Metallography of Welds

Struers

Application Notes

Up until the end of the 19th century, sections of metal were joined together by a heating and hammering process called forge welding. Today, a variety of different welding processes are available, such that welding is extensively used as a fabrication process for joining materials in a wide range of compositions, part shapes and sizes.

Shielded metal arc welding

Many types of manufacturing industries make use of a wide variety of welding processes:

- Aircraft and aerospace industries e.g. wings and fuselages.
- Shipbuilding and marine industries e.g. panels for decks and superstructures.
- Land transportation / automotive industries.
- Oil and petrochemicals industries e.g. off shore production platforms and pipelines.
- Domestic e.g. white goods and metal furniture.

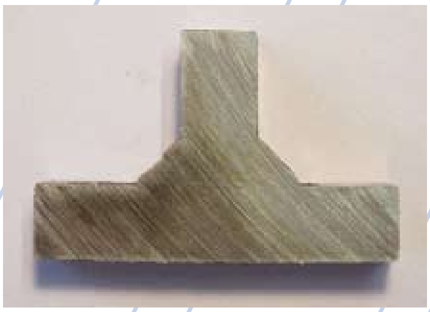
For process control, research and failure analysis, metallography is used to check many different aspects in a weld e.g. the number and size of passes, depth of penetration, extent of HAZ (Heat affected zone), and any defect such as pores and cracks on representative work pieces. As welds are produced in many different materials it is essential to select an appropriate metallographic preparation method.

Polished and colour etched section through a multi pass austenitic stainless steel weld. Colour etched according to Lichtenberger and Bloech. Bright field, 6.5x.

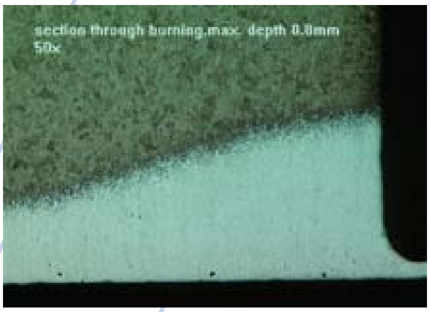
Difficulties during metallographic preparation

The introduction of any thermal damage during the cutting process must be avoided as it can alter the microstructure and properties in the welded joint.

A thorough understanding of the preparation process is necessary to deal with the difficulties presented by the variations in the material properties in and across the welded joint, if flatness between microstructural features with different hardness values is to be achieved.



Thermal damage on a steel weld.



Polished and etched transverse section shows depth to which thermal damage penetrates. Bright field, 50x.

Solution

It is important to select the correct cut-off wheel with the appropriate cutting parameters such that thermal damage of the sample is avoided.

The preparation method should be selected according to the material types of a weld and optimized to minimise the risk of relief between hard and soft phases in the weld, heat affected zone and parent material.

Joining Processes involving heat

The processes which are available for the purpose of joining metals and alloys are

- Soft soldering*
- Braze welding**
- Welding

Features which distinguish welding from soldering and brazing are:

- Soldering (Fig.1) and brazing (Fig. 2) involve melting a material with lower melting point between the work pieces to form a bond between them, without melting the work pieces.
- The materials to be welded are raised above their melting point in the vicinity of the joint, in order for fusion to take place.
- As a consequence of the above, complex chemical and metallurgical changes occur in the materials in the proximity of the welded joint.
- These microstructural changes can have a profound influence upon the joint properties and suitability for service.

*Soft soldering: Soldering is the process in which two metals are joined together by means of a third metal or alloy having a relatively low melting point. Soft soldering is characterized by the value of the melting point of the third metal or alloy, which is below 450°C (840°F). The third metal or alloy used in the process is called solder.

**Braze Welding: Braze welding takes place at the melting temperature of the filler (e.g., 870°C to 980°C or 1600°F to 1800°F for bronze alloys) which is often considerably lower than the melting point of the base material (e.g., 1600°C (2900°F) for mild steel).

