Science & Technology of Welding - A Journey towards the 21st Century

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Abstract

The paper deals with science and technology of several specific areas of welding that have advanced sufficiently in recent years and highlighting the futuristic path of development.

Introduction

Over the 1st half of the 20th century, the manufacturing industry was revolutionized by the introduction of welding. Prior to arc welding, the methods of casting, forging, riveting and bolting were the principal methods utilize in the fabrication of metallic structures. Practical limitations of these methods, nevertheless, prevented them from taking advantage of the economics of the large units, reduced weight and simplified production offered by welding.

Welding technology being a live field, has always kept pace with the demands by the industry. As the century went on, industry demanded better weld quality, greater process stability and improved material weldability. Historically, welding processes have developed empirically and have been applied to technological problems with unusual quickness. The foundation of the welding science had its origin back in the period World War II where an incredible number of joining problems were resolved through painstaking and unceasing work. Today, welding science is uniquely characterized by the wide variety of disciplines it brings together such as arc & plasma physics, material science, chemistry, electrical & mechanical engineering and economics. Several specific areas have advanced significantly in recent years. Welding technology for decades has seen growth more as an art than as science. However, in recent year this trend has been reversed.

It would be interesting to look the growth of the entire welding as a journey and its futuristic path of movement towards 21st century. I therefore intend to make this journey relating to the following aspects:

- Process Development
- Equipment Development
- Consumable Development
- Material Development
- Energy & Environment

Development in Welding Processes

Arc welding, in its many variants, continues to be the major welding technique applied in light and heavy fabrication. Because of the well-established position of arc welding, most developments have been incremental and have yielded significant productivity improvements. For example, Activated flux TIG (A-TIG), which was first developed by the EO Paton Institute of Electric Welding, Kiev [1], offers the potential of overcoming the poor penetration and cast-to-cast susceptibility of TIG. A-TIG will increasingly be used on ferritic and stainless steel fabrications because of the resultant increased productivity and weld quality. Fig.1 shows the relationship between the penetration depth and welding current with and without flux. The penetration depth also increases sharply with the coating density of the flux (Fig. 2) and approximately reaches a constant when the density reaches about 1 mg /cm^2. Higher depth / width ratio of A-TIG welds with flux is associated with decrease surface tension, localized distribution of metal plasma, constricted anode root and the multiplication effect between the Lorentz force and the Marangoni convection.

In high current melt-in mode (>300 A), the GTAW process focus a relatively deep weld pool through the combined effects of high heat input and weld pool displacement caused by magnetically induced 'arc force'. The keyhole mode of GTAW process, which is a novel solution to weld pool instabilities, is an automated welding processes for flat position welding of ferrous and non-ferrous alloys. It is a single pass process generally suited to lower conductivity metals in the range of about 3 mm to 12 mm in the thickness. The conditions used to create the required arc characteristics differ markedly from those of both conventional and high current GTAW process.

The productivity of MIG/MAG welding has continued to increase in recent years and the reasons for this have been summarized as follows [2]:

- The increased use of flux cored/metal cored wires.
- Optimization of shielding gas mixtures for particular applications.
- Power source developments and synergic process control.
- The use of tandem wires.

