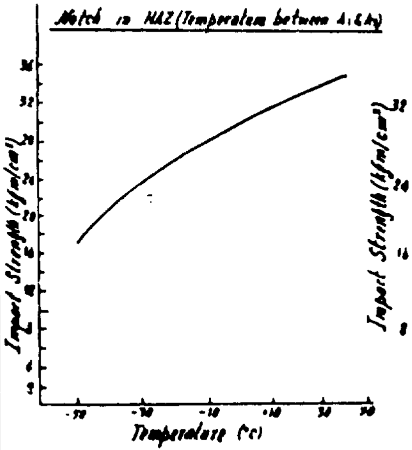


Fig - 6(c)

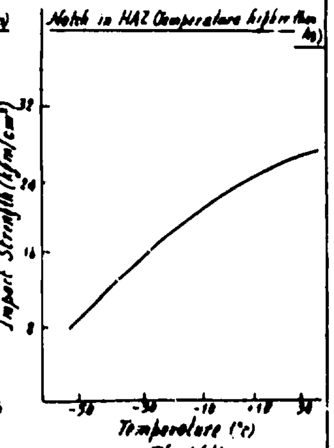


Fig - 6(d)

HEAT No: 3

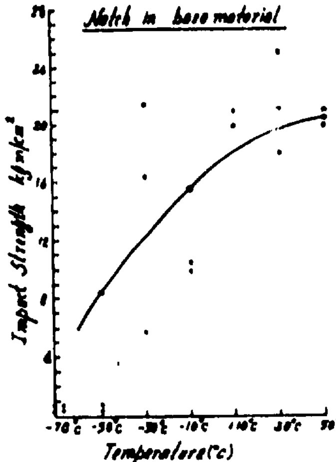


Fig - 7(a)

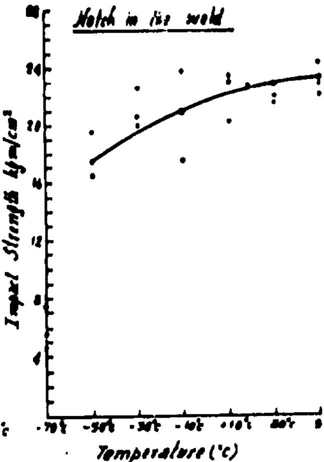


Fig - 7(b)

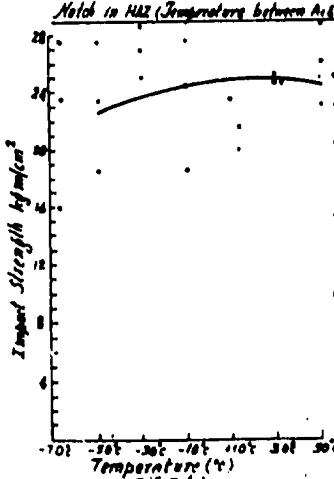


Fig 7(c)

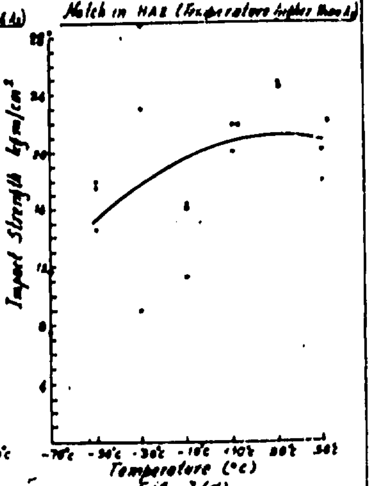
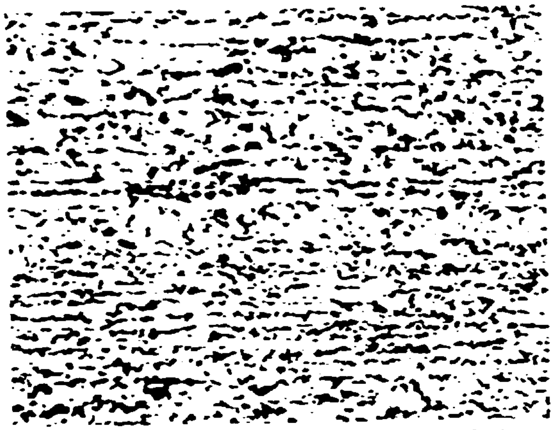
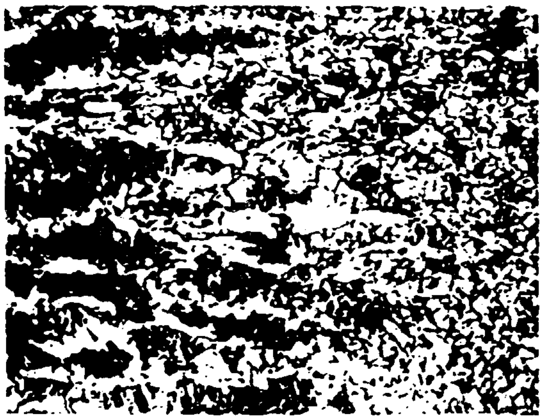