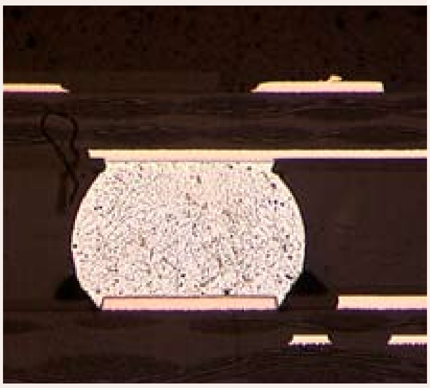
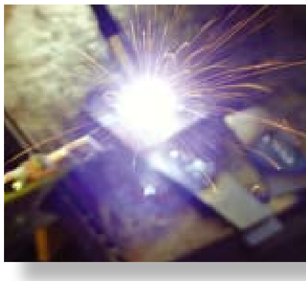
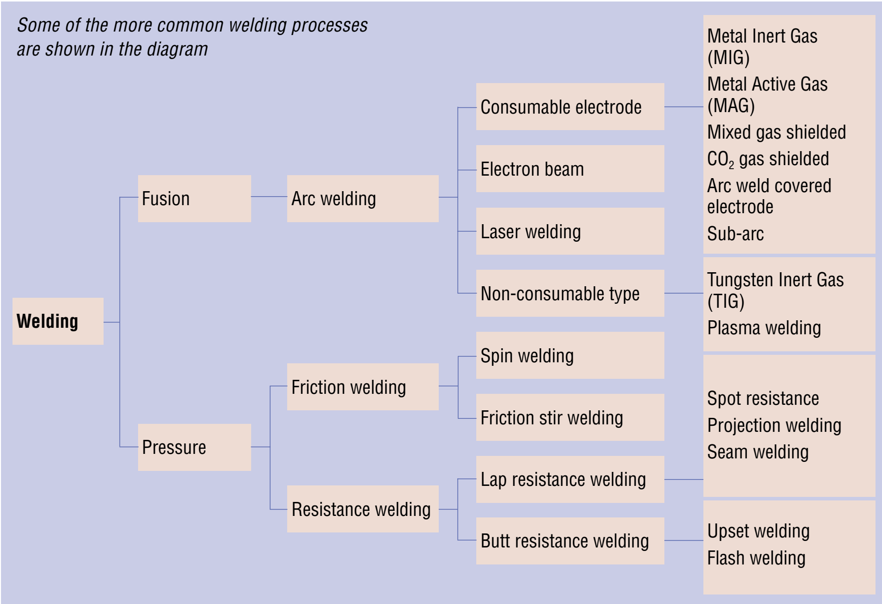


Fig.1: As polished section through solder ball connection between copper conducting tracks in PCB. Bright field, 100x.

Welding Processes





Some of the more common welding processes are shown in the diagram

Generally, the weld is regarded as a junction between two or more pieces of metal in which their surfaces have to be raised to a plastic (e.g. friction welding Fig. 3) or liquid state by the application of heat with or without added metal and with or without the application of pressure.

Each of these processes has their own unique characteristics e.g. penetration, speed of welding, slag generation, heat input, properties of weld, etc. and this in turn can have a considerable influence on the resultant microstructural detail.

Consequently, any study on the effects of a particular welding process will require careful metallurgical examination of representative weld samples, irrespective of whether the objective is to examine the overall integrity of the weld or examine the microstructure/property relationship or to identify the nature and origin of defects. It follows then, that the accuracy of microstructural analysis and interpretation will depend on the production of prepared specimens, free from any artefacts which may have been introduced at any stage in the preparation process.

Robot welding

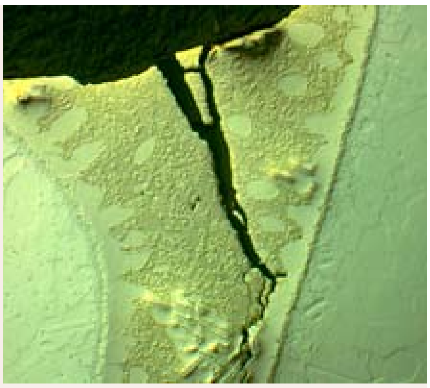


Fig. 2: As polished section through a copper alloy brazing joint in austenitic stainless steel. Differential Interference Contrast, 100x.

