WELDWELL

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SPECTRUM

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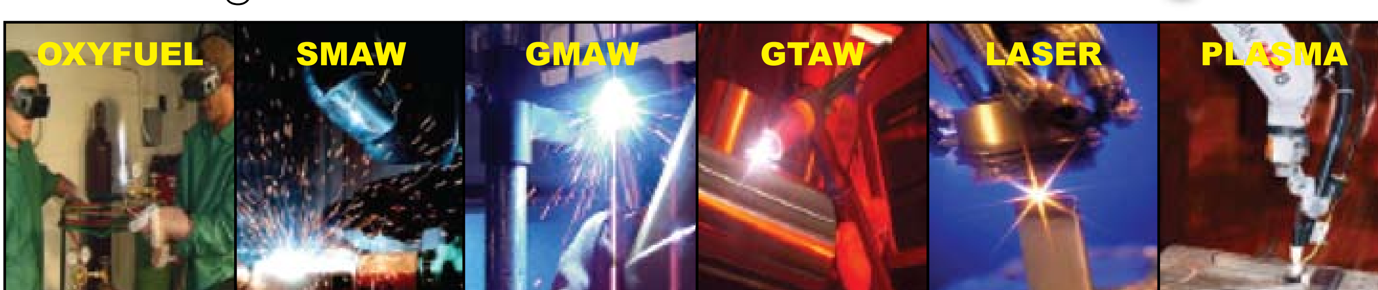

Editorial

Dear Reader,

The sorry state of Indian economy is known to you all. Indian manufacturing activity shrank for the first time in more than four years last month (August), adding to the country's deepening economic malaise to defend the battered Rupee currency. New export orders shrank for the first time in a year. These prompted factories to cut production. Data showed that the Indian economy grew 4.4% in the April-June quarter, the slowest quarterly rate since Jan-March of 2009, hurt by a contraction in mining and manufacturing. A majority of the economists surveyed by Reuters expect this year to be worse. The tell-tale effect of the state of the economy is evident from the poor performance of the welding activities.

The lead article addresses some commonly discussed welding characteristics and procedures of duplex stainless steels. It also describes the welding characteristics of duplex stainless steels which are much more sensitive to minor within-grade variations in chemistry or processing than austenitic stainless steels. The effects of joint design, preheating, heat input and interpass temperature, postweld heat treatment and applicable welding methods are also described. The education section covers new code requirements for calculating heat input due to increasing use of waveform-controlled welding. For calculation of heat input welders, inspectors, and engineers should be aware of the changes. Welding, more than any other fabrication process, exposes the parts to rapid and extreme temperature changes that can lead to cracks in the weldments. This technical article discusses what causes cracks, the proven methods used to prevent cracks from occurring, and some pointers on how to produce satisfactory crack free weld joints by monitoring heat treatment under a wide variety of conditions. This issue also reviews development of GMAW process.

Publication of this newsletter is our humble offerings to the welding fraternity and we are happy to announce successful completion of twenty years of publications. We hope with your good wishes we will serve the fraternity for many more years to come.

Dr. S.Bhattacharya
Editor

Event

STAINLESS STEEL CENTENARY SYMPOSIUM

Stainless Steel Centenary Symposium – A Century of Stainless Steels (SSCS 2013) was organised by The Indian Institute of Metals, Mumbai Chapter, and Department of Atomic Energy in association with Indian National Academy of Engineering at IIT, Bombay, from August 12 – 14, 2013 to celebrate 100 years of Stainless Steel as August 13, 1913 is widely taken to be the date when stainless steels were discovered by Harry Brearley.

Prof. Dewang Kakkar, Director IIT - Bombay, welcomed the delegates and guests and revealed the emphasis presently laid by IIT, Bombay on research. It was followed by a talk on experience of material development at BARC by its Director Mr. Shekhar Basu. The inaugural address was delivered by Dr. R.N Sinha, Chairman AEC and Secretary DAE. He narrated his experience of being associated with usage of Stainless Steel in nuclear industry. Subsequently Dr. Baldev Raj, Ex-Director, Kalpakkam, presented an overview of stainless steel in Nuclear Industry and Mr. N.C.Mathur, President, Indian Stainless Steel Development Association, presented the status of SS industry in India. Dr. Srikumar Banerjee, Ex-Chairman, AEC, delivered Dr. Brahm Prakash Centenary talk.