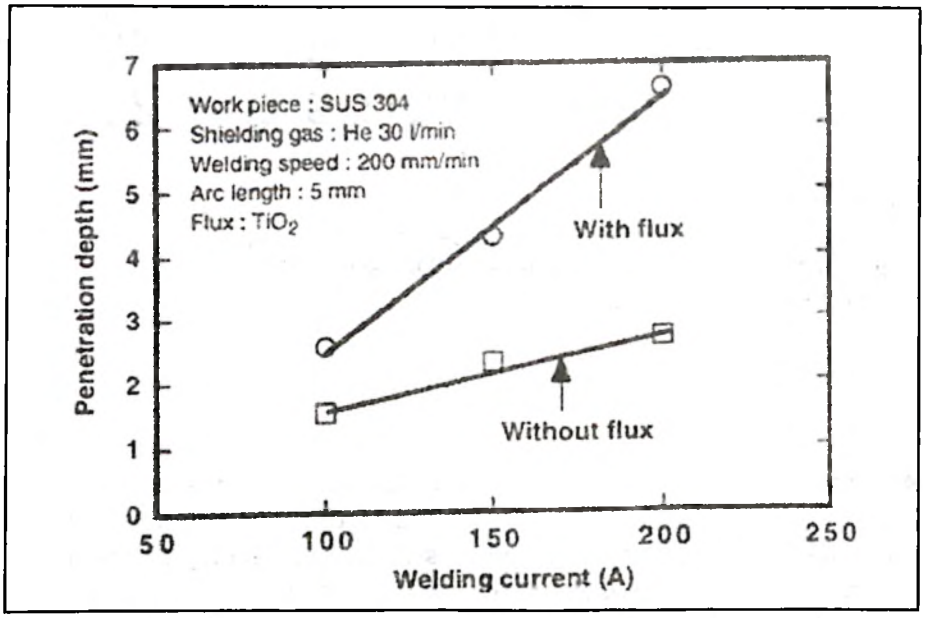

Fig. 1 : relationship between the penetration depth and welding current with and without flux

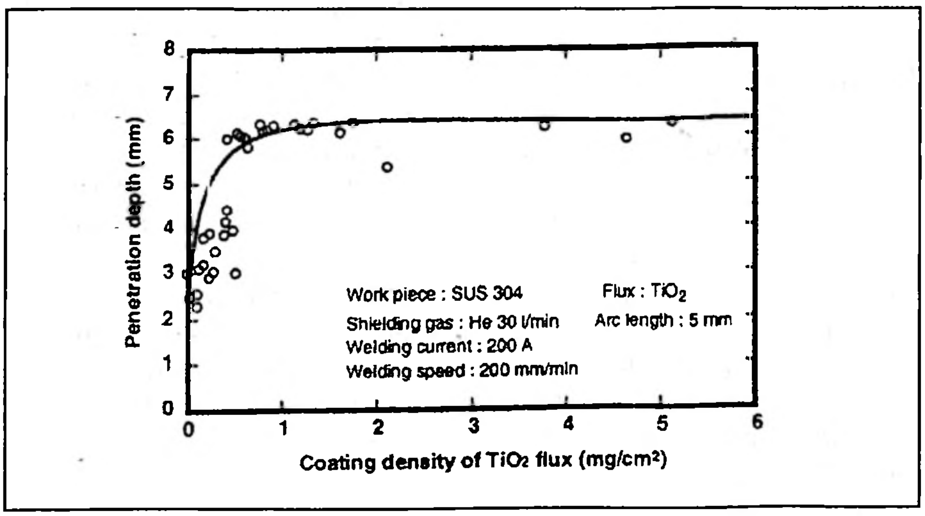

Fig. 2 : Effect of coating density of the flux on penetration depth.

Electro Slag Welding (ESW), which has introduced in the United States in the late 1960's, the process was considered the most productive of any welding process in joining thick components. However, certain welding problems began to surface in terms of welding imperfections and inadequate properties, which led in 1977 to the United States Deapartment of Transportation (USDT) placing a moratorium on the use of ESW for weldments on primary structural tension bridge members. In 1980's USDT launched comprehensive research and development effort in the area of ESW technology. The outcome of R&D resulted new variation of the ESW process called Narrow-Gap Improved Electro Slag Welding process (NGI-ESW) which has attributed in higher productivity rate (higher welding speed), and improved fracture toughness both in welds and HAZ and much higher degrees of freedom from fusion weld defects and cracking [3] because;

- Tubular powder metal-cored wire as per AWS A5.25 specification; typical Electrode wire chemistry : C 0.03% max, Mn 0.8 1.6 %, Si 0.3 0.6%, Ni 2.3 3.0%, Mo 0.3 0.6%, P 0.015% max, S 0.015% max, V 0.005% max, Ti 0.02 0.1%, Al 0.03% max.
- New type of consumable guides made from low-carbon steel to reduce susceptibility to hot cracking and rectangular shape to distribute heat more uniformly.

Table 1: Typical process variables for the NGI-ESW for welding 50 mm plates:

	Conventional ESW	NGI-ESW
Root Opening	32 ± 2 mm	19 ± 1 mm
Amperage	600 ± 100 A	1000 ± 100 A
Voltage	39 ± 1 V	35 ± 0.5 V
Welding Speed	28 mm/min	55 mm/min
Heat Input	50 KJ/mm	37 KJ/mm

Cost comparisons of NGI-ESG with standard ESW and SAW show [4] that labour cost savings are substantial for the NGI-ESG and total cost savings is also significant.