Fig 7(d)

The parent material structure in all the three heats comprised polygonal grains of ferrite and pearlite with grain size finer than ASTM No. 8. Photomicrograph 5 shows the typical parent material structure. The weld metal structure shown in photomicrograph 6 reveals columnar grains in the top layer and polygonal grains at the lower layers. Generally, since the properties of the root of the weld is critical, the improved properties of the grains in the root of the weld which are recrystallised into a polygonal grains by the top layers add to the quality of the joint.

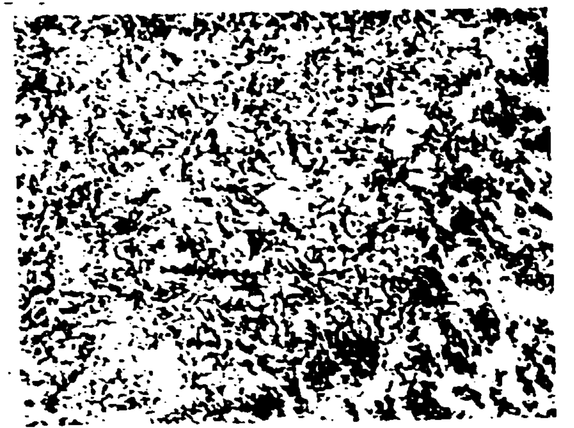


Photomicrograph 5. Magnification: 100X ; Etchant : 3% Nital. Microstructure of the base metal (similar structure for all 3 heats) showing polygonal grains of ferrite and pearlite. The ASTM grain size is finer than ASTM No. 8

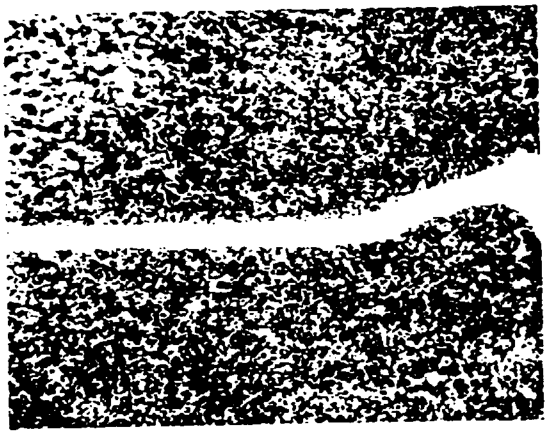


Photomicrograph 6. Magnification : 100X . Etchant : 3% Nital. Weld structure showing columnar grains of ferrite and carbides in the top layer and polygonal grains of ferrite in the bottom layer formed by recrystallisation due to tempering action of the top layer

The narrow coarse-grained region of the heat-affected zone is somewhat detrimental but the maximum hardness level in this region was less than 300 VHN (20 kg load) which is acceptable for the service conditions to which the steel would be subjected to. Photomicrograph 7 shows the refined zone, the weld and the adjoining coarse-grained zone while photomicrograph 8 demonstrates the fine-grained region of the heat-affected zone.