The SSCS covered wide ranging subjects on stainless steel such as melting and refining, forming and fabrication, welding and joining, physical metallurgy, corrosion, case studies in critical applications and newer grades of stainless steel. A total of 82 technical papers were submitted, out of which 72 papers were presented in two parallel sessions. Approximately 350 delegates attended the symposium including few experts from abroad.

An exhibition on various aspects of stainless steels was held at the same venue. It was inaugurated by Dr. Srikumar Banerjee, Ex-Chairman of AEC. There were about fifteen exhibitors who displayed their products and services.

The symposium was supported by a number of industries and research organisations.

Duplex Stainless Steels - Fabrication and Welding

INTRODUCTION

This article addresses some too commonly discussed welding characteristics and procedures of duplex stainless steels in terms of how they differ from austenitic stainless steels. Addressing each of these features is essential for the design of technically and economically effective welding procedures to be qualified.

DIFFERENCES BETWEEN DUPLEX AND AUSTENITIC STAINLESS STEELS

Duplex stainless steels are typically twice as strong as common austenitic stainless steels. The thermal expansion of the duplex grades is intermediate to that of carbon steel and the austenitic stainless steels. The thermal conductivity of the duplex stainless steels is also intermediate to that of carbon steels and the austenitic stainless steels. When there are problems with welding of austenitic stainless steels, those problems are most frequently associated with hot cracking of the weld metal itself. This hot cracking tendency is aggravated by fully or predominantly austenitic solidification, and by the combination of high thermal expansion and low thermal conductivity. For the more common austenitic stainless steels, hot cracking is minimized by adjusting the composition of the filler metal to provide significant ferrite content. For the more highly alloyed austenitic stainless steels where the use of a nickel-base filler metal is necessary, austenitic solidification is unavoidable. In these cases the problems must be managed by minimizing joint constraint and by low heat input, often requiring many passes to build up the weld.

Duplex stainless steels have good hot cracking resistance. Hot cracking of the duplex weld metal is seldom a concern. The problems most typical of duplex stainless steels are associated with the heat-affected zone (HAZ), not with the weld metal. The HAZ problems are not hot cracking but rather a loss of corrosion resistance and toughness, or of post-weld cracking. To avoid these problems, the welding procedure should focus on minimizing total time at temperature in the "red hot" range for the whole procedure rather than managing the heat input for any one pass. Experience has shown that this approach can lead to procedures that are both technically and economically optimal. The data shown in the appendix of ASTM A 923 suggest how rapidly intermetallic phases can precipitate to the extent that corrosion resistance and toughness are significantly affected. With this introduction in mind, it is possible to give some general guidelines for welding of duplex stainless steels and then to apply this background and those guidelines to specific welding methods.

WELDING

The welding characteristics of duplex stainless steels are much more sensitive to minor within-grade variations in chemistry or processing than are austenitic stainless steels. For example, the importance of having sufficient nitrogen in the duplex stainless steel base metal has been repeatedly emphasized. Air cooling of a plate, even when rapid, through the 705 to 980°C range will use up some of the "time on the clock" for the welder to complete the weld before detrimental reactions occurs. Similarly, if a plate is allowed to air cool into this range during transfer to water quenching, that time is no longer available to the welder. The metallurgical condition of the material used in actual fabrication should be the same quality with regard to composition and production practice, as the material used to qualify the welding procedure.

