Volume XVI, Number 1, 1999

Welding Innovation

Advancing Arc Welding Design and Practice Worldwide

Tribute to a Leader

Richard S. Sabo

Some people are simply irreplaceable. My long time friend and colleague, Richard S. Sabo is a case in point. After 31 years with The James F. Lincoln Arc Welding Foundation, and 34 years at The Lincoln Electric Company, Dick is retiring. He will be succeeded, but never replaced.

For the last three decades, it has been my privilege to watch Dick inspire, educate and motivate a truly amazing range of people, from Lincoln employees to vocational school students, from top industry leaders to Foundation Award program participants, and from college professors to members of Congressional committees. He started his professional life as a high school teacher and athletic coach after receiving a Bachelor's degree from California University of Pennsylvania, and a Master's degree from Edinboro University. Although he left a traditional teaching career to become a pieceworker on the Lincoln Electric factory floor in 1965, Dick could not escape the role of educator for long. His natural abilities flourished under Lincoln's unique Incentive Management system, and soon he found himself deeply immersed in publishing welding texts, showcasing Lincoln Electric on “60 Minutes,” and speaking at meetings of the American Welding Society and the American Institute of Steel Construction. His appointment to lead the James F. Lincoln Arc Welding Foundation in 1968 only broadened the scope of his educational mission.

Having spent a lifetime in academia myself, I believe that personal example is one of the best teachers. In this respect, Dick is head and shoulders above the crowd. His strong work ethic, constant focus on results, ability to be a team player, and unfailingly positive attitude are evident to all who meet him or hear him speak. But get to know him a little better, and Dick will eagerly tell you what has really made his life worthwhile: marriage to his high school sweetheart Gail, raising their four children together, and now, enjoying their grandchildren. No one could point to a better example of a life well and fully lived.

The James F. Lincoln Arc Welding Foundation was incorporated in 1936 as a nonprofit organization “…to encourage and stimulate scientific interest in, and scientific study, research and education in respect of, the development of the arc welding industry…” During Dick's tenure as Executive Director of the Foundation, he enhanced the organization's effectiveness by:

- Supporting the School/Shop, College and Professional Award Programs with publicity and cash grants that have made them among the finest such programs in the United States
- Expanding the program of donating complete libraries of books published by the Foundation to high schools and colleges
- In 1984, initiating publication of *Welding Innovation*, a periodical which now has an international circulation in excess of 50,000
- In 1988, appointing the first International Assistant Secretaries of the Foundation
- Establishing creative partnerships with the American and Australian Institutes of Steel Construction to co-sponsor welded bridge award programs
- Continuing the Foundation's ambitious program of publishing welding manuals and design texts

The above accomplishments were very much a part-time activity for Dick over the years, since simultaneously he was serving Lincoln Electric as Director of Corporate Communications and later, Assistant to the Chairman of the Board. Throughout his career, Dick has traveled extensively, delivering over 1,200 speeches, often on themes that emphasized the importance of education, and/or the relationship between profit sharing and productivity. He has truly been an “Ambassador-at-large” for the entire welding industry. The American Welding Society recognized his contributions by naming him the Plummer Lecturer in 1992, and the International Academy of Business Disciplines named him Business Executive of the Year in 1997. In 1992, Lincoln Electric made him “Employee of the Year,” citing his many remarkable public relations achievements on behalf of the company.

To say that it is difficult for me to imagine The James F. Lincoln Arc Welding Foundation without Dick Sabo's leadership would be an understatement. But of course, the Foundation will continue to carry out its important mission of advancing arc welding design and practice worldwide. I came across a quote from Walter Lippman that summed up my thoughts about Dick quite well: “The final test of a leader is that he leaves behind in other men the conviction and the will to carry on.” How true.

Donald N. Zwiep, Chairman

Welding INNOVATION

Cover: The Berri Bridge in South Australia won the 1998 $10,000 Australasian Steel Bridge Award jointly sponsored by the Australian Institute of Steel Construction and the James F. Lincoln Arc Welding Foundation.

Omer W. Blodgett, Sc.D., P.E.
Design Consultant

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Editor
Duane K. Miller,
Sc.D., P.E.

Assistant Editor
R. Scott Funderburk

The James F. Lincoln
Arc Welding Foundation

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The serviceability of a product or structure utilizing the type of information presented herein is, and must be, the sole responsibility of the builder/user. Many variables beyond the control of The James F. Lincoln Arc Welding Foundation or The Lincoln Electric Company affect the results obtained in applying this type of information. These variables include, but are not limited to, welding procedure, plate chemistry and temperature, weldment design, fabrication methods, and service requirements.

Visit *Welding Innovation* online at http://www.lincolnelectric.com/innovate.htm

INTERNATIONAL ASSISTANT SECRETARIES

Australia and New Zealand
Raymond K. Ryan
Phone: 61-29-772-7222
Fax: 61-29-792-1387

Croatia
Prof. Dr. Slobodan Kralj
Phone: 385-1-6168306
Fax: 385-1-6157124

Hungary
Dr. Géza Gremsperger
Phone: 361-156-3306

India
Dr. V.R. Krishnan
Phone: 91-11-247-5139
Fax: 91-124-321985

Japan
Dr. Motoomi Ogata
Phone: 81-565-48-8121
Fax: 81-565-48-0030

People's Republic of China
Dai Shu Hua
Phone: 022-831-4170
Fax: 022-831-4179

Russia
Dr. Vladimir P. Yatsenko
Phone: 07-095-238-5543
Fax: 07-095-238-6934

United Kingdom
Dr. Ralph B.G. Yeo
Phone & Fax:
44-1709-379905

Harmonization of European Welding Standards

By Ralph B. G. Yeo, Intnl. Asst. Secretary
The James F. Lincoln Arc Welding Foundation
United Kingdom

Background

Sir Winston Churchill's 1946 vision of "The United States of Europe" eventually led to the harmonization of European welding standards. He anticipated that a close alliance of European nations would soften the nationalism and social unrest that were major causes of World Wars I and II. The Treaty of Rome, signed in 1957, set up the European Economic Community (EEC) to encourage the free movement of capital, goods, services, and people. The success of the EEC led to the formation in 1960 of the European Free Trade Association (EFTA) of countries around the periphery of the EEC. Recently, a number of newly-independent Eastern European countries have applied for European Union (EU) membership. The EU now has more than 370 million inhabitants, and significant further growth is inevitable.

An essential component of the EU is the Single Market and its elimination of all trade barriers. The European Coal and Steel Community (Belgium, France, West Germany, Italy, and Luxembourg) which was formed in 1951, reached the earliest effective accords. The elimination of customs barriers in 1993 led to significant increase in cross-border trade of alcohol and tobacco products, but was less effective in encouraging the movement of engineering products. It was recognized that attention needed to be given to the more pervasive, but effective, technical barriers, mainly engineering standards, type testing, and certification. The governing European Council, whose members are the heads of states and governments of the member states, instructed the European Commission (the civil servants) to accelerate the process of harmonization. (The elected European Parliament has responsibility mainly for budgetary affairs.) The Council issues Harmonization Directives, proposed by the Commission, to be incorporated into the statutory systems of the various nationalities, and with which standards must comply. Some were instituted without delay, but many of the most significant barriers persisted because of different approaches to engineering standards, type testing, and professional qualifications. They required agreement before they could be installed across the EU. The major authorities dealing with harmonization are CEN (Comité Européen de Normalisation, European Committee for Standardisation) and CENELEC (Comité Européen de Electrotechnique, European Committee for Electrotechnical Standardisation), both of which have representation from the member countries. CEN deals with codes, materials, and methods. CENELEC is responsible for electric welding equipment.

Technical Committee 121 of CEN tackled the formidable tasks required to reach agreement on welding standards. Several important ground rules were adopted. Where possible, existing ISO standards would be adopted, using the ISO number preceded by 2, such as EN 29000, and when harmonization work was started in a particular area, the modification of relevant national standards would cease. The harmonized standards, identified by their EN numbers, contain identical information, published in English, German, and French. They are identified as BS EN, DIN EN, and AFNOR EN, respectively, in Britain, Germany and France. Other languages require their own translations. When published, a European standard has the status of a national standard, and any conflicting national standards are withdrawn.

The fundamental feature of ENs is that they are stand-alone documents

In addition to the work on standards, a 1993 CE Marking Directive and Decision set out general harmonized conformity assessment procedures. One of the significant benefits of harmonization is that approval of a product by a suitable testing authority renders the product satisfactory in other EU countries, regardless of whether it is made locally or imported. Conformance with standards and directives, such as those for personal protective equipment, is certified and indicated by an attached CE mark. The product can then be sold throughout the EU without further national standards assessments.

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European standards are entirely different in structure, content, and designation from those adopted by AWS and ASTM, although American standards are widely known and used in Europe. This paper provides an introduction to the major engineering standards that apply to welded fabrications.

Overall Organization of European Standards

The fundamental feature of ENs is that they are stand-alone documents, and it is estimated that 300-400 standards will be required for welding and NDT! For instance, they include a specific standard for an operation as simple as the measurement of preheat temperature. Whereas AWS D1.1 contains most of the welding information required for steel structures, the equivalent Eurocode 3 contains little direct welding information but it refers to a series of other individual standards which fall into groups to cover design, weld engineering, production, and quality.

Application Standards (Design Codes)

A series of design codes to cover the basis of design and actions on structures are in the draft for development stage, and will appear as a series ENV 1991-1999. DD ENV 1993: Eurocode 3, covers the design of steel structures. These codes themselves will contain very little welding information, but reference will be made to other individual standards dealing with steels, welding practices, welding procedures, approvals, etc.

Steel

The following group of standards covers weldable structural steels:

EN 10025: 1993, *Hot rolled products of non-alloy structural steels*.

EN 10113: 1993, *Hot rolled products in weldable fine grained structural steels*.

EN 10155: 1993, *Structural steels with improved corrosion resistance*.

EN 10210: 1997, *Hot formed welded structural hollow sections of non-alloy and fine grain steels*.

EN 10219: 1997, *Cold formed welded structural hollow sections of non-alloy and fine grain steels*.

The grade designations for steels are informative and provide guidance to designers and fabricators. The designations include indications of nominal yield strength (mainly 235, 275, 355, 420, and 460 N/mm^2), steel quality (standard quality steel, deoxidation, etc,) 27J impact transition temperature (R=20°C, O=0°C, 2=-20°C, L=-50°C), steelmaking additions, and if applicable, method of production, and suitability for a particular application, e.g., cold forming. Steels can be supplied in the Normalized (N), Normalized Rolled (NR), or Thermomechanically Rolled (TMR) conditions.

The concept of pre-qualified joints has not been accepted in Europe

All European structural steel standards require the use of a full designation to indicate the combination of the product form and the grade. For example, plate or sections with yield strength of 355 N/mm^2, impact toughness of 27J@ -20°C, suitable for cold forming are designated: BS EN 10025: 1993, Grade S355K2G4C.

The maximum carbon equivalent values (CEVs) of the various grades are specified to assist in estimating preheat (from EN 1011-2, when issued).