Fig. 3: Fusion interface on pressure friction welded low alloy steel showing heat affected zone and associated plastic deformation. Bright field, 25x.

Cross section through electron beam weld in nickel base alloy showing a welded columnar microstructure with few scattered gas pores. Bright field, 50x.

Pipe welds

Taking Test Sections from Welds
Metallographic principles and practices can be applied to the examination of welded sections to satisfy a number of objectives; the more common of which are listed below:

- **Welder Approval Testing**
  In this type of test, an individual welder welds an appropriate test piece, under specified conditions. This test piece is then examined by measurement, visual inspection, and examination of a prepared section through the weld. If the weld reaches the agreed standard, that welder is approved to weld the same type as the test weld.

- **Procedure Approval Testing**
  In this type of test, it is a welding procedure in a particular material with a particular joint configuration which is being approved. The completed weld is examined by a variety of means, one of which includes a prepared section through the welded joint. A hardness traverse across parent material, heat affected zone and weld metal is normally carried out.

- **Production Quality Control**
  In this type of test a representative number of welds are sectioned and examined as part of a production process.

- **Failure Analysis**

- **Research and Development**

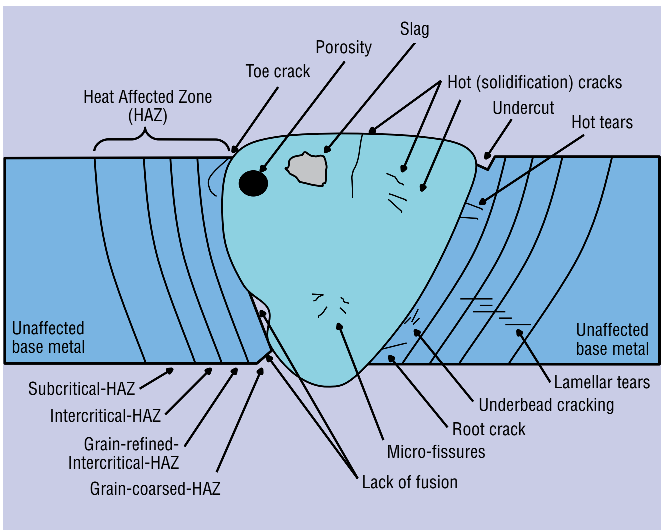
Two levels of metallographic inspection
The examination of metallographic sections through welded joints is commonly carried out at two levels of inspection:

Macro: Where magnifications up to 50x are employed with stereomicroscopes.

Micro: Where examination is at higher magnifications (up to 1000x) using optical microscopes.

Macro examination is commonly carried out on unmounted cross sections through welded joints and simply involves cutting and coarse/fine grinding techniques. The resultant finish is adequate for etching, followed by an examination of the macro features of the weld joint.

For micro examination techniques and hardness traverse, the provision of a polished, optically flat surface will be required. This involves cutting, mounting and grinding and polishing. One has to be aware from the outset, that artefacts can be introduced at any stage of the preparation process. This is particularly true of welded sections because not only do microstructural variations occur over relatively short distances but welds can also involve joints between dissimilar metals having widely different properties.



Drawing showing the various regions of the HAZ in a single-pass weld and the possible defects.

Recommendations for the preparation of weld microsections

CUTTING

For most welder approval tests it is suggested that macro sections are cut in the transverse direction through weld stop/start positions. It is at these locations where any lack of skill on the part of the welder will result in the formation of weld defects.

For weldability and other studies the section must be truly representative. Often, flame cutting is used as a primary cutting technique e.g. to remove a more manageable welded section from a larger fabrication. It is important in these cases that the macro/micro section is cut by an abrasive wet cutting process and is sectioned well away from the influence of any thermal damage from a primary thermal cutting operation.