CLEANING BEFORE WELDING

The need to clean prior to welding applies to all stainless steels. But the duplex stainless steels are more sensitive to contamination, and especially to moisture, than the austenitic stainless steels. The chemistries of the base metal and the filler metal have been developed assuming no additional sources of contamination. Dirt, grease, oil, paint, and sources of moisture of any sort will interfere with welding operations and adversely affect the

By Ralph Davison, Technical Marketing Resources, USA.
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corrosion resistance and mechanical properties of the weldment. No amount of procedure qualification is effective if the material is not thoroughly clean before welding.

JOINT DESIGN

Duplex stainless steels require good joint preparation. For duplex stainless steels, a weld joint design must facilitate full penetration and avoid autogenous regions in the weld solidification. It is best to machine rather than grind the weld edge preparation to provide uniformity of the land thickness or gap. When grinding must be done, special attention should be given to uniformity of the weld preparation and the fit-up. Any grinding burr should be removed to maintain complete fusion and penetration. For an austenitic stainless steel, a skilled welder can overcome some deficiencies in joint preparation by manipulation of the torch. For a duplex stainless steel, these techniques can cause a longer than expected exposure in the harmful temperature range, leading to results outside of those of the qualified procedure.

PREHEATING

As a general rule, preheating of duplex stainless steel is not recommended because it slows the cooling of the heat-affected zone. Preheating should not be a part of a procedure unless there is a specific justification. Preheating may be beneficial when used to eliminate moisture from the steel as may occur in cold ambient conditions or from overnight condensation. When preheating to remove moisture, the steel should be heated to about 95°C uniformly and only after the weld preparation has been cleaned.

Preheating may also be beneficial in those exceptional cases where there is a risk for forming a highly ferritic HAZ because of very rapid quenching. Examples include welding a thin sheet to a plate, as with a liner to a vessel or a tube to a tubesheet, or any very low heat input weld where there is exceedingly rapid cooling.

HEAT INPUT AND INTERPASS TEMPERATURE

Compared to austenitic stainless steels, duplex stainless steels can tolerate relatively high heat inputs. The duplex solidification structure of the weld metal is resistant to hot cracking, much more so than that of highly austenitic weld metals. Duplex stainless steels, with higher thermal conductivity and lower coefficient of thermal expansion, do not create the same high intensity of local thermal stresses at the welds of austenitic stainless steels. While it is prudent to avoid severe restraint, hot cracking is seldom a common problem.

To avoid problems in the HAZ, the weld procedure should allow rapid (but not extreme) cooling of this region. The temperature of the work piece is important because the plate itself provides the most effective cooling of the HAZ. Typically, the maximum interpass temperature is limited to 150°C. That limitation should be imposed when qualifying a weld procedure, and production welding should be monitored to assure that the interpass temperature is not higher than that used in the qualification. Electronic temperature probes and thermocouples are the preferred instruments for monitoring the interpass temperature. When a large amount of welding is to be performed, planning the welding to provide enough time for cooling between passes is good, economical practice.

The size of the test piece used in qualifying a weld procedure may affect the cooling rate and the interpass temperature. There is a risk that the test piece for qualification of a multipass weld procedure may come to a lower interpass temperature than can be reasonably or economically achieved during actual fabrication. Therefore, the qualification might not detect the loss of properties that can occur. The higher interpass temperature slows the cooling and increases the time at temperature for the HAZ in actual practice.

POSTWELD HEAT TREATMENT

Postweld stress relief is not necessary or useful for duplex stainless steels. Unlike the L-grade austenitic stainless steels, the duplex stainless steels are sensitive to even relatively short exposures to temperatures in the 300 to 1000°C range. Thermal stress relief in the 300 to 700°C range may cause precipitation of alpha prime phase (475°C embrittlement), causing a loss of toughness and corrosion resistance. Stress relief in the range of 700 to 1000°C leads to rapid precipitation of intermetallic phases with moderate to severe loss of toughness and corrosion resistance. Any heat treatment of a duplex stainless steel for whatever reason, should be a full solution anneal, meeting the minimum temperatures specified for the mill product in the ASTM specifications, followed by water quenching. For 2205 that minimum temperature is 1040°C in most cases.