Joint Types

Joints should be specified using symbols and principles from EN 22553:1995, *Welded, brazed and soldered joints - Symbolic representation on drawings*. The concept of prequalified joints has not been accepted in Europe. Most structural steelwork contracts require the use of approved welding procedures, leading to excessive test costs (often incurred because of inadequate documentation) and relatively slow adoption of more productive new methods.

Welding Practices

Welding practices for different materials are covered by the various parts of EN 1011, *Recommendations for welding of metallic materials*. Part 2, *Arc welding of ferritic steels*, which should be issued in 1999, is devoted to structural steels. It contains general recommendations for good welding practices, and a series of tables and nomographs give estimates of preheat temperatures to prevent cold cracking, based on the principles included in BS 5135: 1984, *Process of arc welding of carbon and carbon manganese steels*. Those principles involve the concepts of carbon equivalent, weld metal diffusible hydrogen, combined thickness, and heat input. Combined thickness is measured at 75 mm from the joint line (Figure 1). Preheat temperature is estimated from nomographs that relate minimum preheat temperatures required to avoid cracking with combined thickness and heat input for different combinations of

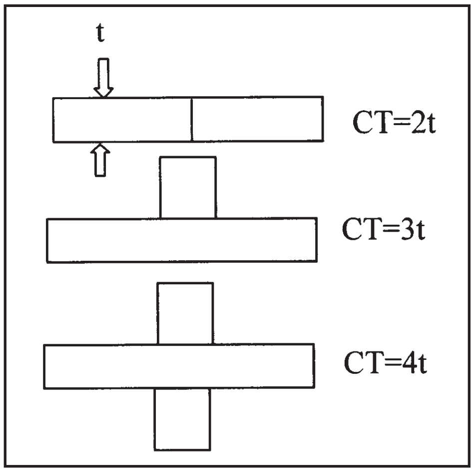

Figure 1. Measurement of combined thickness (CT).

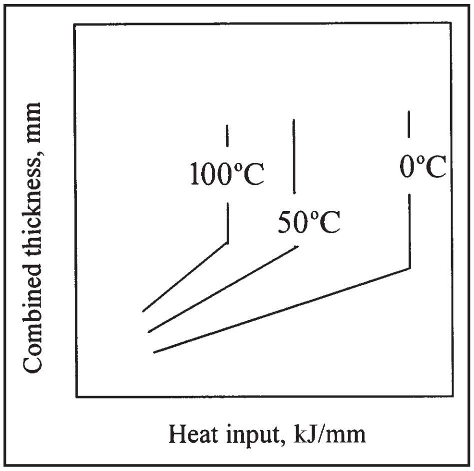

Figure 2. Example nomograph for estimating minimum preheat temperature.

CEV and weld metal hydrogen levels (Figure 2).

Welding Procedures

The former national standards for specification and approval of welding procedures were similar in nature but their requirements differed in many details. The new ENs attempt to retain most of those national approaches to procedure approval. The overall principles are contained in EN 288: *Specification and approval of welding procedures for metallic materials*, Part 1: *General rules for fusion welding*, the requirements of the welding procedures specifications are shown in EN 288, Part 2, *Welding procedure specification for arc welding*, and the various testing procedures are covered in other parts. Part 3 1992, *Welding procedure tests for the arc welding of steels*, specifies how a Welding Procedure Specification is approved by making welding procedure tests for steels. Other methods of procedure approval include the use of previous welding experience, approved welding consumables, standard welding procedures, and pre-production welding tests, all of which are covered in separate parts of EN 288.

The introduction of EN 288-3 does not invalidate previous welding procedure approvals made to former national standards or specifications, providing the intent of the technical requirements is satisfied and the previous procedure approvals are relevant to the application and production work on which they are to be employed. Also, where additional tests have to be carried out to make the approval technically equivalent, it is only necessary to do the additional tests on a test piece which should be made in accordance with this standard. Although the AWS welding positions are widely used in Europe, EN 288 uses the designations shown in Figure 3.

Welder Approval

The testing of welder skills is an important factor in ensuring the quality of the welded fabrication. BS EN 287, *Approval testing of welders for fusion welding, Part 1: 1992, Steels*, shows the criteria that must be satisfied to identify the ability of the welder to make specific welds. Each criterion included is considered to be a significant factor in the approval testing, and the ability of a welder to understand the technology and to follow verbal or written instructions are further optional requirements in this standard. The designation system devised for BS EN 287 approval was developed for computerized identification of approved welders, by means of a series of abbreviated designations to identify the criteria.

...weld repairs can be made almost anyplace, and in almost any environment

Welding Consumables

A harmonized set of European standards has been agreed upon for the major process consumables.

BS EN 440: 1994, *Wire electrodes and deposits for gas shielded metal arc welding of non-alloy and fine grain steels. Classification.*

BS EN 439: 1994, *Shielding gases for arc welding and cutting. Classification.*

BS EN 499: 1994, *Covered electrodes for manual arc welding of non-alloy and fine grain steels. Classification.*

BS EN 758: 1997, *Tubular cored electrodes for metal arc welding with and without a gas shield of non-alloy and fine grain steels. Classification.*

BS EN 756: 1995, *Wire electrodes and wire-flux combinations for submerged arc welding of non-alloy and fine grain steels. Classification.*

BS EN 760: 1996, *Fluxes for submerged arc welding. Classification.*

These standards cover the classification tests and resulting designations for yield strength and impact energy (which are included in all the classifications), welding position capability, characteristics of the flux (if present), and weld metal diffusible hydrogen. They also contain information specific to the individual processes: flux type for shielded metal arc (SMAW), flux-

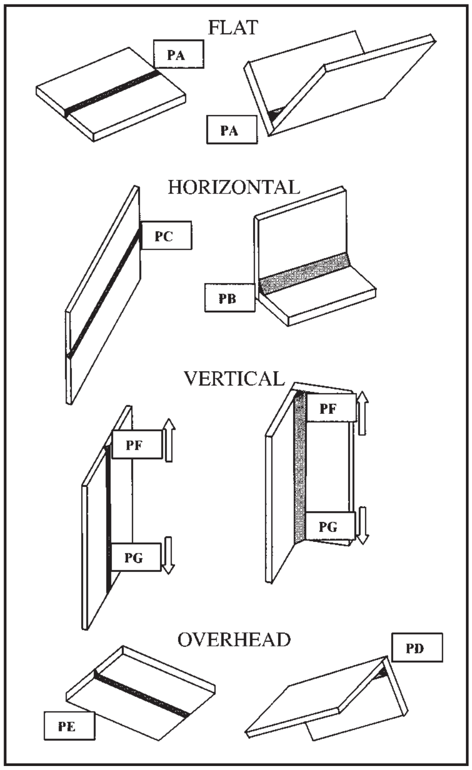

Figure 3. EN welding position designations.

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cored (FCAW) and submerged arc welding (SAW); electrical requirements and electrode efficiency for SMAW; shielding gas for FCAW and GMAW welding; characteristics of SAW fluxes; and wire-flux combinations for SAW.

The symbols used to classify weld metal yield strength are shown in Table 1, and the minimum test temperature for 47J impact strength is shown in Table 2.

Table 1. Symbols used to classify weld metal yield strength in EN standards for consumables.

Minimum YS, N/mm^2	355	380	420	460	500
Symbols	35	38	42	46	50

Table 2. Symbols used to classify weld metal impact strength.

47J Transition, °C	20	0	-20	-30	-40	-50	-60
Symbols	A	0	2	3	4	5	6

The common designation for positional capability is shown in Table 3.

Examples of designations of welding consumables are shown in Table 4.

Table 5 indicates examples of equivalent designations for some popular grades. EN designations are informative but still unfamiliar and difficult to remember. To make reference easier, the SMAW and FCAW designations have a shortened compulsory partial designation (information required by designers) that refers to yield strength, impact toughness, and flux type, for example, E 46 3 1Ni B. The full designation, E 46 3 1Ni B 54 H5, (required

Table 3. Designation of welding position capability.

Symbol	Welding position capability
1	All positions
2	All positions, except vertical down
3	Flat butt weld, flat fillet weld, horizontal-vertical fillet weld
4	Flat butt weld, flat fillet weld
5	Vertical-down and positions according to symbol 3

Table 4. Examples of designations for welding consumables that deposit weld metal with minimum yield strength of 460 N/mm^2 and impact energy of 27J at -30^{o}C in standardized classification tests.

Process	Designation	Additional information
GMAW	Weld metal: **EN 440 - G 46 3 M G3Si1**	Weld metal produced with mixed shielding gas using the wire grade G3Si1
	Wire: **EN 440 - G3Si1**	Wire electrode with chemical composition of 0.06-0.14%C, 0.70-1.00%Si, 1.30-1.60%Mn
	Shielding gas: **EN 438 - M24**	Gas mixture containing 10% carbon dioxide and 3% oxygen and balance argon
SMAW	Complete designation: **EN 499 - 46 3 1Ni B 54 H5**	Weld metal chemical composition of 1.1% Mn and 0.7% Ni (1Ni). The electrode has a basic covering (B), a metal recovery of 140%, and may be used with AC and DC (5) in flat position butt and flat position fillet welds (4). Hydrogen does not exceed 5 ml/100 g deposited weld metal (H5)
	Mandatory designation: **EN 499 - 46 3 1Ni B**	
Flux-cored	**EN 758 T 46 3 1Ni B M 4 H5**	Weld metal chemical composition of 1.1 % Mn, 0.7% Ni (1Ni). The wire has a basic type flux (B), is suitable for flat butt and flat and horizontal-vertical fillet welds (4), and gives weld metal hydrogen of less than 5 ml/100 g deposited metal (H5)
	EN 758 T 46 3 1Ni B M	
Submerged arc	Wire-flux combination **EN 756 - S 46 3 AB S2**	Weld metal produced with an alumina-basic flux (AB) and a 1% Mn steel wire (S2). (If this weld is made by a two-pass technique the 46 is replaced by a designation of 4T.)
Submerged arc	Flux **EN 760 - S F CS 1 67 AC H10**	Flux for submerged arc welding (S), fused (F), calcium silicate type (CS), for application to welding of structural steels (1), with silicon pick-up of 0.2% (6) and manganese pick-up of 0.5% (7), capable of use with alternating current (AC), and giving weld metal hydrogen of less than 10 ml/100g deposited metal
The designations shown in this table are the examples given in the European standards. They correspond with the mechanical properties of steel grade S355J2G3 of BS EN 10025: 1993. Actual weld metal properties depend on additional factors, especially dilution and arc energy. It may not be necessary to use a low-alloy MMA electrode to weld S355J2G3 steel.		

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Table 5. Comparison of AWS and EN classifications for popular grades.

Process	AWS classification	Closest EN classification
SMAW	E6013 E7018	E 38 2 R 12 E 42 3 B 32 H10
GMAW	E70S-6	G3Si1
FCAW	E70T-1 E71T-8	T 42 0 RC 3 H10 T 46 3 Y N 2
SAW	— F7A2-EM12K (weld metal)	AB/AR 1 78 AC H5 (flux) F 3 T 2 AR-S2Si (weld metal)

by fabricators) also includes their operating characteristics. It is likely that the AWS designations will continue in Europe for some time, especially for SMAW electrodes.