CO_2 Laser equipments were first developed in 1960's and industrially applied in 1970's. For example, a 25 KW CO_2 Laser has been installed in Japan for the manufacture of line pipe [5], other industries which have assessed the technology include shipbuilding, structural steel work and earth moving equipment. However, the first area of welding applications was in the aerospace and automobile sectors for the fabrication of precision components. One of the most significant recent developments in the area of sheet welding is the laser tailored blanks used in automotive manufacture since the inaugural substantial weight and cost saving.

As illustrated in Fig.3, a part of the body is initially prepared by pieces of blank materials and these are laser welded linearly in the flat position, and then press formed into 3D-shape. The method was first attempted by Toyota and Audi.

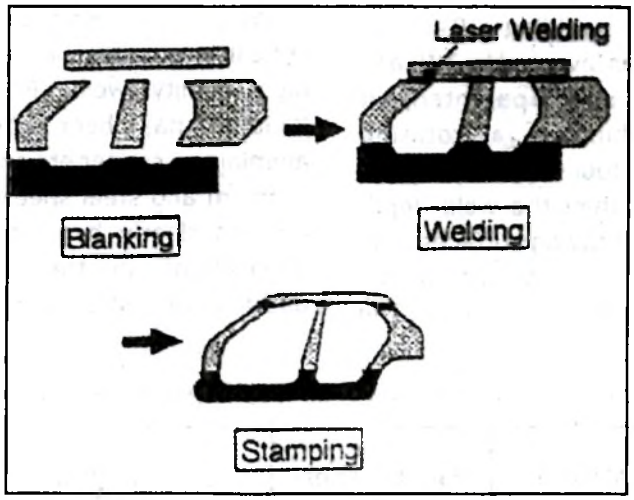

Fig.3: Laser tailored blank welding

In recent years, laser welding using two laser beams, or dual beam laser welding (DBLW), has become an emerging welding technique. In DBLW, the dual beams can be arranged either side by side or in tandem as shown in Fig.4 furthermore, with the help of a bendable mirror a laser beam can be splited into two beams that are then arranged side by side during welding.

A study on using side-by-side laser beams for improved fit up tolerance has been reported in welding tailored blanks [6]. The rule of thumb is that the air gap between two work pieces should be less than 10% of the sheet thickness for butt joints and 25% for lap joints in conventional single-beam lasers could substantially increase the fit tolerance in welding tailored blanks [7].

DBLW arranged in tandem has been reported to provide benefits over conventional single beam laser welding such as improved weld quality [8]. For steel, surface quality was improved with fewer surface defects such as undercut, surface roughness, spatter and underfill. Weld hardness and centerline cracking susceptibility were also reduced. In aluminium, quality improvements were in the form of smooth weld surface and fewer weld defects such as porosity, surface holes and undercut. The improved weld quality in DBLW is derived mainly from the improved stability in terms of less plasma plume fluctuation [8].

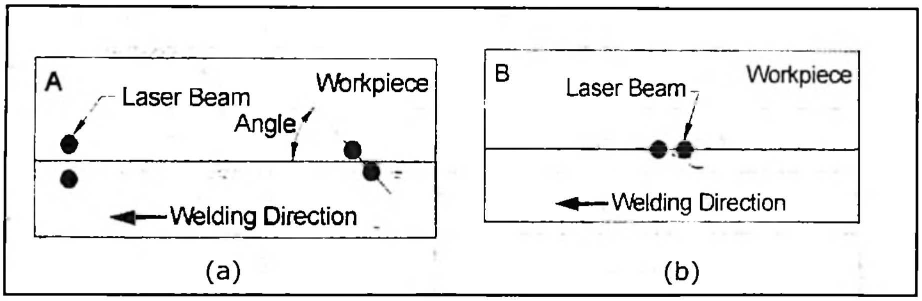

Fig.4: Dual beam laser: (a) Side-by-side, (b)in Tandem

The most exciting recent development has been that of friction stir welding [9], The technique was invented by TWI and has since been patented, it involves plunging a rotating shoulder pin tool with a pin length slightly less than the weld depth required joint faying surfaces until the shoulder is in intimate contact with the work surface. The particular welding conditions employed (rotational and traverse speed, applied force) and the tool shape and dimensions used are critical in obtaining a defect free, high quality weld. Friction stir Welding has been applied to aluminium, copper etc and even to titanium and steel sheets and the process clearly has many future applications in the aerospace, automotive, ship building etc. because of its simplicity, cleanliness (no fume is emitted), low cost (no consumables required), high quality of the welds produced.