Some types of equipment manufactured from duplex stainless steel require a full anneal. For example, the forming of large heads or the fabrication of some valve and pipe assemblies may require annealing. When there is a full solution anneal and quench subsequent to welding, that heat treatment is a part of the welding procedure. Annealing can restore the equilibrium phase balance and eliminate the problems associated with excessive ferrite and intermetallic phases. If the common duplex filler metals are used, typically overalloyed with nickel, phase balance in the fully annealed weld may shift toward austenite. Water quenching is essential after the final anneal, but air cooling from intermediate thermal exposures, such as in hot forming, has been found to be practical and economical.

PHASE BALANCE IN THE WELD

Modern duplex stainless steel mill products are balanced to have about 40-50% ferrite with the balance being austenite. It is generally agreed that the characteristic benefits of duplex stainless steels (strength, toughness, corrosion resistance, resistance to stress corrosion cracking) are achieved when there is at least 25% ferrite with the balance austenite. The ferrite in the weld metal is typically in the range of 25 to 60%. In some welding methods, particularly those relying upon flux shielding, the phase balance of the filler has been adjusted toward more austenite to provide improved toughness, offsetting the loss of toughness associated with oxygen pickup from the flux. There have been no reports of problems associated with the ferrite contents at the lower end of this range, typically seen in SMAW (shielded metal arc, or stick) or SAW (submerged arc) welds.

Rapidly quenched autogenous welds, e.g., arc strikes, repair of arc strikes, small GTA repair welds, etc., tend to have high ferrite, greater than 60%. Such welds can have low toughness and reduced corrosion resistance. Metallographic evaluation of the phase balance in the HAZ is an appropriate test for welding procedure qualification. However, metallographic evaluation is not technically or economically effective for evaluation of annealed mill products or production welds. Magnetic evaluation of the phase balance is widely used but has serious accuracy limitations when used on welds or HAZ.

APPLICABLE WELDING METHODS

Second-generation (nitrogen-alloyed) duplex stainless steels saw rapid development in the early 1980s. With only limited understanding of the formation of intermetallic phases, early views of welding duplex grades focused on limiting heat input, possibly because this approach is what is typically applied to special austenitic grades. With such severe limitations on heat input, many of the more economical welding methods with high deposition rates, such as submerged arc welding, were thought to be inappropriate for the duplex stainless steels. However, the final properties of the duplex stainless steels are of such interest that much effort was directed to learning how to use the more economical processes. Now virtually all welding processes, except for oxyacetylene with its associated carbon contamination of the weld, are applied to duplex stainless steels. Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW), Shielded Metal Arc Welding (SMAW), Flux Core Arc Welding (FCAW), Submerged Arc Welding (SAW), and Plasma Arc Welding (PAW) have all seen practical application. Electric Resistance Welding and Electron Beam Welding, although much less common, have also been qualified and used in particular fabrications. There are important differences among the welding procedures. For example, the decision to use a flux-shielded weld and selection of flux for that weld effect toughness.

New code requirements for calculating heat input*

Waveform-controlled welding has led to certain changes in QW-409.1 of ASME IX for calculation of Heat Input. Welders, inspectors, and engineers should be aware of the changes

INTRODUCTION

Welding waveforms are used to limit distortion, weld open roots, and to control HAZ properties. Waveform control is essential for common processes like uphill GMA pulse welding. Power sources that support pulsing (GMAW-P, GTAW-P etc.) are the most common waveform-controlled power sources. Those marketed as synergic, programmable, or microprocessor-controlled are also likely to support waveform-controlled welding.

The correlation between heat input and mechanical properties is blurred when heat input is calculated using current and voltage readings from conventional meters. This includes external meters and even those located on the welding power sources. It is not that the meters are incorrect – in fact, most are calibrated and tested to NIST standards. Rather, the inaccuracy involves the means of capturing and displaying the data. Conventional DC meters display average voltage and average current. Conventional AC meters display RMS values. To accurately indicate the energy input to a weld, the voltage and current readings must be multiplied together at very rapid interval that will capture brief changes in the welding waveforms. This frequency is in the order of magnitude of 10000 times per second. Specialized meters are required to accomplish this.