> **...it is not as easy to substitute one European consumable for another**

Compared with AWS standards, finding and using equivalents to AWS grades can be difficult, and caution is necessary. Furthermore, it is not as easy to substitute one European consumable for another. When impact testing is required, an approval is valid only for the specific make used in the procedure test. However, the additional European information on the chemical nature of the fluxes can be very useful. Consequently, the writer has found the combination of AWS and EN classifications for a product to be a better guide than the individual classifications.

Table 6. List of EU documents dealing with welding equipment.

Standard	Subject
EN 60 974-1	Power Sources
EN 50 060+ A1	Hobby Transformers
EN 50 078	Guns and Torches
EN 60 974-11	Electrode Holders
EN 60 974-12	Cable Couplers
EN 50 192	Plasma Cutting Systems
EN 50 199	EMC Product Standard
HD 22.6 S2 HD 516S1/A6	Welding Cables
HD 407 S1	Use of welding equipment
HD 427 S1	Installation of welding equipment

Welding Equipment

Manufacturers of welding equipment and the fabricators that use it must comply with regulations introduced for health and safety. The safety, noise emission, welding performance, and electromagnetic compatibility are covered by a number of standards and Harmonization Directives. Standards for power sources and other equipment have been drafted to conform to the safety requirements of a series of important Directives, especially those for low voltage and electromagnetic compatibility. Compliance with the standards is indicated by the CE mark. The important standards are shown in Table 6. In brief, the individual standards conform to the Directives, resulting with details such as 80 V rms OCV for transformers, 113 V DC for rectifiers, 55 V rms for hobby transformers, etc. The noise emission limit is 96 dbA but a lower level is being considered.

Quality Control

Welding belongs to the category termed “special” in EN 29000, because the results cannot be verified entirely by inspection. Continuous monitoring and/or compliance with documented procedures are required to ensure that requirements are satisfied. A series of standards devoted to the control of weld quality has been developed. These have proved to be contentious and their implementation is not comprehensive. EN 729, *Quality requirements for welding*, is published in four parts: Part 1, *Guidance for selection and use*, provides guidelines for three systems (levels) of welding quality control, the requirements for which are shown in further parts. Part 2 covers *Comprehensive quality requirements*, and is similar to the requirements of EN 29001 and 29002, with technically demanding contractual requirements. Part 3 covers *Standard quality requirements* with well-controlled predictable welding. Part 4 covers *Elementary requirements*, which entail minimum documentation for simple and routine techniques. Certification showing conformance with the requirements of EN 729 is best sought from an accredited third-party organization.

To ensure that suitable levels of welding technology and control are applied, fabricators are required to show the availability of Welding Coordinators with suitable levels of knowledge set out in EN 719, *Welding coordination, Tasks and responsibilities*. Acceptance of the categories of European Welding Engineer, European Welding Technologist, and European Welding Specialist (in decreasing order of educational requirements) is growing, but not uniformly, across the EU.

Conclusions

The European Union is becoming stronger and larger, and it will continue to grow as a unified producer and consumer. To ensure the safety and performance of products to be sold without barriers across the Single Market of the EU, such products will have to meet a growing list of standards, only some of which could be discussed briefly in this paper. Ignorance of those standards will be a significant barrier for suppliers from within and outside the EU.

Acknowledgements

G. B. Melton, provided expert interpretation of standards and directives for equipment.

Lincoln Electric Professional Programs

Production Welding

The expertise you need to improve quality and productivity

September 27-30, 1999

Production Welding is a 4-day program conducted by Lincoln Electric's staff of expert welding engineers. It covers welding process selection, welding variables and procedures, the basics of weld design and metallurgy, and nondestructive testing. Aluminum welding has been added to the curriculum this year. 2.7 CEUs. Fee: $395.

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The expertise you need to improve quality and function while reducing welding costs

October 26-28, 1999 March 7-10, 2000

Blodgett's Design of Steel Structures is a 3-day program which addresses methods of reducing costs, improving appearance and function, and conserving material through the efficient use of welded steel in a broad range of structural applications. Seminar leaders: Omer W. Blodgett, Duane K. Miller, and R. Scott Funderburk. 2.0 CEUs. Fee: $495.

Blodgett's Design of Steel Weldments

The expertise you need to improve quality and performance while reducing the manufacturing costs of weldments

September 14-18, 1999 April 11-14, 2000

Blodgett's Design of Steel Weldments is a 3-day program for those concerned with manufacturing machine tools, construction, transportation, material handing, and agricultural equipment, as well as manufactured metal products of all types. Seminar leaders: Omer W. Blodgett, Duane K. Miller, and R. Scott Funderburk. 2.0 CEUs. Fee: $495.

All continuing education programs are conducted in the state-of-the-art Welding Technology Center at Lincoln Electric's world headquarters in Cleveland, Ohio. Space is limited, so register early to avoid disappointment. For full details, visit our website at http://www.lincolnelectric.com, or you may call 216/383-2240, or write to Registrar, Professional Programs, The Lincoln Electric Company, 22801 St. Clair Avenue, Cleveland, Ohio 44117-1199.

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Key Concepts in Welding Engineering

by R. Scott Funderburk

A Look at HEAT Input

What is Heat Input?

In arc welding, energy is transferred from the welding electrode to the base metal by an electric arc. When the welder starts the arc, both the base metal and the filler metal are melted to create the weld. This melting is possible because a sufficient amount of power (energy transferred per unit time) and energy density is supplied to the electrode.

Heat input is a relative measure of the energy transferred per unit length of weld. It is an important characteristic because, like preheat and interpass temperature, it influences the cooling rate, which may affect the mechanical properties and metallurgical structure of the weld and the HAZ (see Figure 1). Heat input is typically calculated as the ratio of the power (i.e., voltage x current) to the velocity of the heat source (i.e., the arc) as follows:

$$H = \frac{60\,EI}{1000\,S}$$

where,

H = heat input (kJ/in or kJ/mm)
E = arc voltage (volts)
I = current (amps)
S = travel speed (in/min or mm/min)

This equation is useful for comparing different welding procedures for a given welding process. However, heat input is not necessarily applicable for comparing different processes (e.g., SMAW and GMAW), unless additional data are available such as the heat transfer efficiency (Linnert, 1994).

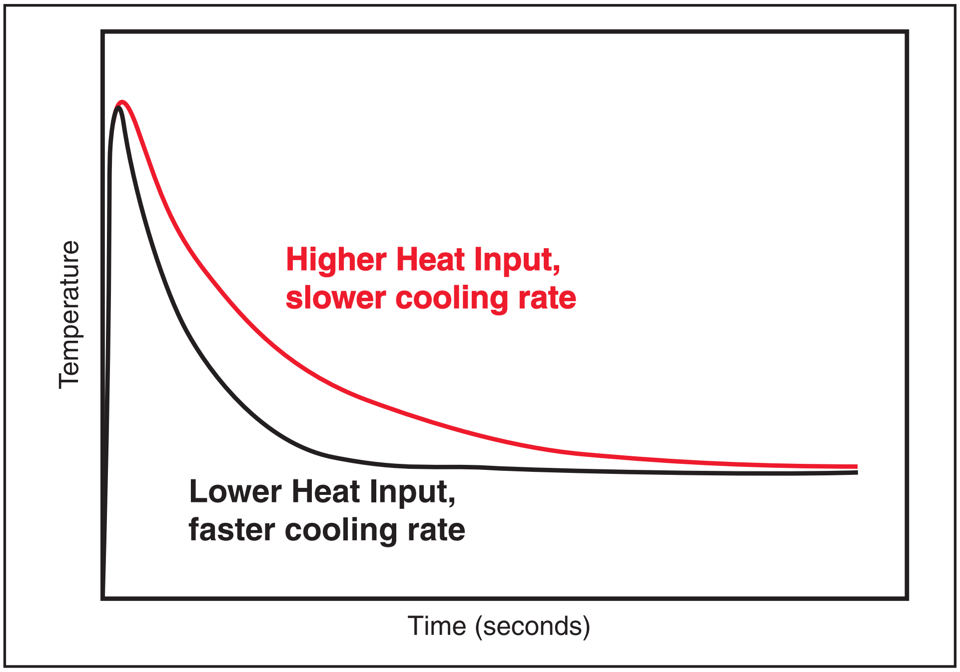

Figure 1. Heat input influences cooling rate.

How is Heat Input Measured?

Heat input can not be measured directly. It can, however, be calculated from the measured values of arc voltage, current and travel speed.

Arc Voltage

In determining the arc voltage (E), the voltage should be measured as close to the arc as possible, as opposed to the value displayed on the welding machine voltmeter. Measuring the voltage across the arc provides the actual voltage drop across the welding arc. The welding machine voltmeter reading is always higher than the arc voltage due to the resistance of the welding cables (see Figure 2). The machine voltage, therefore, can be used only for approximate calculations and, in the case of significant voltage drops, may lead to heat input calculation errors.

> **Heat input is a relative measure of the energy transferred during welding**

Current

The welding current (I) is measured with either an inductance meter (tong meter) or a shunt with appropriate metering equipment. The current is

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never fixed with respect to time, especially on a microsecond level. With SMAW, the current is also a function of the arc length, which is dependent on the welder's skill. Therefore, the current used in the heat input calculations should be the average value.

Travel Speed

The travel speed (S) is the forward velocity of the arc measured in either inches per minute or millimeters per minute. Only the forward progress contributes to the travel speed. If a weaving technique is used, only the forward speed counts, not the oscillation rate. For vertical welding, the upward or downward speed of the arc is used. The travel speed must be in terms of minutes and not seconds for the dimensions to balance in the heat input equation.

When the travel speed is measured, the arc should be established for an amount of time that will produce an accurate average speed. A continuous welding time of 30 seconds is suggested. If this is not possible for the production joint (e.g., short welds), a test weld should be run on a mock-up joint that will provide a sufficient length to determine the travel speed. The travel speed accuracy with manual or semi-automatic welding is dependent on the welder. However, with automatic welding, the speed is set on the motor controlled travel carriage.

Transient Values

For processes in which the voltage and current vary significantly with time, such as short-circuiting GMAW, the average values of these variables are used in calculating the heat input. For example, with GMAW-pulsed arc, the current is pulsed at a specified frequency from a minimum value (background current) to the maximum value (peak current). The average value between the maximum and minimum current and voltage will provide an approximate heat input value for these welding processes.

With SMAW, the resistance of the electrode changes as it is melted, which results in a voltage change. The temperature of the electrode also increases while its length is reduced during welding, both of which influence the overall resistance. Average values are used in this case as well.

The current is never fixed with respect to time

The transient nature of these factors is usually not considered when calculating heat input, and the averages are adequate for procedure qualification or simple comparison of welding procedures. However, for scientific experimentation of cooling rate and heat input a more accurate analysis procedure may be required, including instantaneously monitoring the voltage, current and travel speed to calculate the actual heat input.