Up to now, most of the production applications have focused on non-automotive means of transformation such as train, airplane and ships. While most of FSSW efforts to date have focused

Table 2: Plate thickness, FSW parameters and tool materials for FSW process:

Material to be welded	Plate thickness (mm)	Tool rotation rate (rpm)	Tool traverse speed (mm/min)	Tool materials
12% Cr steel	12	--	240	--
Low carbon steel	12,15	--	102	--
AISI 1010	6.4	450-650	25-102	Mo and W-based alloys
304L	3.2,6.4	300,500	102	W- alloy
304	6.0	550	78	Polycrystalline cubic boron
304L, 316L	5,10	300-700	150,180	--
AI 6XN	6.4,12.7	--	102	W- alloy
HSLA-65	6.4,12.7	400-450	99-120	W
DH-36	6.4	--	102-457	W- alloy
C-Mn	6.4	--	--	Polycrystalline cubic boron nitride

on aluminium alloys, there is considerable interest in it for steels. The lower heat inputs associated with FSW (relative to fusion welding processes) are expected to produce less metallurgical changes in the HAZ and to minimize distortion and residual stresses in steels which is extremely important in welding of thick-section components, such as in the ship building and heavy manufacturing industries. Furthermore, problems with hydrogen cracking in steels would be eliminated due to solid-state nature of FSW process.

Some FSW studies were recently conducted on low carbon steel and 12% Chromium alloy steel [10], mild steel AISI 1010 [11,12], austenitic stainless steel 304L [13, 14-17] and 316L [17], HSLA-65 (ASTM A945) [18] and DH-36 [18].

A novel variant of the "linear" friction stir welding (FSW) process, Friction Stir Spot Welding (FSSW) creates a spot, lap-weld without bulk melting. Two distinctive variants of the FSSW process have been reported in the open literature [19-22]. The first approach used by Mazda, employed a fixed pin tool geometry [19,21]. The protruded pin leaves a characteristic exit hole in the middle of the joint. The second approach [22] utilizes delicate relative motions of the pin and the shoulder to refill the pin hole. In comparison, the fixed pin approach is very fast. The fixed pin approach was used to weld 600 Mpa dual phase steel and 1310 Mpa martensitic steel using a single tool made of polycrystalline cubic boron nitride.

Development in Welding Consumables

The first attempt to use the intense heat of a carbon electrode arc for welding was probably due to Auguste de Meritens in 1881 [24,25]. Around 1889, arc welding has been introduced gradually into manufacturing in England. Acceptance of the carbon arc process was generally slow because if introduced carbon particles into the weld pool. Shortly after, Slavianoff and Coffin [24] developed independantantly the process in which the carbon electrode was replaced by a metal rod. The earliest electrodes were made of bare wires of Swedish iron. Frequently, the arc overheated the weld metal, created spatters, and the metal deposited by the electrode was embrittled due to air contamination. In an attempt to overcome these difficulties, researchers developed electrodes that were lightly coated with various organic or mineral materials, commonly named light fluxes [26]. Arc stability, which was known to depend on the presence of a conducting gas or vapor in the arc, was the major issue.

Although much progress was made with the use of bare or light flux electrodes, it was soon recognized that despite satisfactory strength, the welds exhibited low ductility, low impact and fatigue resistance. The poor mechanical performance was attributed to the formation of oxides and nitrides as a result of atmospheric contamination and vaporization of essential elements. In 1907, Kojelberg from Sweden proposed the ides of using a heavy flux coating to prevent atmospheric contamination. The development of extrusion process in 1927 for applying a covering to the metal rod made the shielded metal arc welding process feasible.

Development of Arc Welding Consumables

1900- 1960 Period

- Flux coated electrodes
- Interesting characteristics of rutile (E 6012 and E 6013)
- Iron powder added coated electrodes (E 6024)

1960- 1980 Period

- Post World War II period was marked by the commercial introduction of basic low H_2 and Iron powder covered electrodes
- O_2 control with rear earth metals.

1980-2000 Period

- Understanding of the fundamental behaviour of welding consumables and creating a data base for the consumables designers of the future.
- Hydrogen control has become increasingly important as modern higher strength steel gain popularity.
- Production of electrode containing Ti and B.