In order that deformation from cutting is minimised and the risk of thermal damage on the cut surface is avoided, it is important that:

- The correct type of abrasive cut-off wheel is selected.
- An appropriate feed speed is used.
- There is an adequate level of coolant supplied during cutting.

MOUNTING

Normally, macro sections for procedural testing are prepared unmounted because of time constraints, and because a finely ground finish is usually adequate for macro examination. If semi-automatic preparation is an option, then there are a number of specimen holders which will accommodate unmounted cross sections from welded joints.
If mounting is required then there is the option of hot compression mounting or cold mounting. It is not uncommon, however, in weld examination to have relatively large cross sections. In this case, section sizes up to 120 x 60 x 45 mm can be accommodated in Struers UnoForm, rectangular moulds for cold mounting.

MECHANICAL PREPARATION

Macro sections

Traditionally, welded sections for macro examination are prepared manually on successively finer grades of silicon carbide paper to a 1200 grit finish.
This is usually sufficient for hardness traverse through parent material, heat affected zone, and weld metal, as well as being suitable for macro etching to facilitate weld macro examination. Silicon carbide paper is limited in respect of its cutting life (1.0-1.5 mins) and this is exacerbated with increasing section size.
As an alternative grinding/fine grinding media for manual preparation the Struers MD-Piano discs offer a number of advantages:

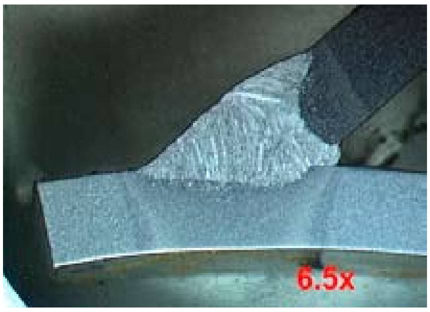
- A longer cutting life.
- A constant removal rate over a longer time period.
- Suitable for a wide range of materials hardness (HV150-2000).
- Less waste.

MD-Piano discs are resin bonded diamond discs which have been developed for coarse and fine grinding of materials in the hardness range HV150-2000 and they are available in comparable grain size to SiC-Paper 80,120, 220, 600, and 1200.

Micro sections

Weld specimens can involve wide variations in material hardness across the specimen either because of a phase changes during welding, or because the joint incorporates dissimilar metals. The weld metal may contain hard precipitates or some indigenous weld defect. As a consequence, it is important that the preparation method should ensure that polish relief between microstructural features is minimal and all microstructural elements are retained. In this respect, semi-automatic or automatic preparation equipment is preferred as it provides a consistency and reproducibility of polish which facilitates accurate microstructural analysis. Preparation methods for the wide range of welded materials which can be experienced cannot be covered in this document.
There are, however, four methods detailed in the following which cover the more commonly used welded materials.

Rectangular mounts of various welds.



Ground and etched macro section through a MIG (Metal Inert Gas) weld in carbon steel, etched with 4% Nital. Bright field, 6.5x

Carbon and low alloy steel welds

Step	PG	FG	DP 1	DP 2
Surface	MD-Piano 220	MD-Allegro	MD-Plus	MD-Nap
Suspension		DiaPro Allegro/Largo	DiaPro Plus	DiaPro NapB
Lubricant	Water			
rpm	300	150	150	150
Force (N)	150	210	180	150
Time	1 min.	4 min.	4 min.	1 min.

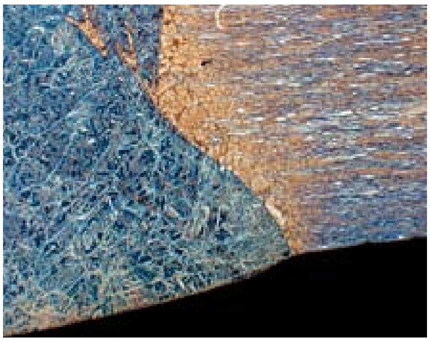
Valid for 6 mounted specimens, 30 mm dia. clamped in a holder. As an alternative to DiaPro, DP-Suspension P, 9 µm, 3 µm and 1 µm can be used together with DP-Lubricant blue.