Revisions to ASME Section IX provides a new method of calculating heat input that allows comparison of the heat input from various welding power sources and various welding waveforms. This will allow production welding to take place with a welding procedure specification (WPS) that specifies either conventional or waveform-controlled welding, which is supported by a procedure qualification record (PQR) using either conventional or waveform-controlled welding.

CALCULATING HEAT INPUT

Many welding codes use the equation shown in Equation 1 to calculate heat input. Because the welding process (GMAW, SAW, etc.) is an essential variable, a process or efficiency factor is not included in the heat input calculation. The new equations in the 2010 edition of ASME Section IX are shown in Equation 2 and 3, either of which gives equivalent results. Both equations are shown because some welding power sources and meters display energy values, and others display power values.

$$\frac{\text{Voltage X Amperage X 60}}{\text{Travel sped (in/min or mm/min)}}$$

Equation 1: Traditional heat input equation, ASME Section IX QW-409.1 (a)

$$\frac{\text{Energy (Joules)}}{\text{Weld bead length (in. or mm)}}$$

Equation 2: New heat input equation for meter displaying energy measurement (Joules) ASME Section IX QW-409.1(c)(1)

$$\frac{\text{Power (Joules/s) X arc time (s)}}{\text{Weld bead length (in. or mm)}}$$

Equation 3: New heat input equation for meter displaying power measurement (Joules/s or W) ASME Section IX QW-409.1(c) (2)

Three examples from GMA welding are shown in Table 1. The axial spray waveforms are essentially constant, and the difference between the measurement methods is minimal. For the two waveform-controlled procedures, there is an error between the measurement methods that can be in a positive or negative direction. It is clear from the significant differences why a new measurement method is needed.

*Teresa Melfi, Chair and member of various AWS A5 Committees,
Published in Welding Journal, Vol. 89, No. 6, June 2010

CHANGES IN ASME SECTION IX

The ASME IX Standards Committee has subcommittees that address procedure and performance qualifications, material, general requirements, and brazing. The first result of this group addresses a change in measurement and calculation method for heat input. QW 409.1 is the main Section IX variable that deals with heat input. Currently, there are two ways to calculate input. Method (a) is the tradition heat input equation shown in equation 1. Method (b) is a measurement of the volume of weld metal deposited. A new method (c) is added in the 2010 edition, which includes Equation 2 and 3.

Any of the methods can be used when welding following procedures that are of waveform controlled. When welding following waveform-controlled procedures, only methods (b) or (c) are permitted. With these methods, it is possible to determine the compliance of a production weld made using a waveform-controlled welding procedure to an existing qualified procedure, even when the procedure qualification was performed using non-waveform controlled welding. An appendix to ASME Section IX has been provided to guide users through these code changes. The appendix provides guidance with new procedure qualifications, existing qualified procedures, and comparing heat input between waveform-controlled welding. ASME Section IX does not mandate separate performance qualification for waveform-controlled welding.

HOW TO COMPLY WITH ASME CODE CHANGES

To use method (c) of the code, a reading of energy (Joules) or power (Joules/s) must be obtained using a meter that captures the brief changes in a welding waveform and filters out extraneous noise. The simplest place to obtain this is from the welding power source. In many power sources output pulsing waveforms will display these readings, although some might require software upgrades to enable this. For a power source that does not support the display of energy or power, external meters are available. With the proper software installed, it is simple to access the energy reading. When an arc is started, the energy value will begin to increment. The value will continue to increase, showing the real-time energy put into that weld. When the welding stops, the final energy value will be displayed until welding resumes again. This value represents the amount of energy that went into that weld, from arc start to arc stop. To calculate the heat input, the final value is simply divided by the length of the weld.