Figure 2. The arc voltage is always lower than the machine voltage due to the resistance of the welding cables.

Weld Size is Related to Heat Input

The cross-sectional area of a weld is generally proportional to the amount of heat input. This intuitively makes sense, because as more energy is supplied to the arc, more filler metal and base metal will be melted per unit length, resulting in a larger weld bead. If a welder makes one weld with a fast travel speed and another with a slow travel speed, keeping current and voltage the same for both, then the weld made at the slower travel speed will be larger than the faster one. The following equation is an approximation for the fillet weld leg size based on heat input (Miller, 1998):

$$\omega = \sqrt{\frac{H}{500}}$$

where,

ω = fillet weld leg size (in)
H = heat input (kJ/in)

Although the precise relationship between heat input and fillet weld size also depends on other variables, including the process and polarity, this equation is a helpful tool, especially in creating and reviewing welding procedures. For example, if a minimum fillet weld size is specified, then the corresponding minimum heat input can be determined and controlled.

Cooling Rate is a Function of Heat Input

The effect of heat input on cooling rate is similar to that of the preheat temperature. As either the heat input or the preheat temperature increases, the rate of cooling decreases for a given base metal thickness. These two variables interact with others such as material thickness, specific heat, density, and

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thermal conductivity to influence the cooling rate. The following proportionality function shows this relationship between preheat temperature, heat input and cooling rate:

$$R \propto \frac{1}{T_o H}$$

where,

R = cooling rate (°F/sec or °C/sec)
T_o = preheat temperature (°F or °C)
H = heat input (kJ/in or kJ/mm)

The cooling rate is a primary factor that determines the final metallurgical structure of the weld and heat affected zone (HAZ), and is especially important with heat-treated steels. When welding quenched and tempered steels, for example, slow cooling rates (resulting from high heat inputs) can soften the material adjacent to the weld, reducing the load-carrying capacity of the connection.

How Does Heat Input Affect Mechanical Properties?

Varying the heat input typically will affect the material properties in the weld. The following table shows how the listed properties change with increasing heat input. An arrow pointed up,↑, designates that the property increases as heat input increases. An arrow pointed down,↓, designates that the property decreases as heat input increases. Next to the arrow is the approximate amount that property changed from the minimum to maximum value of heat input tested.

Table 1. How Material Properties are Affected by Increasing Heat Input for SMAW

Property*	Change
Yield Strength	↓ 30%
Tensile Strength	↓ 10%
Percent Elongation	↑ 10%
Notch Toughness (CVN)	↑ 10%, for $15 < H < 50$ kJ/in ↓ 50%, for $50 < H < 110$ kJ/in
Hardness	↓ 10%

* SMAW with a heat input range of 15 to 110 kJ/in.

Other than notch toughness, all of the mechanical properties show a monotonic relationship to heat input, that is, the mechanical property only increases or decreases with increasing heat input. Notch toughness, however, increases slightly and then drops significantly as heat input increases. The change in notch toughness is not just tied to the heat input, but is also significantly influenced by the weld bead size. As the bead size increases, which corresponds to a higher heat input, the notch toughness tends to decrease. In multiple-pass welds, a portion of the previous weld pass is refined, and the toughness improved, as the heat from each pass tempers the weld metal below it. If the beads are smaller, more grain refinement occurs, resulting in better notch toughness, all other factors being even.

Tests have been conducted with SMAW electrodes and procedures that provided heat inputs varying from 15 kJ/in (0.6 kJ/mm) to 110 kJ/in (4.3 kJ/mm) (Evans, 1997). This represents a very large heat input range, which encompasses most applications of SMAW.

If the changes in heat input are relatively small, as opposed to those of the previous table, then the mechanical properties may not be significantly changed. In another study, no significant correlation between heat input and mechanical properties was established for submerged arc welding (SAW) with typical highway bridge fabrication heat input levels of 50 to 90 kJ/in (Medlock, 1998). In this case, the tests results did show varying properties; however, no discernable trends were established.

Welding Codes

As discussed previously, heat input can affect the mechanical properties and metallurgical structure in the weld and HAZ of weldments. The AWS Welding Codes have specific provisions related to heat input for this very reason. Below are the requirements for heat input from AWS D1.1 and D1.5.

AWS D1.1 Structural Welding Code — Steel

The AWS D1.1 Structural Welding Code — Steel controls heat input in three areas: (1) qualified Welding Procedure Specifications, (2) minimum fillet weld sizes and (3) quenched and tempered steels.

Qualified Welding Procedure Specifications (WPSs)

When heat input control is a contract requirement, and if the procedure used in production has a corresponding heat input that is 10% or greater than that recorded in the Procedure Qualification Record (PQR), then the qualified WPS must be requalified (AWS D1.1-98, Table 4.5, item 18). This is primarily due to concerns regarding the potential alteration of the weld metal and HAZ mechanical properties.

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Minimum Fillet Weld Sizes

The code also controls the heat input by limiting the minimum size of fillet welds (AWS D1.1-98, Table 5.8). According to the Commentary, "For non-low-hydrogen processes, the minimum size specified is intended to ensure sufficient heat input to reduce the possibility of cracking in either the heat-affected zone or weld metal" (AWS D1.1-98, para. C5.14). For multiple-pass fillet welds, the Commentary includes the following:

> "Should fillet weld sizes greater than the minimum sizes be required for these thicknesses, then each individual pass of multiple-pass welds must represent the same heat input per inch of weld length as provided by the minimum fillet size required by Table 5.8." (AWS D1.1-98, para. C5.14).

Quenched and Tempered Steels

When quenched and tempered steels (e.g., A514 and A517) are to be welded, the heat input, as well as minimum preheat and maximum interpass temperatures, must conform to the steel producer's specific written recommendations (AWS D1.1-98, para. 5.7). If high heat input welding is used, the HAZ can be significantly weakened due to high temperatures and slower cooling rates. However, the requirement does not universally apply to all quenched and tempered steels. For example, with ASTM A913 Grades 60 or 65, which are quenched and self-tempered, the heat input limitations of AWS D1.1 paragraph 5.7 do not apply (AWS D1.1-98, Table 3.1 and 3.2, footnote 9 and 4, respectively).

AWS D1.5 Bridge Welding Code

The AWS D1.5-96 Bridge Welding Code has provisions for heat input in two areas: procedure qualification and fracture critical nonredundant members.

Procedure Qualification

There are three different methods for qualifying procedures in D1.5: the Maximum Heat Input Method, the Maximum-Minimum Heat Input Method, and the Production Procedure Method. For the Maximum Heat Input Method, the heat input must be between 60% and 100% of the value from the Procedure Qualification Record (PQR) used to qualify the WPS (AWS D1.5-96, para. 5.12.1). With the Maximum-Minimum Heat Input Method, the heat input must fall between that of the two required qualification tests. If the Production Procedure Method is used, the heat input can only deviate from the PQR by the following: an increase of up to 10% or a decrease not greater than 30% (AWS D1.5, Table 5.3, item 17).

D1.1-98 controls heat input in three areas

Fracture Critical Nonredundant Members

Chapter 12 of D1.5 applies to fracture critical nonredundant members (FCMs). The minimum preheat temperature for a FCM is selected based on the heat input, material grade and thickness, and filler metal diffusible hydrogen content (AWS D1.5, Tables 12.3, 12.4 and12.5). Although the focus in chapter 12 of D1.5 is the minimum preheat temperature, the heat input value is an equally controlling variable.

Summary

Heat input is a relative measure of the energy transferred during welding. It is a useful tool in evaluating welding procedures within a given process. The cooling rate, weld size and material properties may all be influenced by the heat input. Some welding codes place specific controls on the heat input. To ensure high quality in welded construction, it is important to understand and apply these principles when notch toughness and HAZ properties are to be controlled and when welding high alloy steels.

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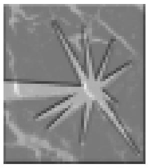
1998 Awards for Engineering & Technology Students



JURY OF AWARDS

Pedro Albrecht
Professor of Civil Engineering
University of Maryland

Glen E. Johnson
Professor of Mechanical Engineering
University of Dayton

William Schmidt
Professor of Mechanical Engineering
University of Arkansas

Donald N. Zwiep
Chairman of the Jury
Chairman, The James F. Lincoln Arc Welding Foundation

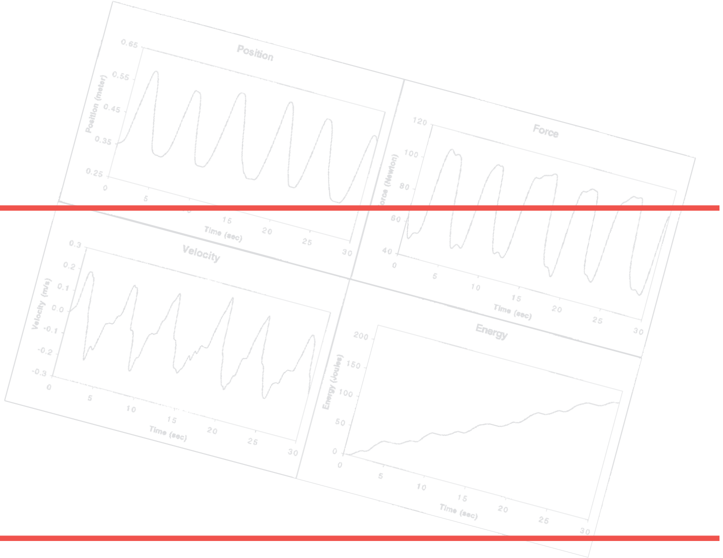
In addition to the following awards to undergraduate and graduate students, The James F. Lincoln Arc Welding Foundation also provided grants of $250 to the following universities in recognition of each Best of Program, Gold, Silver, or Bronze Award received by students of that university:

Dartmouth College
Stanford University
University of Illinois
University of Minnesota
University of Wyoming
Worcester Polytechnic Institute

UNDERGRADUATE DIVISION

Best of Program *$2,000*

Restoring Functional Mobility in the Elderly Through In-Bed Exercise
Solomon Diamond
Thayer School of Engineering
Dartmouth College
Faculty: Francis E. Kennedy



Gold Award *$1,000*

Drill Chuck Design
Lawrence J. Baskett
Irak U. Rosas
Candace Norman-Riley
Mechanical Engineering Dept.
Stanford University
Faculty: Drew V. Nelson

Silver Awards *$750 Each*

Redesign of Toggle Stop
Henry Chou
Eugene Hahm
Carmen Hernandez
General Engineering Dept.
University of Illinois
Faculty: Henrique Reis

Study of Fiber Optic Cable Cutting Process
Jason Colwell
Maitreya V. Madhyastha
Mechanical and Industrial Engineering Dept.
University of Illinois
Faculty: J.W. Nowak