Polished and etched micro section through MAG (Metal Active Gas) welded carbon steel. Microstructure consists of acicular and primary ferrite. Etched with 2% Nital. Bright field, 200x

Stainless steel welds

Step	PG	FG	DP 1	DP 2
Surface	SiC-Paper 220#	MD-Largo	MD-Dac	MD-Chem
Suspension		DiaPro Allegro/ Largo	DiaPro Dac	OP-AA
Lubricant	Water			
rpm	300	150	150	150
Force (N)	150	180	150	120
Time	1 min.	5 min.	4 min.	2 min.

Valid for 6 mounted specimens, 30 mm dia. clamped in a holder. MD-Largo can be replaced by MD-Plan. As an alternative to DiaPro, DP-Suspension P, 9 µm and 3 µm can be used together with DP-Lubricant blue. MD-Chem with OP-AA can be replaced by MD-Nap with DiaPro NapB.



Weld-base metal interface on Duplex stainless steel. Mechanically prepared; electrolytically etched in 40% aqueous sodium hydroxide solution. Bright Field, 25x.

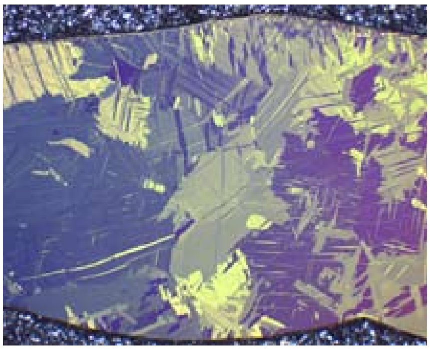
Same material. Weld microstructure consists mainly of delta ferrite and austenite. Bright Field, 200x.

Titanium welds

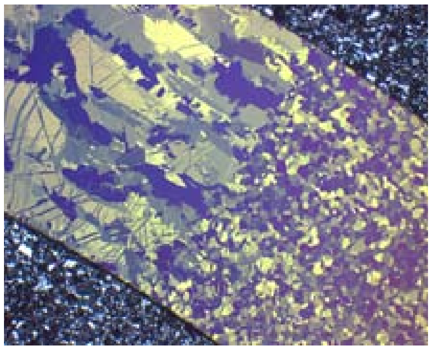
Step	PG	FG	OP
Surface	SiC-Paper 220#	MD-Largo	MD-Chem
Suspension		DiaPro Allegro/Largo	OP-S*
Lubricant	Water		
rpm	300	150	150
Force (N)	150	180	120
Time	1 min.	5 min.	5-10 min.

Valid for 6 mounted specimens, 30 mm dia. clamped in a holder. As an alternative to DiaPro, DP-Suspension P, 9 µm, can be used together with DP-Lubricant blue.

*Note: OP-S with an addition of 10-30% by volume hydrogen peroxide (30%).



Weld area. Mechanically polished weld section of full penetration weld in grade 1 titanium. The weld microstructure consists of Widmanstätten α phase. Polarised light with a sensitive tint plate (λ1/4-plate), 50x.