Photomicrograph 7. (representative of all the three heats) Magnification : 100X : Etchant : 3% Nital Microstructure of the combined zone comprising weld metal of the topmost layer which consists of acicular and proeutectoid ferrite (right corner), coarse-grained bainitic structure of the HAZ next to the fusion line (middle) followed by the fine grained region in the extreme right



Photomicrograph 8. (representative of all the three heats Magnification . 100X ; Etchant : 3% Nital Microstructure of the region next to the coarse-grained heat affected zone, consisting of extremely fine polygonal grains of ferrite and pearlite with ASTM grain size No. 8

Table 5 gives a sketch of the hardness levels across the weld, HAZ and parent material in the three different heats of the steel along with the hardness values. Barring an isolated instance of a maximum underbead hardness of 297 VHN in the heat-affected zone of the second heat, the underbead hardness level was lower than 250 VHN thus demonstrating the good weldability of the steel.

CONCLUSIONS

The HSLA 'I' sections have good resistance to hot cracking. However, from the results of investigations carried out in one of the heats, it can be observed that there could be a tendency to hot cracking in some of the melts due to high sulphur content. Hence, it is essential to determine the

TABLE 5

HARDNESS SURVEY (HEAT-I) (VICKERS-10 Kg LOAD)

1........................20 21........................40

Heat-1				Heat-II				Heat-III			
1	199	21	221	1	150	21	181	1	221	21	206
2	206	22	221	2	160	22	181	2	221	22	206
3	206	23	221	3	165	23	181	3	221	23	206
4	206	24	221	4	179	24	181	4	229	24	215
5	221	25	221	5	206	25	181 (FL)	5	229 (FL)	25	211
6	221	26	221	6	206	26	179	6	221	26	215
7	206 (FL)	27	206 (FL)	7	190.6 (FL)	27	176	7	215	27	236 (FL)
8	193	28	221	8	170	28	160	8	203	28	221
9	193	29	221	9	176	29	165	9	206	29	221
10	206	30	213	10	176	30	170	10	218	30	215
11	193	31	206	11	176	31	170	11	224	31	211
12	193	32	206	12	183.4	32	187	12	229	32	221
13	191	33	206	13	183.4	33	193	13	221	33	221
14	187	34	213	14	183.4	34	170	14	221	34	229 (FL)
15	213	35	221	15	199	35	160	15	236	35	221
16	221	36	206 (FL)	16	206 (FL)	36	160	16	236 (FL)	36	215
17	206	37	221	17	206	37	165	17	229	37	206
18	221	38	221	18	181	38	170 (FL)	18	221	38	206
19	221	39	221	19	165	39	176	19	215	39	206
20	206	40	213	20	170	40	181	20	214	40	206

chemical composition of each of the heat and ensure that the Mn S ratio is reasonably high (> 50) and the inclusion content is at low levels.

The cold cracking susceptibility of the HSLA 'I' sections is significantly low in that the C.T.S. test failed to reveal any cold cracks even when the electrodes were not redried properly and no preheat was employed. However, as a precautionary measure, it is necessary to redry the electrodes at 400 C for 1 hour in order to avoid cold cracks in actual structures, which can have higher restraint than that simulated in the C.T.S. test.

Welding procedure qualification of the steel section employing properly redried electrodes and without preheat gave satisfactory tensile properties for the weldment. Since the flange mid-thickness of the 'I' sections was limited to 10 mm, it cannot be concluded that 'I' sections with higher flange mid-thickness do not require preheat.

The Charpy-V impact strength vs. testing temperature curves indicated that the steel sections as well as the weldments made of it had low ductile-brittle transition temperatures. While the fine-grained region of the HAZ had very good impact toughness even at temperatures below —50 C, the weld and the base material (except in cases where the inclusion contents are high) also have satisfactory impact toughhess enabling safe application at sub-zero temperatures. The narrow coarse-grained region of the HAZ which exhibited a relatively higher transition temperature may not give rise to major cracking problems since the maximum underbead hardness is below 300 VHN.

The microstructure of the parent material, weld and the heat-affected zone do not exhibit any undesirable hard constituents to cause cracking. Even the coarse-grained zone in the HAZ just adjacent to the fusion line limited to a very narrow area. The hardness survey across the three zones further confirmed the absence of hard constituents, since the maximum underbead hardness was lower than 300 VHN and most of the indentations in the HAZ gave values less than 250 VHN.