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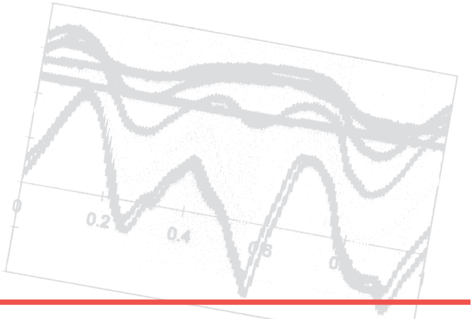
Redesign of a Two-Stage Axial-Flow Water Pump
Kevin V. Lung
Kristian Pala
Joshua D. Rieke
Mechanical and Industrial Engineering Dept.
University of Illinois
Faculty: J.W. Nowak

Design, Manufacture & Test of a Full-Suspension Mountain Bike
Jonathan W. Fairbanks
Christopher M. Lambert
Keith M. Levesque
Matthew D. Morin
Mechanical Engineering Dept.
Worcester Polytechnic Institute
Faculty: Raymond Hagglund

Power Post Puller
Randal W. Six
Mechanical Engineering Dept.
University of Wyoming
Faculty: David Walrath



Merit Awards

$250 Each

Dual Wheel and Drum Service Stand
Christopher T. Key
Mike Melinkovich
Mechanical Engineering Dept.
University of Wyoming
Faculty: Donald F. Adams

Transmission Downsizing
Troy Shawgo
Max Sutlin
David Weinberg
General Engineering Dept.
University of Illinois
Faculty: Daniel L. Metz

Water Pump Test Rig Design
Sean Leonard
Derrick Umphlett
Vivian Vlamakis
General Engineering Dept.
University of Illinois
Faculty: Daniel L. Metz

Enhanced Control & Performance of Hydraulic Valve Actuation
Matthew Mickiewicz
Brian p. Ramsey
Jeffrey Wolven
Mechanical and Industrial Engineering Dept.
University of Illinois
Faculty: J.W. Nowak

Ice Slurry Secondary Refrigeration System Performance
Dar-Lon Chang
Angela McConnell
Collin A. Webb
Mechanical and Industrial Engineering Dept.
University of Illinois
Faculty: J.W. Nowak

Gunsmith Screwdriver Failure Mode Analysis
David Balsiger
Craig Eastin
Kristine Forsythe
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Dishwasher Dryness Sensing System
Brent Crossley
Gregory Lyons
Heena Shah
General Engineering Dept.
University of Illinois
Faculty: J.V. Carnahan

Automated Figure Skate Profiling System
Michael Czarnota
Thomas D. Hull
Balmes Tejeda
Mechanical and Industrial Engineering Dept.
University of Illinois
Faculty: J.W. Nowak

Packaging System Design
Sarah Beckman
Joshua Benoist
Melodie Luk
General Engineering Dept.
University of Illinois
Faculty: Deborah Thurston

Single Sided Hole-Making Method
Joshua Ibarra
Donald India
Khris Richardson
General Engineering Dept.
University of Illinois
Faculty: W. Brent Hall

Rocker Lever Adjusting Screw
Charles Crouch
Trevor Hutchinson
Christopher Wahl
General Engineering Dept.
University of Illinois
Faculty: Edward Kuznetsov

Seal Design in Automotive Coolant Valve
Daniel Beedon
Amy Leung
Carolyn Sperle
Stephen Stone
General Engineering Dept.
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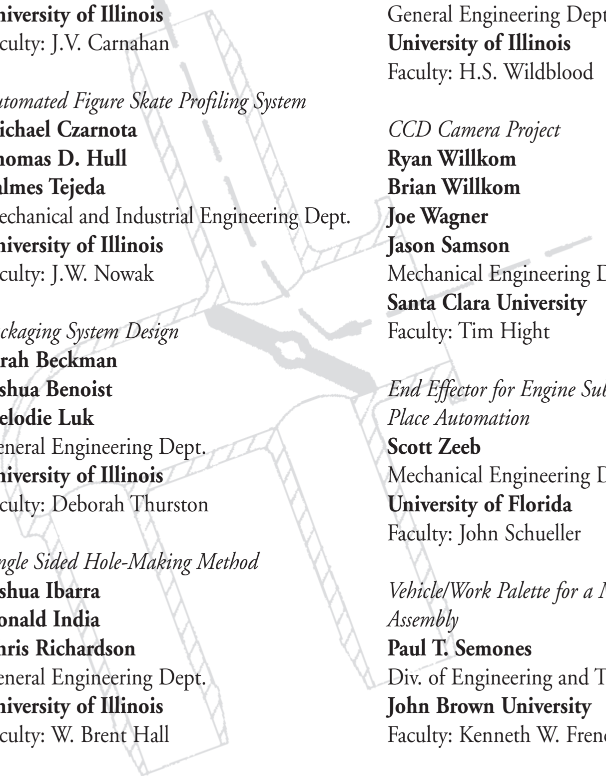
Faculty: H.S. Wildblood

CCD Camera Project
Ryan Willkom
Brian Willkom
Joe Wagner
Jason Samson
Mechanical Engineering Dept.
Santa Clara University
Faculty: Tim Hight

End Effector for Engine Subframe Pick & Place Automation
Scott Zeeb
Mechanical Engineering Dept.
University of Florida
Faculty: John Schueller

Vehicle/Work Palette for a Melt Manifold Assembly
Paul T. Semones
Div. of Engineering and Technology
John Brown University
Faculty: Kenneth W. French, Jr.



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Merit Awards

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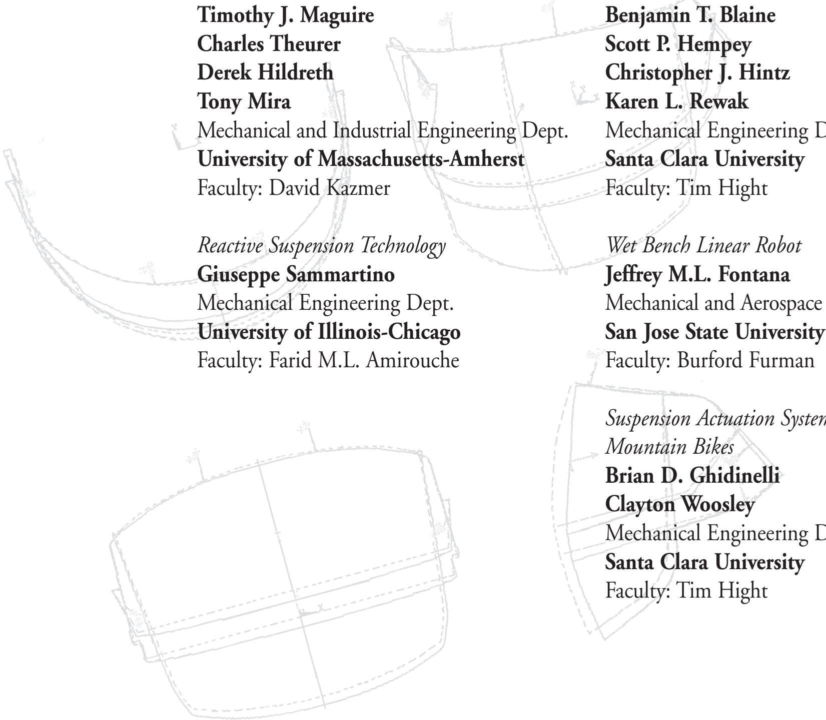

Stereo Lithography Apparatus
Timothy J. Maguire
Charles Theurer
Derek Hildreth
Tony Mira
Mechanical and Industrial Engineering Dept.
University of Massachusetts-Amherst
Faculty: David Kazmer

Reactive Suspension Technology
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Mechanical Engineering Dept.
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Faculty: Farid M.L. Amirouche

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GRADUATE DIVISION

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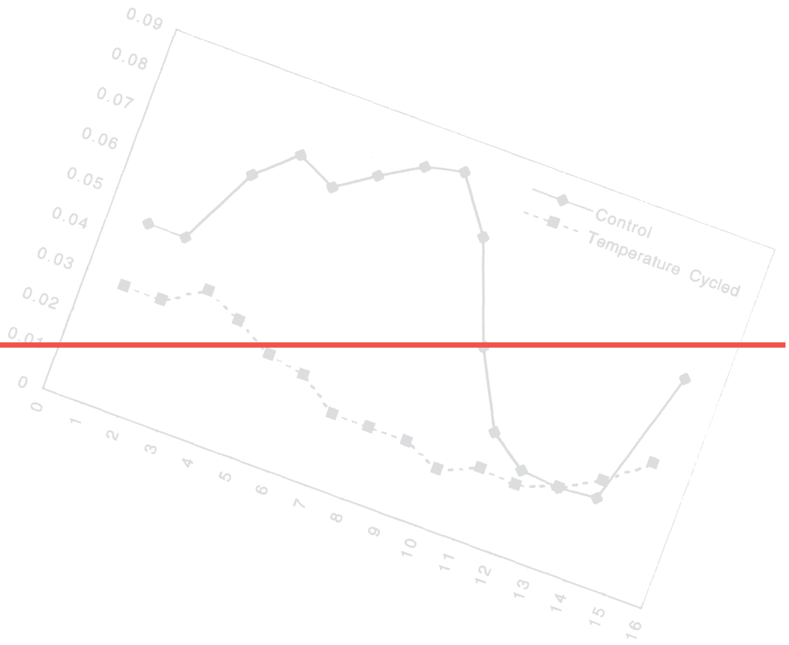

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Brett Cryer
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ABC Motors Entry System
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Inelastic Stability of Tapered Structural Members
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Merit Awards

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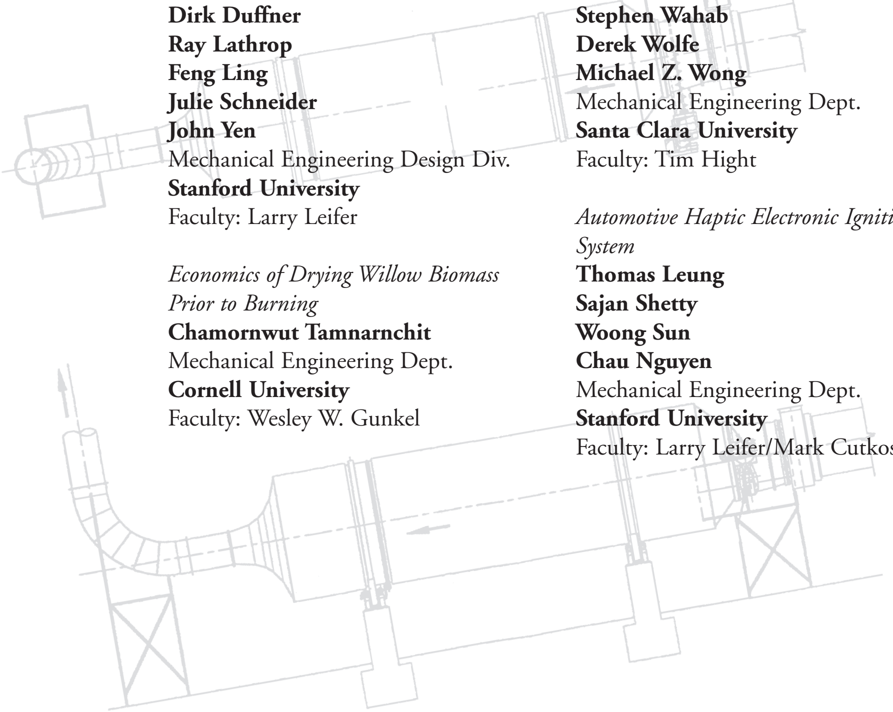

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Ray Lathrop
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Julie Schneider
John Yen
Mechanical Engineering Design Div.
Stanford University
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Economics of Drying Willow Biomass Prior to Burning
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Cornell University
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Design File

Watch Out For "Nothin' Welds"

Practical Ideas for the Design Professional by Duane K. Miller, Sc.D., P.E.