SUMMARY

ASME Section IX has changed to recognize modern welding waveforms. The changes involve the measurement of energy or power made at very rapid intervals. And the use of these to calculate heat input. These code changes establish the relationship between heat input across a range of power sources and welding waveforms. Welders, inspectors, and engineers should be aware of the new ways to calculate heat input. While no code can guarantee good workmanship, these changes make it easier for welders to use waveforms that help improve their welds. The new method will allow flexibility in the way one compares the heat input used in procedure qualification and in production welding.

Table 1: Heat input differences calculated using Equation 1 vs. Equation 2

Power calculation types	Power (KW)	% difference compared to true energy results
Traditional average power measurement	2.96	10.0%
Power measurement from True Energy	2.69	
Axial spray		
Traditional average power measurement	5.25	- 0.38%
Power measurement from True Energy	5.27	
Pulse		
Traditional average power measurement	3.5	- 13.58%
Power measurement from True Energy	4.05	

Monitoring heat treatment to improve weld quality*

Welding, more than any other fabrication process, exposes the parts to rapid and extreme temperature changes that can lead to cracks in the weldments. This article discusses what causes cracks, the proven methods used to prevent cracks from occurring, and some pointers on how to produce satisfactory crack-free weld joints under a wide variety of conditions

INTRODUCTION

Controlled pre- and post-weld heat treatments can dramatically impact weld metal characteristics. In all cases, careful monitoring of the temperatures is critical. The welders often use a contact-type temperature indicator as the touch preheats the flange to be welded. Use of crayons that are formulated to melt at a precise temperature to alert when the desired temperature has been reached is very common.

AREAS MOST SUSCEPTIBLE TO CRACKING

There are two areas in the joint that may crack as a result of the welding operation. The first is a portion of the heat-affected zone (HAZ) adjacent to the weld. The second area that may crack under certain conditions is the weld metal.

Weld metal is less prone to cracking than the HAZ because the weld metal used for most purposes generally has such a low carbon content that it does not change its properties as markedly as the base metal even under the most rapid rate of cooling likely to occur during welding.

Welders are usually most concerned about cracks in the base metal in the immediate vicinity of the weld. This is the metal closest to the weld that cools most rapidly, and in many cases undergoes critical changes in the structure and properties that may lead to cracking.

EFFECTS OF HEAT TREATMENT

Heating the joint area before welding (preheating) can most often prevent cracking. Preheating performs several important functions affecting weld quality:

1. Removes hydrogen to reduce the effects of hydrogen-induced cracking
2. Minimizes hard zones adjacent to weld
3. Minimizes shrinkage stresses
4. Reduces distortion.

The preheating operation effectively improves the agility of a welded joint to withstand service condition.

WELDING OPERATION

The making of any weld involves two metallurgical processes:

1. Melting of the edges of the joint and the electrode material, followed by solidification, which forms a single integral weld structure
2. Heating and subsequent cooling of the zone of the base metal adjacent to the weld.

The heat generated during welding has two effects on the welded joint. Depending on the metal's composition, the temperature reached, and cooling rate there will be specific effects on the microstructure of the metal, strength, toughness, ductility, shock and corrosion resistance.

Heat can cause distortion and shrinkages stresses in the weld joint depending on the amount of restraint, heating and cooling rates, and the time at maximum temperature. These two effects are interdependent and occur simultaneously,

The welded joint, although actually a single integral structure, may be considered to consist of three distinct zones that merge into one another: the weld metal, the HAZ, and the base metal.

**Pramathesh Desai, The American Welder, Welding Journal, Vol. 89, No. 6, June 2010*

The weld metal is the portion that has been in molten state. It consists of a mixture of the electrode material that has been deposited and the base metal that has been melted during welding. The HAZ consists of several distinctly different structures whose precise characteristics and extents depends upon the welding conditions.

FACTORS AFFECTING WELD CRACKING

The factors that affect weld cracking include the following:

1. Composition of the metal / alloy
2. Rate of heating
3. Maximum temperature reached
4. Length of time at temperature
5. Rate of cooling
6. Hydrogen entrapment.