Future development

It is most likely that in the 2000 to 2010 decade, welding electrodes will continue its firm course of development, with focus on performance enhancement. In terms of market share, it appears that submerged arc welding will remain unchanged, shielded metal arc welding will continue to decline, and the gas metal arc welding will gain steadily. The clear winners will be the flux-cored and metal-cored wires with continuous growth, replacing some of the solid wires in the area of low alloy steels welding. However, increase of applications and improvement of the operability of flux-cored wires remain the focus in the future years.

Alongside with the welding technology and, materials development, it is important for the welding engineers and researchers to solve more difficult but more fundamental issues. For example, for high oxygen levels, high toughness is still a problem to be overcome. Again, the welding materials that provide low hydrogen generally lack operability. The development of improved consumables that combine low hydrogen and good operability is desired.

2000- 2010 Period

- Focus on performance enhancement
- SAW will remain unchanged. SMAW will continue to decline and GMAW will gain (Flux cored and Metal cored wires with continuous growth)
- Improvement of the operability of flux-cored remain the focus in the future years.

Development of Welding Equipments:

There has been a continuing drive to develop "real time" in-process quality control systems for arc welding particularly for equipment concerned with precision welding. Substantially improved power sources were introduced in the early 1980s with power transistor control of welding current. These power sources have enabled widespread use of pulsed welding with the capacity of synergic control. The principal advantages of the pulse mode and synergic control are that the arc does not extinguish during metal transfer and the better and more forceful arc has potential for high deposition rates, smoother bead profiles and lower spatter levels.

Waveform control technology

Every arc welding machine has a waveform characteristic. In simple machines, the waveform characteristic is based on the design of the transformer and choke. More complex machines combine hardware design with electronics to give optimized control of the waveform.

A waveform is the output response of an arc welding machine to the action of the electric arc itself. In simple m/c waveform characteristic based on the design of the transfer and choke but in complex m/c hardware design with electronics gives optimized control of waveform

Effects of Waveform

- Offer control of heat input independent of WFS (lower heat input and Improved electrode efficiency)
- Improved operator factor
- Produces smooth arc and metal transfer
- Improved productivity
- Reduces smoke and spatter

Developments in Materials

Pipe Line

Cross-country pipeline by far after the most efficient and safer mode of transport for highly volatile products like oil, natural gas or any other liquid/gaseous media with least damage to the environment. Moving petroleum products by

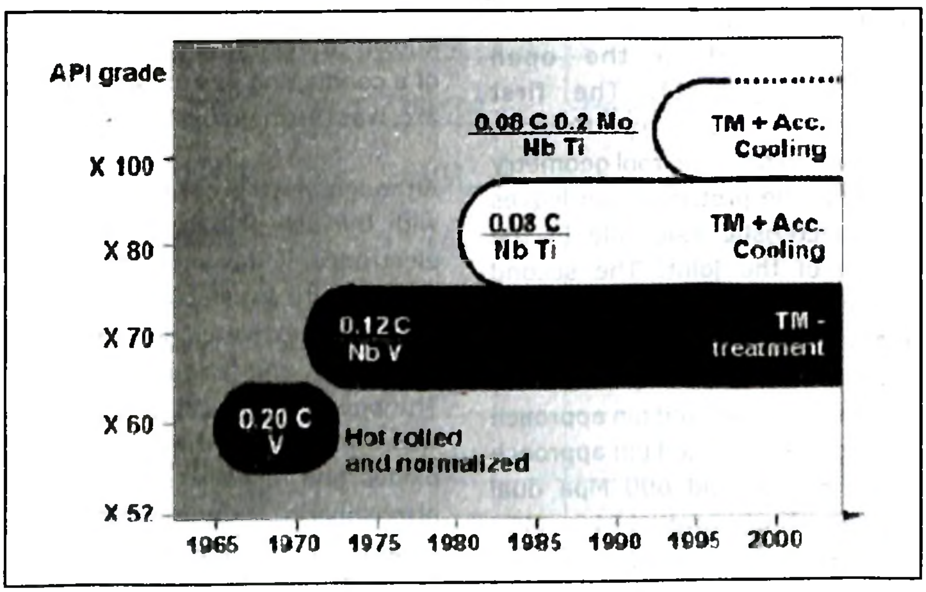

Fig. 5 : History of Pipe Line Steels.

pipelines is 50% cheaper than using any other mode of transport. Considering that transportation cost accounts for 25% of the total product cost, transportation by pipelines can bring down prices of petroleum products by 12.5% [27]. The joining of pipe into the long distance for a system of transmission pipelines requires high quality weld at a faster speed, like other field, high strength steels are being developed with a considerable savings in steel as well as transportation/handling costs (Fig.5) Although several processes and combination of processes are being used, Surface Tension Transfer process developed by Lincoln Electric has been validated and used for both semi-automatic and mechanized root pass application.