A "nothin' weld" - now there's a term you won't find in *AWS A2.4 Standard Welding Terms and Definitions*! But designers, fabricators and engineers need to know about "nothin' welds" since they can lead to disastrous results.

What is a "nothin' weld?" For the purposes of this discussion, a "nothin' weld" is one that has essentially no throat, and yet the external, visually discernible characteristics of the connection give all indications that the expected weld, complete with the expected weld throat, has been achieved. Unlike a weld that is undersized or filled with surface-breaking porosity that would alert an inspector to the need for more thorough scrutiny, "nothin' welds" look just like the intended weld.

The capacity of any weld is a function of the following: length x throat x allowable strength. Regardless of the allowable weld strength or the length of the weld, if the weld throat is zero (or nearly zero) the connection has no load carrying capacity. "Nothin' welds" have weld throats that approach zero, so the structural or mechanical implications can be disastrous.

Four examples of "nothin' welds" will be cited, their causes discussed, and the practical means by which they can be avoided will be explained. Finally, an actual case study will be presented.

T-Joints with Poor Fitup

Under ideal circumstances, the two members that constitute the T-joint should be brought as closely into contact as possible before those members are joined with a fillet weld. Along the length of a T-joint, perfect fit is never possible, and so some small gaps will exist. Larger gaps may be tolerable in certain situations. However, as the size of the gap between the two members increases, and if the fillet weld leg size is kept the same, the actual weld throat decreases. This is illustrated in Figure 1. Taken to the extreme, this gap could approach the same dimension as the fillet weld leg size, creating a "nothin' weld." Externally, the weld may look identical to that of a properly prepared joint. Figure 1 shows the increased stress level that results from the applied load on the decreasing throat size. It should cause little surprise when such welds fail in service.

The AWS D1.1-98 Structural Welding Code addresses the issue of fitup in paragraph 5.22.1, which states, "The parts to be joined by fillet welds shall be brought into as close contact as practicable... If the separation is greater than 1/16 in (1.6 mm), the leg of the fillet weld shall be increased by the amount of the root opening, or the contractor shall demonstrate that the required effective throat has been obtained." This principle is illustrated in the final schematic of Figure 1, and as illustrated by the numbers in the Table, acceptable stress levels can be maintained when the appropriate compensation is made.

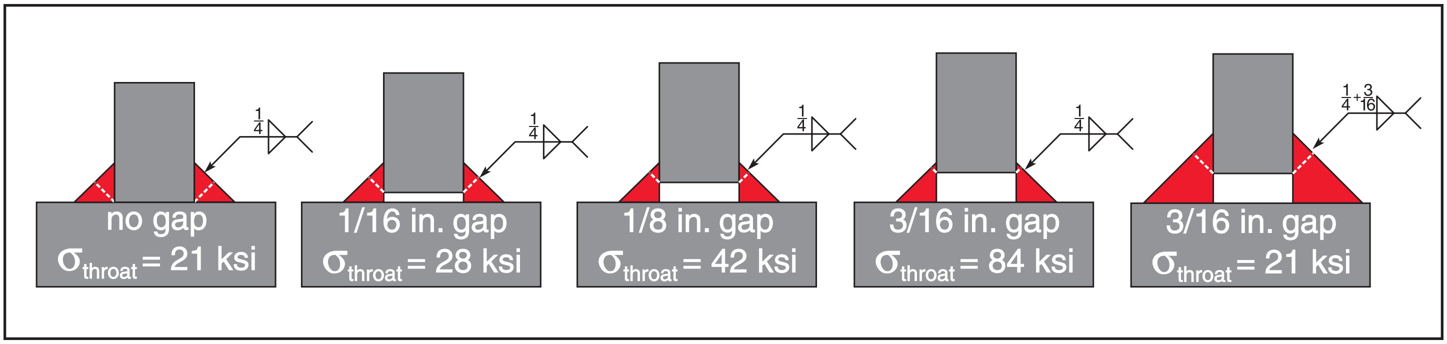

Figure 1. Increasing the root opening of a T-joint without increasing the fillet weld size increases the stress on the throat.

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The most straightforward method to avoid this type of "nothin' weld" is to obtain good fitup. When good fitup cannot be achieved, it is important to note those joints that contain areas of poor fitup so that compensation can be made for these conditions. This requires an effective visual inspection program that includes pre-welding inspection.

Fillet Welds and Lap Joints

A second example of "nothin' welds" occurs when fillet welds are put on the edges of lap joints where the member with the vertical edge of the fillet weld is relatively thin, typically less than 3/8 in (10 mm).

While this is less of an issue with the commonly used semi-automatic welding processes of today, welders using SMAW electrodes (with their inherently broader arc) can inadvertently melt away the top edge of the member. This creates an illusion of a full-sized fillet weld equivalent to the thickness of the top plate. In reality, and as illustrated in Figure 2, the resulting weld throat may be much smaller than the designer intended.

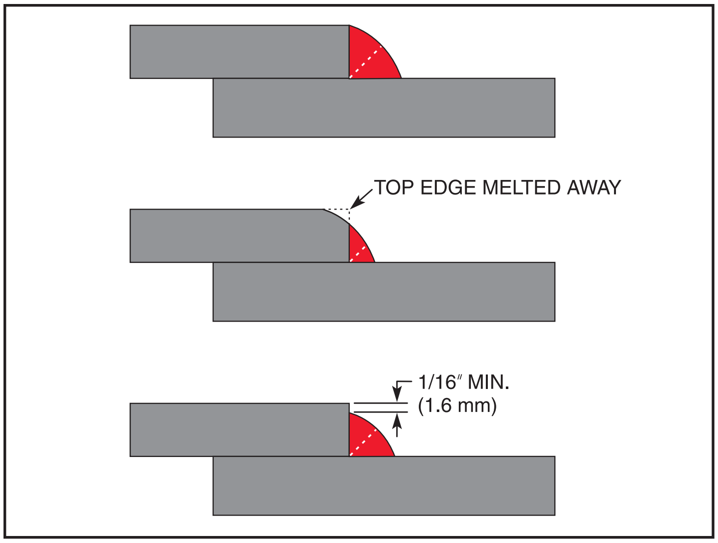

Figure 2. Melting top edge of lap joint can misrepresent actual throat.

The AWS D1.1 Structural Welding Code addresses this by calling for maximum fillet weld sizes on the edges of lapped members as stated in paragraph 2.4.5: "The maximum fillet weld size detailed along edges of material shall be the following: (1) the thickness of the base metal, for metal less than 1/4 in (6.4 mm) thick; (2) 1/16 in (1.6 mm) less than the thickness of base metal, for metal 1/4 in (6.4 mm) or more in thickness…" This is not applied to the thinner members because, from a practical point of view, these welds normally achieve the full throat thickness. The most straight-forward way to avoid the creation of this "nothin' weld" is to leave the 1/16 in (1.5 mm) unwelded portion above the upper weld toe. Additionally, welders should be taught of the implications of this practice and be discouraged from melting the top edge.

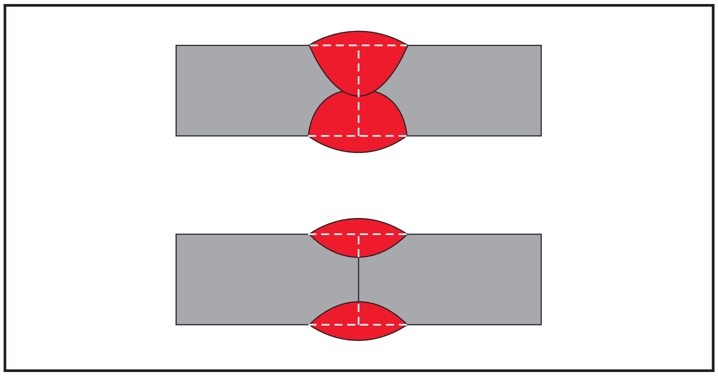

Figure 3. Examples of square edged joints, including the designer's expectation and what actually can be delivered in production.

Square-Edged Groove Welds

On a square-edged groove weld, the base metal at the joint is not beveled or prepared in any other way. A gap may be provided between the two members to be joined, resulting in a root opening that helps facilitate joint penetration. In other cases, the joint may be butted tight, and joint penetration is fully dependent upon the penetration supplied by the welding process. Figure 3 illustrates how a "nothin' weld" can occur with square-edged groove welds. While the designer expected a complete joint penetration weld like that in the top illustration, a combination of variables can lead to the partial joint penetration weld shown in the lower example. In the extreme, the strength of the connection may be due only to the surface reinforcement. Yet, the visually discernible weld on the surface cannot be used to gauge the likely degree of penetration that has been achieved.

The D1.1 places fairly severe restrictions on the use of these joint types. For example, prequalified joint details B-P1a, B-P1b and B-P1c are limited to a maximum thickness of 1/4 in. All other thicknesses require some type of joint preparation, whether the intended weld is a complete joint penetration groove weld or partial joint penetration groove weld. For non-D1.1 Code work, or when using non-prequalified joint details, it is possible to successfully make CJP groove welds on materials as heavy as 1 in (25 mm) thick if welded from both sides, even when a square-edged groove weld is employed. However, rigorous control must be placed on the welding procedures used in production, and electrode placement with respect to the joint is critical. Spot checks of production parts are highly recommended to ensure that the production system is sufficiently robust to ensure consistency. Alternately, groove weld details that employ prepared surfaces for vee and beveled groove details, for example, can be employed to avoid this form of a "nothin' weld."

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Metal Removal Operations

Sometimes “nothin’ welds” are created by machining or grinding operations that are performed after the weld is made. Often in this situation, a weld is deposited that is fully compliant with the design intent, but a significant portion of the weld throat is reduced by a metal removal process. Overcoming this problem is fairly simple: the designer must consider the final connection, after machining of the part, and make sure that the required weld throat will be maintained in those conditions. It is essential that the designer consider all the tolerances that could accumulate, resulting in maximum metal removal, and verify that even under these conditions, adequate weld throats will be maintained.