The chemical composition of metal / alloy has a very important bearing on the hardness and brittleness of the weld joint for several reasons. Higher carbon content (in steel) promotes the formation of martensitic, and the final hardness or martensite itself depends on the carbon content of the steel. This is why steels with higher carbon content are not considered easily weldable. Certain alloying elements such as molybdenum, manganese, vanadium and chromium also have a distinct hardening effect that promotes the formation of the crack-inducing martensite.

Some contend that weld cracks result from the hydrogen introduced into the base metal from the coating on the welding rods. As hydrogen is more soluble in molten than in solid steel, it tends to escape from the supersaturated solution as the metal cools down.

POSTWELD HEATING EFFECTS

Post weld heat treatment (PWHT) is often necessary to reduce cracking. During the welding process, the metal pieces being joined are subjected to extreme temperatures that can cause the crystalline structure of the metal to pass through various metallurgical phases. The PWHT reduces the hardness in the HAZ of the metals and effectively increases their ductility.

MONITORING THE WELD TEMPERATURES

Today, preheating is most commonly performed with the automatic electrical resistance method. But, how long the joint should be heated in order to reach the desired preheat temperature remains an inexact science. The preheat time depends on the metal thickness and many other factors, making it necessary to check the temperature from time to time to verify the preheating is proceeding properly.

An effective way to monitor the preheat temperature is to mark the desired surfaces with a calibrated phase-change temperature-indicating crayon. When the temperature rating of the crayon is reached, the mark will melt giving a distinct visual indication. Since the temperature indicator is in intimate contact with the surface to be tested, the phase change is virtually instantaneous.

Crayons are generally reliably accurate, conform to industry welding codes, and are traceable to NIST standards. Other applications of crayons are for verifying interpass and postweld heat treatment temperatures, and cool-down and annealing temperatures for manual and semiautomatic welding.

Annealing is an important operation following welding. Annealing consists of controlled reheating to restore the over-hardened metal to the approximate hardness of the rest of the material. To do this, the piece is repositioned. The welding machine is energized and, in what is essentially a manually controlled operation, heat is varied until the correct annealing temperature is reached.

Even in procedures where the welding operation is fully automatic, the annealing is not usually automated. The welded assembly may need to be stress-relieved to an appropriate ductile condition by annealing. Using the correct temperature is extremely important. If it is too hot, the weld strength will be substandard. If it is not hot enough, the weld will remain hardened and brittle.

Review of GMAW Welding

Gas metal arc welding (GMAW), sometimes referred to by its subtypes metal inert gas (MIG) welding or metal active gas (MAG) welding (also known as CO_2 welding), is a welding process in which an electric arc forms between a consumable wire electrode and the workpiece metal(s), which heats the workpiece metal(s), causing them to melt, and join. Along with the wire electrode, a shielding gas feeds through the welding gun or torch, which shields the process from contaminants in the air.

The principles of MIG welding history began to be developed around the turn of the 19th century, with Humphry Davy's discovery of the electric arc in 1800. At first, carbon electrodes were used, but by the late 1800s, metal electrodes had been invented by N.G. Slavianoff and C. L. Coffin. In 1920, an early predecessor of GMAW was invented by P. O. Nobel of General Electric. It used a bare electrode wire and direct current, and used arc voltage to regulate the feed rate. It did not use a shielding gas to protect the weld, as developments in welding atmospheres did not take place until later that decade.

It was not until 1948 that GMAW was finally developed by the Batelle Memorial Institute. Originally developed for welding aluminum and other non-ferrous materials it used a smaller diameter electrode and a constant voltage power source. It offered a high deposition rate but the high cost of inert gases limited its use to non-ferrous materials and cost savings were not obtained.

In 1953, the use of carbon dioxide as a welding atmosphere was developed, and it quickly gained popularity in GMAW, since it made welding of steel more economical.

In 1958 and 1959, the short-arc variation of GMAW was released, which increased welding versatility and made the welding of thin materials possible while relying on smaller electrode wires and more advanced power supplies. It quickly became the most popular GMAW variation.