Ship Building

Shipbuilding industry has also energetically promoted high performance of ships and improved productivity in construction in response to vessel diversification (trend toward exclusive use of ships). A new class of ship steels such as Nitrous steels where nitrogen is the main alloying elements, show 3-4 times better strength whereas the ductility, fracture toughness the weldability, the weldability, corrosion resistance and the workability remain on their high level. Apart from shipbuilding, these steels will find applications in oil and gas production, power, chemical and petroleum engineering. Composite materials based on polyester and epoxy resins reinforced with glass Cr Carbon fibers are finding more and more applications in shipbuilding.

One of the promising avenues in modern ship design and construction is to more extensively apply light three-dimensional honeycomb structures, which enable one to save 20-30% of the weight compared to other kindly of structures with similar performances. The fabrication of such structures largely requires laser welding that ensures high productivity and accuracy at minimum residual stress and deformation levels.

Material development in shipbuilding [28]

- TMCP steel : for Container ship
- Anti-corrosion steel : for Crude oil tankers
- Nitrous Steel
- Cladded steel plates (e.g. : D36, E36) : for chemical tankers
- Composite materials based on polyester and epoxy resins reinforced with glass or carbon fibers for both surface ships and submarines
- Sandwich metal-&-polymer damping material consisting of alternating layers of a high-tensile corrosion-resistant aluminium alloy and a low-epoxy-number bonding material for Deck, Hulls etc.

Automobile

Automobile sector is another areas where there will be sea changes both in terms of materials and fabrication technologies used. Several aluminium alloys as well as MMCs are tending to replace the steels. However, the steel manufacturers are investing largely to develop newer steels and cost competitive steel designs (Fig. 6). All these are leading to extensive applications of tailored blank welding, a combination of welding and special adhesive bonding processes, Friction Stir Welding etc.

Materials development towards 21st century [29]

New materials developed on growing with years :

To enhance production efficiency

- ☐ To live more conveniently
- ☐ To elevate structural integrity
- ☐ To elevate environment friendliness

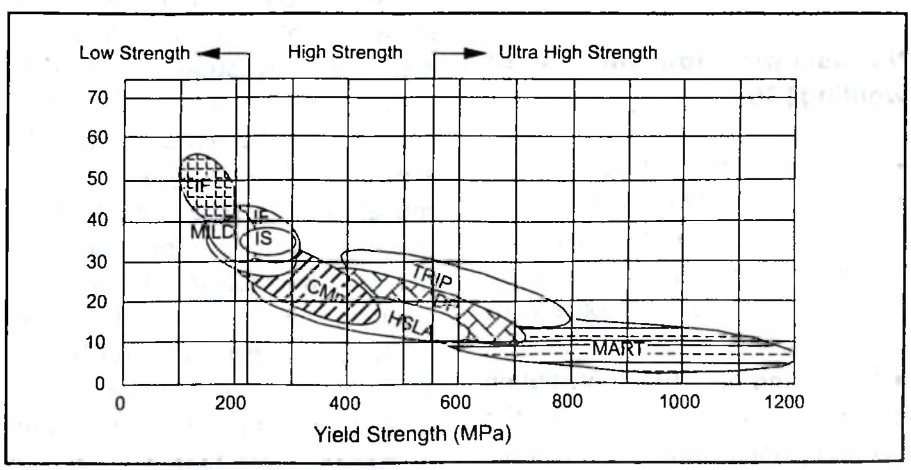

Fig. 6: Materials Strength vs. Formability

Fundamental issues on welding consumables

New concept for welding consumables development

- Ti-B addition is remarkably effective in weld metal toughness with low oxygen content
- For high oxygen level, high toughness is still a problem to be overcome
- Development of improved consumables that combine low hydrogen and good operability.

Materials and welding consumables

- Until recently, design of consumables was largely empirical.
- Alternative methods are now being exploited
  1. To keep up with rapid developments in parent alloy.
  2. More sever operating conditions.