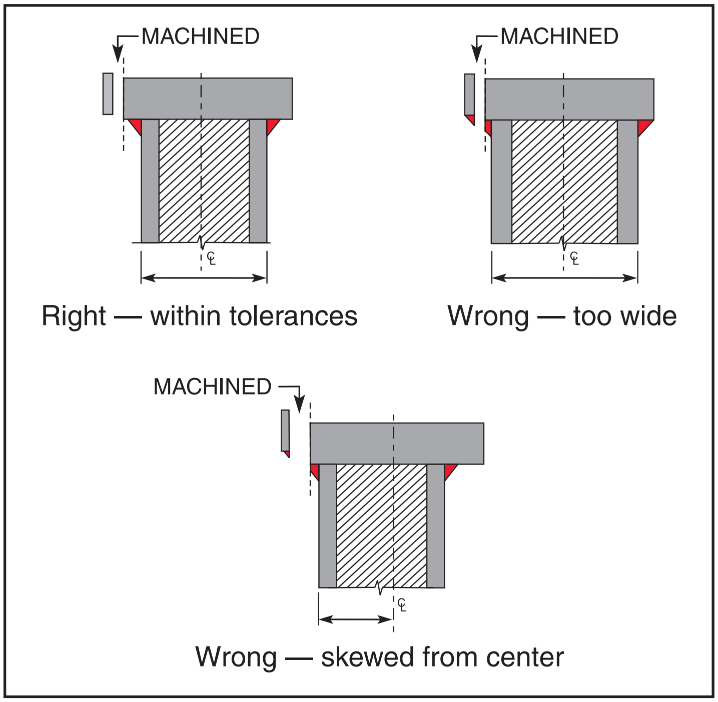

Figure 4. When machining weld metal, tolerances are critical.

Figure 4 illustrates how these problems can arise, and the important role that tolerances play in avoiding the creation of these problems. Perhaps one reason that this occurs is that the typical tolerances associated with many steel welding applications may be in the general magnitude of ±1/8 in (3 mm), whereas machining tolerances may be much more rigorously controlled.

Case Study

This case study is basically an example of the first type of “nothin’ weld” that was described: a fillet weld in a poorly fit joint. What compounded this problem further is that poor fitup was inherent to the detail that was selected. A part was stamped from 3/16 in (4.8 mm) sheet metal, formed into a channel, and assembled into a skewed joint configuration. To minimize cost of material preparation, the end of the inclined member had a 90° edge. Due to forming tolerances, fitup would never be exact and the inclined nature of the skewed joint created a narrow included angle. The designer expected a PJP groove weld with a reinforcing fillet weld would be applied. To ensure this, welding procedures were developed that assured adequate penetration as long as the part was welded in the flat position. See Figure 5.

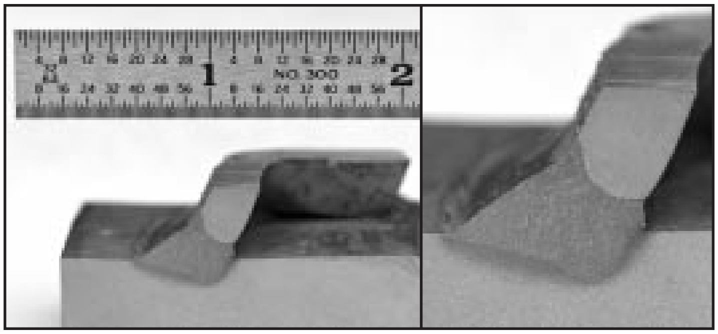

Figure 5. Weld with adequate throat.

However, during production a “nothin’ weld” was created. Although all the facts will probably never be known, it appears that the welder chose to perform this operation in the horizontal position, minimizing penetration into this groove, yet resulting in a “nothin’ weld” with virtually no throat that was visually indistinguishable from the expected fillet weld. See Figure 6.

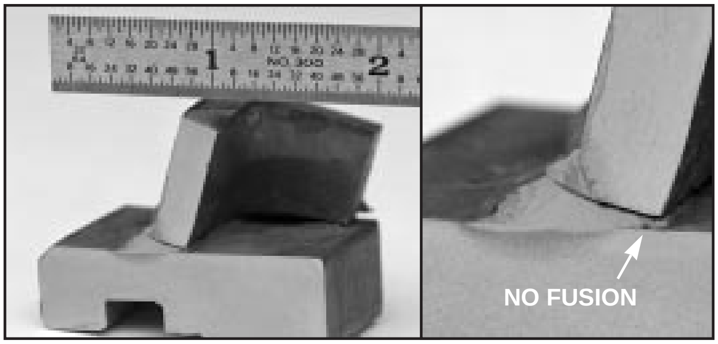

Figure 6. A “nothin’ weld.”

Four of these brackets supported a bearing cartridge that was part of a rotating machine. After several dozen hours of operation, the welds on one bracket failed, followed by failure of the corresponding welds on the other three brackets. When the bearing support was lost, the entire machine was ruined. To overcome this problem, a rigorous in-process inspection and monitoring of the welding operations was initiated to ensure that the welder made the welds in the prescribed position. After-the-fact weld inspection was obviously incapable of detecting this “nothin’ weld.”

Conclusion

“Nothin’ welds” can be avoided by proactively anticipating the unexpected, and taking specific measures to ensure that the expected weld throat is consistently delivered in the finished product.

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Manager, Engineering Services

Instructor of AWS D1.1 WPS

Duane Miller is currently serving as the vice-chair of the American Welding Society's Structural Welding Code Committee and is a past co-chair of the AWS Bridge Welding Committee. He has lectured and conducted seminars in the United States, Asia, Australia and Africa. He is currently involved with the FEMA-funded SAC research effort investigating seismic issues. Dr. Miller previously served as chair of the AWS Presidential Task Group on the Northridge Earthquake Welding Issue. He has authored many papers and magazine articles, as well as two handbooks on various aspects of welding technology.

Walter D. Bullock

Software Engineer, Arc Works Group

Instructor of Arc Works Products

Walter Bullock is a lead designer of Arc Works Software Products. Not only an expert in programming, Walter has solid code knowledge on associated products. He often works with customers to be sure that their needs are implemented as solutions in making Arc Works the best product available on the market. Due to many customer requests, he is our preferred instructor of the Arc Works Seminar.

Harry A. Sadler

Manager, Application Engineering

Instructor of ASME Section IX WPS

Harry Sadler currently serves on the Pressure Vessel Research Council, the Board of Directors of the Welding Research Council, and is a member of the Materials Subgroup of the Section IX Subcommittee of the ASME Boiler and Pressure Vessel Committee. Mr. Sadler earned his BS Degree in Metallurgy from Penn State University and is a member of the American Welding Society, American Society of Mechanical Engineers, and is a former Certified Welding Inspector. As manager of Applications Engineering, he is responsible for evaluating customer's welding applications, procedures, equipment, and consumables in order to improve quality, functionality, and/or reduce fabrication costs.

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A Steel Bridge Over the River Murray

By Ian Ide, Principal
Vic Nechvoglod, Senior Bridge Engineer
Connell Wagner Pty Ltd
Adelaide, Australia
David O’Sullivan, Director
Built Environs Pty Ltd
Adelaide, Australia
Stefan Ahrens, Manager
Ahrens Engineering
Sheaoak Log, Australia

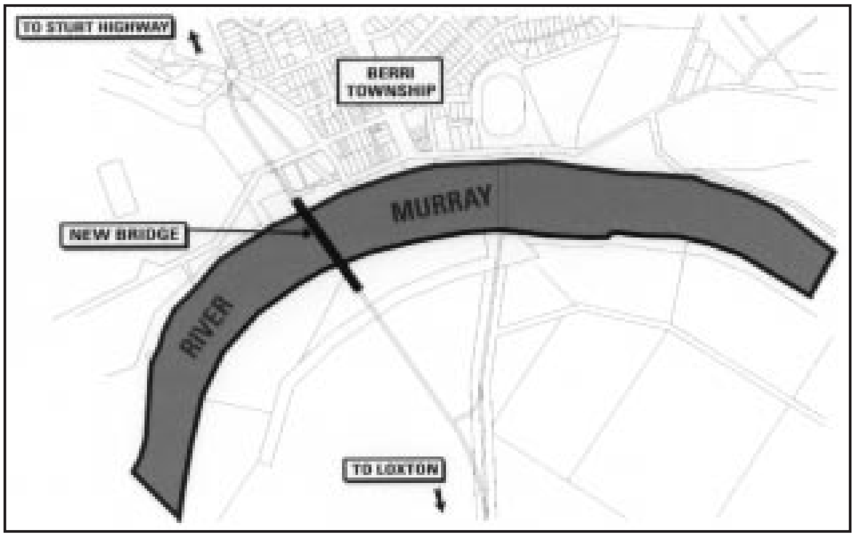

Figure 1.

Introduction

The Berri Bridge over the River Murray was needed to provide a direct road link between the Riverland townships of Loxton and Berri, some 200 km (125 mi) northeast of Adelaide in South Australia. With a proposal put together by Built Environs Pty Ltd and Connell Wagner Pty Ltd, this was the first private sector initiated major bridge infrastructure project in South Australia. Planning consumed more than two years, hundreds of hours, and several hundred thousand dollars. The planning phase included negotiations and discussions with various interest groups, some ten South Australian government departments and authorities, and the Department of Transport. The final proposal was for a 330 m (1,083 ft) long bridge over the River Murray, as well as approximately 1,500 m (4,900 ft) of approach roads, embankment, and associated roadway structures, including an underpass. In the end, the project received unanimous support from all sectors of the community, including the Aboriginal Community, which provided part of its reserve land for the Loxton abutment (see Figure 1).

The Design Approach

The design approach to the Berri Bridge involved a cooperative effort by the designer, the contractor and the steel fabricator from the very inception of the project. The final design was completed after consideration of the alternatives with regard to constructability, steel fabrication, quality control, tolerances, and the construction risks associated with each component of the work. For example, the final design for the fabrication of the steel girders was not documented until the fabricator verified production procedures, tolerances and testing requirements, and had examined and commented on the proposed steelwork specification.

All pier pilecap footings were designed with identical pilecaps with eleven piles each in order to manage construction risks. Also, the river pier piles were chosen to be steel tubes which could be readily extended to achieve the required pile capacity even with the eleven pile design configuration. The use of steel tube piles also facilitated a modification of the pilecap forms to allow construction of the pilecaps to continue when the river was at an above-average level during a critical stage of erection.

All the piers and pier crossheads were dimensionally identical, allowing for repeated use of forming and reinforcement details. This theme of risk control and repeatability of form was evident throughout the construction of the Berri Bridge.

Bridge Description

The Berri Bridge is an incrementally launched, composite steel girder and two-lane concrete deck bridge 330 m (1,083 ft) in length, with eleven spans. The spans vary from 20 m (65 ft) at each abutment to 40 m (130 ft) at the navigation span, with the typical span measuring 33 m (108 ft). The bridge is straight in plan, but has a vertical circular curve of 2,485 m (8,150 ft) radius (see Figure 2).

The abutments are spread footings founded behind gravity retaining walls. The Berri abutment provides the longitudinal fixed support. All piers are supported on piled footings. These include bulb-base cast-in-situ driven piles for land piers and driven steel tube piles for river piers. The capacity of these piles could be increased by extending the shaft and/or increasing the bulb-base as another risk control measure.

A compact girder design was adopted to ensure a limited state of girder flange yielding

Ian Ide, Principal of Connell Wagner, said, “The initial intention was that the bridge be a concrete box structure with integral deck, although the option of adopting steel girders with composite concrete deck was also examined...The decision to adopt the steel option was made shortly before the final agreement was signed. This proved to be a winner.”