The spray-arc transfer variation was developed in the early 1960s, when experimenters added small amounts of oxygen to inert gases.

Today, GMAW is one of the most popular welding methods, especially in industrial environments.

It is used extensively by the sheet metal industry and, by extension, the automobile industry.

There, the method often used is to do arc spot welding, thereby replacing riveting or resistance spot welding.

It is also popular in robot welding, in which robots handle the workpieces and the welding gun to quicken the manufacturing process.

Generally, it is unsuitable for welding outdoors, because the movement of the surrounding atmosphere can cause the dissipation of the shielding gas and thus make welding more difficult, while also decreasing the quality of the weld.

The problem can be alleviated to some extent by increasing the shielding gas output, but this can be expensive.

In general, processes such as shielded metal arc welding and flux cored arc welding are preferred for welding outdoors, making the use of GMAW in the construction industry rather limited.

Furthermore, the use of a shielding gas makes GMAW an unpopular underwater welding process, and for the same reason it is rarely used in space applications.

Recent Developments

The development path for MIG has, in simple terms, progressed from dip transfer to globular transfer and then to spray transfer. Some of the important developments in the recent times are given below:

MIG Pulse Welding

The process, synergic MIG pulse welding, is employed when one wants to obtain control of the droplet transfer and the production of heat in the arc.

This process holds the following advantages:

- Little or no spatter also at low mean current values
- The possibility to control the heat input in the weld grooves
- A reduction of the number of porosities in the weld metal

But the latest development is SuperPulse MIG welding, which gives the advantages of pulse welding combined with the finish of TIG welding. With the level of control available in SuperPulse machines, the operative can effectively manage the welding parameters to 'mix and match' the modes of transfer to suit the material and the required combination of speed and quality.

As the MIG process utilises a filler wire, this creates the opportunity to use a wire of a considerably different composition to that of the parent metal, for applications such as hard facing or building up the surface of worn track in the rail industry. By judicious selection of the filler wire and weld parameters, MIG can also be used to join dissimilar metals.

Another application for which MIG is increasing in popularity is brazing. The main advantage here is that it enables good strength to be achieved when joining thin materials - even down to 0.5mm - and an example of MIG brazing is found in the automotive industry. Robotic welding (or brazing), whether in the automotive industry or elsewhere, almost invariably uses MIG.

More recently, pulsed current has been applied, giving rise to a new method called the pulsed spray-arc variation.

Tandem MIG welding

Arc welding with two wires was first developed back in the 1940s for submerged arc welding, to give increased productivity. The technique was later applied to MIG/MAG welding with two torches, but equipment limitations prevented the widespread adoption of the process.

In more recent developments, two wires were fed through one torch with a common contact tip, either with one or two power sources. This process is referred to as twin wire or double wire MIG/MAG welding. However, it was not until the process was developed with two electrically isolated contact tips in the same torch that the single torch process has become viable. The tandem process has now achieved widespread recognition, because modern developments in inverter power sources and electronics permit independent, but synchronised, control over each wire resulting in improved process stability over the complete range of operation from dip transfer to spray transfer and pulse.

Developments in MIG/MAG welding concentrated on with extended electrode stick-outs and four-component gas mixtures in which arc stability is maintained by electronic control.

Hybrid MIG

In the last few years, several groups have worked on the development of hybrid laser / GMAW welding (HLAW), for various segments of the industry. Depending on the intended application, the objectives are significantly different. Nevertheless, new HLAW applications usually benefit from the ability of the process to produce deep welds in one pass without having to chamfer the parts. The HLAW welds are drastically smaller than GMAW welds.

HLAW process requires particular care and knowledge, and its implementation can be quite costly. But once this process is in production, it can bring huge benefits in terms of productivity as well as savings in consumables and labor cost. And with the great performances and decreasing cost of the high power fiber and disk lasers, one can expect better and better ROI's, and stronger presence of the HLAW process on the shop floors.

Education is an ornament in prosperity and a refuge in adversity. - Aristotle