Need for more aggressive and in-depth research of innovative welding consumables innovative concepts in terms of consumable design and manufacturing with the support of the welding related industries.

Nanoscopic approaches to welding [30]

- Nanoscale microstructure and element distribution has contributed greatly to the development of advanced materials having excellent properties.
- In welding field the contribution of nano-scale information to the practical application in industries will become more important.

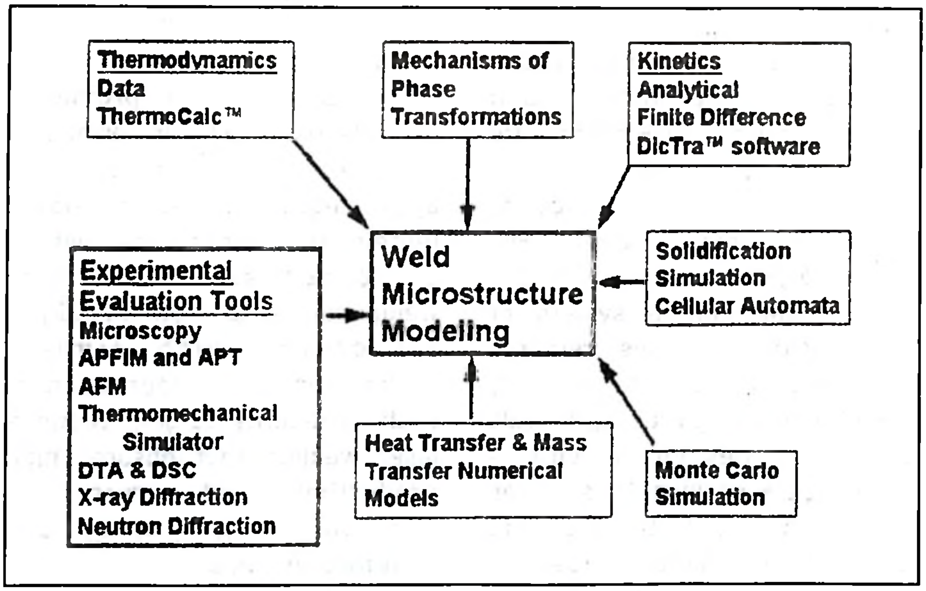

Fig. 7 : Various research tools used to develop microstructure model

Mathematical modeling in welding [31]

In recent years, phenomenological modeling of welding processes has provided unprecedented insight into understanding both the welding process as well as the welded materials that could not have been obtained by even the most ambitious experiments alone. Off all the challenges and opportunities facing welding today, the complexity of the weld microstructure remains one of the most urgent and most daunting areas of investigation. During welding, the interaction of the heat source with the material loads to significant changes in the microstructure and properties of the base material. Therefore, the process microstructure property relationships are critical to the understanding of weldment performance. Fig. 7 Shows several analytical, experimental and numerical tools that are used in modeling activities.

ENERGY AND ENVIRONMENT [32]

One of the greatest problems facing both the developed and under developed nations of the world is how to maintain and improve living standards without a corresponding destruction of the environment. It can be argued that the single most important factor in realizing an improvement in most people's way of life is a reliable and economic supply of energy.

The welding industry has a duty in the widest sense to ensure that the technology is the best and most efficient available. Take pre-heat for example, two levels of pre-heat are recognized, those based on welding consumables having a hydrogen content of less than 15ml/100g and those above, i.e. hydrogen controlled and non-hydrogen controlled. A reduction in preheat of 25°C would have immediate and significant benefits through a reduction in energy consumption during the preheating process. This philosophy can be extrapolated by allowing electrodes or processes having guaranteed lower levels of diffusible hydrogen. Expected savings through one such experience could account for the total expected reduction in green house gas emissions for the whole sector.

How do we control the Welding Process, to Minimise Fume ?

Fume generation from GMAW is a strong function of the diameter of the droplet and wire feed speed [32]. Fume generation increases as the droplet size increases and wire feed speed increases. The smaller the droplet, the smaller the temperature droplet, for the same wire melt off rate. This means that vapour pressure of the metal is lower for smaller droplets.

How to maintain and improve living standards without a corresponding destruction of the environment ?