After consideration of alternatives, an early decision was made to adopt the incremental launching technique as the minimum cost solution for this bridge. In addition, it was judged that this approach would reduce construction time and risks, principally due to fewer construction activities being required over water. The launching operation for the 330 m (1,083 ft) bridge was completed in just ten weeks.

Bridge Girder Configuration

A four girder option was the minimum cost solution, given the construction method and the weight reduction achieved by using a minimum thickness deck. Typically, the girders are a constant 1,395 x 23 mm (55 x 7/8 in) web, 395 x 20 mm (15.5 x 13/16 in) top flange, and 550 x 40 mm (22 x 1.5 in) bottom flange. The bottom flange was increased to 550 x 50 mm (22 x 2 in) at the main navigation span. All steel is grade 300 L15, except the bottom flange which is grade 350 L15. In keeping with the theme of repeatability and simple detailing, the girders are made up of 68 fabricated beam segments of equal length and camber, differing only in the location of the bracing cleats and bearing stiffeners.

A compact girder design was adopted to ensure a limited state of girder flange yielding. This was regarded as a prerequisite for the redundant pier philosophy since the navigation span would increase from 40 m (131 ft) to a maximum of 73 m (240 ft) if a pier were removed. The girder spacing was chosen to ensure essentially even loads on the bearings and piers under dead load. This was important during launching and for pier design under the pier removed load case.

Bracing was selected to ensure that the girders would develop their full flange yield moment capacity. The girder web was designed to ensure that web buckling would not occur during launching and included allowances for construction tolerances, for bearing installation, girder soffit fabrication, and the casting bed assembly.

In keeping with the principle of repetition, all girders and bracings were identical, and the girder web thickness and top flange were selected to be constant for the full length of the bridge. This allowed the use of “telescoping” deck forms necessary to achieve the planned weekly launch. The bracings were designed to serve the secondary but important role of temporary support for the telescoping deck forms to ensure a weekly launch cycle.

Bearings

The pot bearings were designed to meet service and launch loads. A number of configurations and types of bearings were considered in the concept stages and tests were carried out on some innovative concepts. Launching over the permanent bearings using Teflonâ pads was finally adopted as a proven economical option for the bridge.

Pier Redundancy

The navigation span was required to be 40 m (130 ft) to allow adequate clearing for shipping. The requirements for ship impact on the bridge indicated the design vessel to be a 1,760 tonne vessel traveling at 4 knots, with a river velocity of about one meter (3.3 ft) per second. All river piers were designed to accommodate this loading.

Connell Wagner recognized that the cost to construct the five river piers for this loading was prohibitive and proposed the concept of “pier redundancy” for the steel girder option. “Pier redundancy” means that if any pier were removed, the bridge would not collapse and would continue to provide limited service. “The steel option is the only one suited to this concept because of its lightness and ductility,” explained Vic Nechvoglod, designer for Connell Wagner. He continued, “...the superstructure has the overload capacity to carry limited one-way traffic on the centerline of the bridge with any one of the river piers removed. I believe this is the first bridge in the world to be designed in this way.”

Design for Repetition

The principle of repetition was fundamental for economy in the design of nearly all components, including the piles, girders and pedestrian hand

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rails. Designers worked closely with the builder and fabricator on the design and detailing of all steelwork. Matters pertaining to fabrication of the girders and detailing at minimum cost were discussed several times before the design was finalized. Fabrication initiatives included in the design were:

- Trial welding of the flange to the web.
- Flange butt welding, bracing cleat and bearing stiffener welding.
- A full scale mock-up of a girder splice site weld.
- Trial welding of sections to indicate practical tolerances.
- Beam camber allowance for welding.
- Inclusion of the fabricator's input into the final specification.

In establishing the segment lengths, trucking load limits and costs were reviewed, and the girders split into 17 equal lengths of just under 20 m (65 ft). The transport of segments longer than that would have required police escorts at substantial extra cost. To reduce fabrication splicing costs, BHP provided plates rolled to the required length, except for the 40 mm (1-5/8 in) and 50 mm (2 in) bottom flange plates, which would have been too heavy to handle. The segment length was incorporated into the final design after consideration of costs by the fabricator, construction staff and designer.

the steel girder superstructure is flexible and torsionally soft

To reduce on-site activity, time, and costs, the girders were assembled in pairs with the bracing installed in the painter's yard after painting. The girder pair assembly was then transported to the site. Girder bracing was bolted to enable adjustment on site as an emergency procedure to meet launch tolerance requirements (see Figure 3). Bracing was provided in the outer two bays of the girders, leaving the central bay completely clear. This clearance was designed to serve two main functions: it would allow clear travel space for the launching bracket and jacking system to enable a continuous launch of approximately 39 m (128 ft), at a launch rate of about 12 m (39 ft) per hour; and it would allow space for guide frames on each pier to engage a drop-down concrete panel in the deck soffit, which provided guidance and lateral restraint during construction and launch.

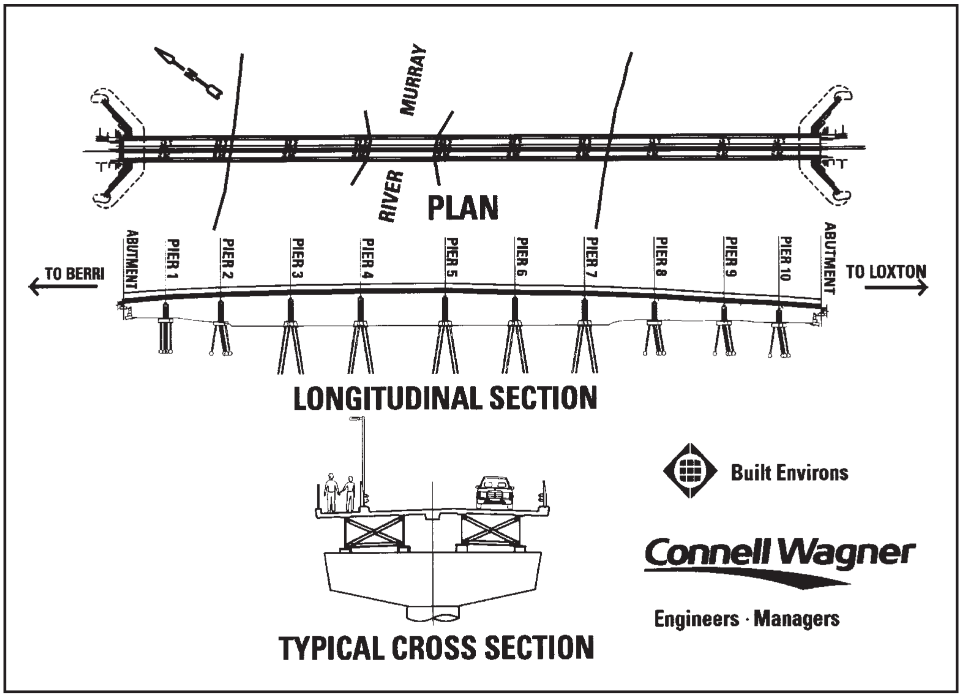

Figure 2.

The design, including all construction activities, was aimed at achieving a one-week launching cycle. This was achieved for eight of the nine launches. Each launch cycle included the field weld splicing of two segments to each of four girders (eight splices per launch), erecting formwork, fixing reinforcement, pouring 39 m (128 ft) of deck, and installing 39 m of traffic barrier and hand railing.

The concrete deck was poured on all but the first 30 m (98 ft) of girders. This 30 m section of undecked girders was designed to double as the "launching nose," thus reducing construction time and costs (see Figure 4).

Novel and innovative design for temporary works included a launching bracket for fixing the jacking system to the girders, and a lifting mechanism for the launch nose to raise it onto the bearings. Both were jointly developed by Built Environs and Connell Wagner and provide examples of the benefit of a cooperative approach in adapting designs to meet construction requirements. In this case, the need for a special "launch nose" was avoided and construction costs were minimized by achieving 39 m (128 ft) continuous launch operations on a weekly cycle. The tops of piers, abutments and girder details were designed as an integral part of the launch bracket and jacking system at the design stage.

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Risk Management

At Berri, available site foundation information indicated that considerable settlement of the bridge approach embankments would occur during their construction. This posed a significant risk to construction by incremental launching, which required close control of all support bearings, including the launch assembly bearings located on the approach embankment. The risk would have been particularly grave in the case of a prestressed concrete box type superstructure which typically requires tolerances of ± 1 mm (1/32 in) on bearing levels to avoid damage during the launching operation.

In comparison to a concrete box superstructure, the steel girder superstructure is flexible and torsionally soft, thereby allowing higher tolerance on bearing levels, and in the torsion or “twist” of the superstructure as a whole. For the typical 33 m (108 ft) span at Berri, a differential pier level of ± 5 mm (3/16 in) of the outer bearings could be tolerated. Such flexibility allowed a margin for error and greatly reduced the risk in fabrication and construction of the superstructure. This margin for error was built into the design as a “fall back” procedure in the event that specified fabrication and/or assembly tolerances were breached. For the Berri Bridge, a critical tolerancing requirement was related to the girder soffit levels, which had to be within ± 3 mm (1/8 in) at any one cross-section of the four girders. This in turn required that the specified camber and camber tolerances for the 68 fabricated 20 m (65 ft) long beam segments had to be closely controlled. It was decided at the design stage that the first four of these beam segments should be used to “proof” the proposed fabrication procedures and welding with regard to tolerance and camber. These four segments were designed for the undecked portion of the launching nose and therefore could be used with increased camber tolerances. The first four segments produced using the proposed fabrication procedures confirmed the initial design camber predictions.

Notwithstanding this reassuring result, it was decided to maintain the beam cross bracing as bolted connections, rather than all-welded ones, as a “fall back” precaution which allowed for the on-site unbolted and level adjustment of the individual 20 m (65 ft) beam segments prior to field splicing, deck casting and launching. This turned out to be a prudent precaution, for while 65 out of the 68 beam segments were uniformly consistent in camber, three of the last few segments were out of camber tolerance and had to be “adjusted” prior to field splicing. The problem appears to have been caused by an error in a computer controlled web profiling machine. This potentially costly and time-delaying deficiency was managed with no pause in construction, and the incident serves to illustrate the management of risk in construction that is possible when there is close cooperation between designer, contractor and fabricator.

"Pier redundancy" means that if any pier were removed, the bridge would not collapse

Conclusion

The Berri Bridge was completed on budget and two months ahead of schedule, despite delays that were caused by high river levels. Its opening was celebrated by a crowd estimated at 10,000, including many residents of the Riverland townships of Loxton and Berri who had lobbied for thirty years for a bridge linking their communities. The bridge won the coveted Institution of Engineers Excellence Award (South Australia) in 1997, the Institute of Building Award in 1998, and the 1998 $10,000 Australasian Steel Bridge Award jointly sponsored by the Australian Institute of Steel Construction and the James F. Lincoln Arc Welding Foundation.

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Figure 3

Figure 4

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