The single most important factor is a reliable and economic supply of energy

The welding industry has a duty to ensure that the technology is most efficient available and will create a sustainable environment

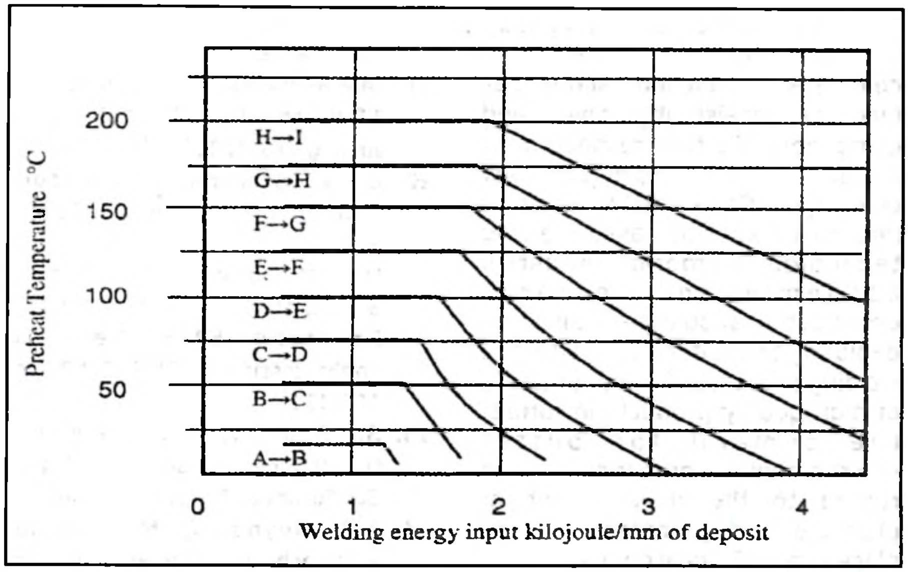

Fig. 8 : Welding energy input kilojoule/mm of deposit

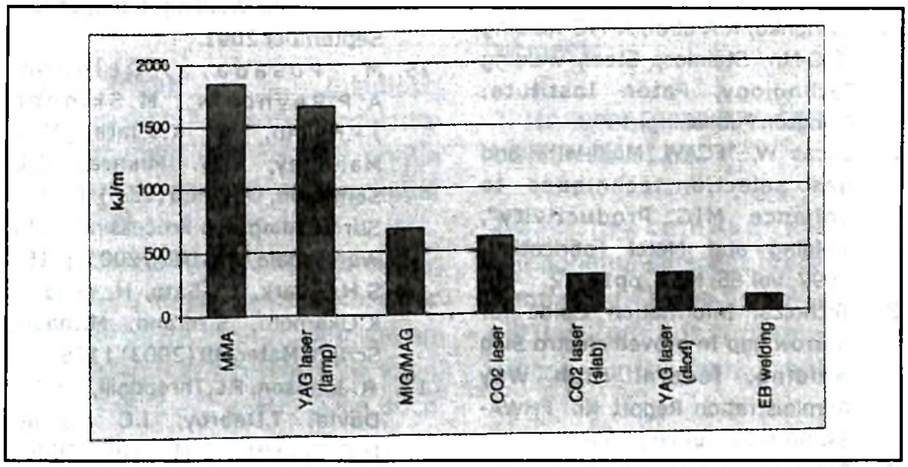

Fig. 9 :Total energy required per meter to join 4mm sheet

Environment in Welding Industry

- Development today must not undermine the development and environment needs of present and future generation
- Knowledge and innovative technology should be shared to achieve the goal of sustainability
- In order to achieve sustainable development, environmental protection shall constitute an integral part of the process.

Preheat:

Two levels of preheat : Hydrogen controlled and Non-Hydrogen controlled Fig. 8.

Preheat temperature Vs Welding energy input

- *A reduction in preheat of 25°C is possible for the same joint weldability index simply by using a hydrogen controlled electrode.*
- *Significant benefits through a reduction in energy consumption which could account for reduction in gas emission.*

Energy efficiency in welding

Sustainable development requires to minimize energy consumption in welding Fig. 9.

Summary

Welding will continue to be preferred method by which metals and other engineering materials are joined into quality products.

New technologies and simulation processes for the modeling of complete production sequences lead to consistently open and compatible. In this respect, new material always represent new challenges. Collaborative research leading to science based welding technology among industry, academia and research organization should be focused on exploring the suitability of advance welding processes for manufacture of high quality products in future, the demand for better environmental compatibility with regard to the development of products and processes will be placed on main focal points.

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