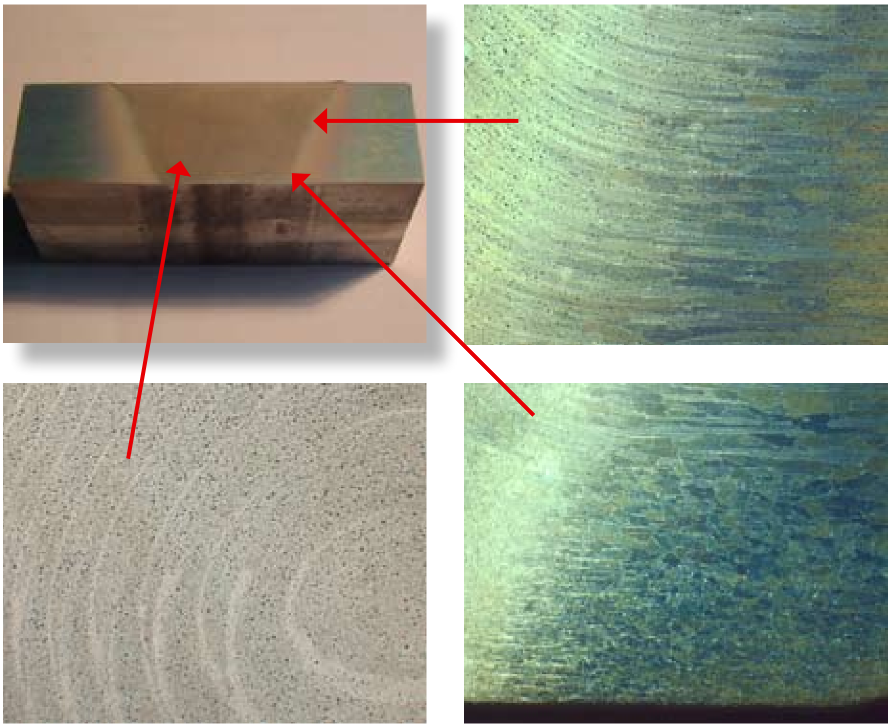


Same material. Parent-heat affected zone interface. Polarised light with a sensitive tint plate (λ1/4-plate), 50x.

Aluminium Welds (Friction stir welding)

Step	PG	FG	DP	OP
Surface	SiC-Paper 320#	MD-Largo	MD-Mol	MD-Chem
Suspension		DiaPro Allegro/ Largo	DiaPro Mol	OP-S
Lubricant	Water			
rpm	300	150	150	150
Force (N)	120	150	120	100
Time	1 min.	5 min.	4 min.	1-2 min.

Valid for 6 mounted specimens, 30 mm dia. clamped in a holder. As an alternative to DiaPro DP-Suspension P, 9 µm and 3 µm can be used together with blue and red lubricant.



Aluminium friction stir weld, etched externally according to Barker, using 15V for 3 min. Polarised light with a sensitive tint plate (λ1/4-plate), 25x

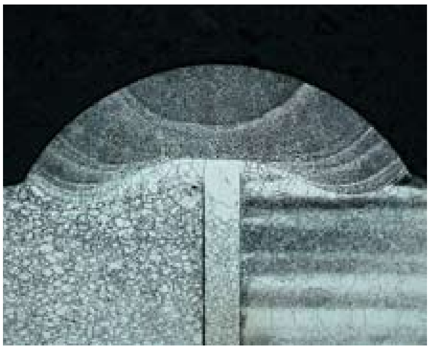
Etching

ELECTROLYTIC POLISHING/ETCHING

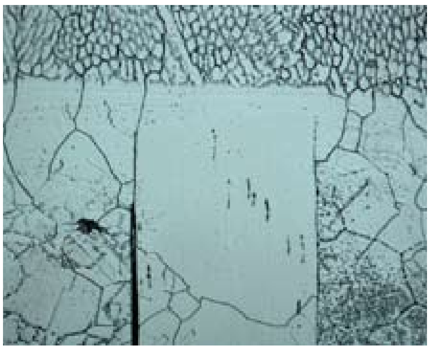
It is not uncommon, in shop floor production control applications, to find electrolytic polishing/etching being used as a method for obtaining prepared weld cross sections for macro examination. Here the sections are cut on an abrasive cut off machine, then after a single grinding stage, the specimens are electrolytically polished and etched to provide a section suitable for macro examination. The advantages of this technique are:

- Its speed.
- Its ease of operation.
- Minimises user contact with acidic etchants.
- A more suitable option for a wide range of stainless steel types and other metals difficult to etch just chemically.

For applications where detailed microstructural analysis is required the specimens for electrolytic polishing and etching should be ground to 1000 grit.



Mechanically polished and electrolytically etched section through micropulse Tungsten Inert Gas weld in Inconel 625 alloy. Etched in 10% oxalic acid; 10 Volts for 10 secs. Bright field, 2.5x.



Same material. Microstructure in the weld consists of primary solid solution and fine irresolvable secondary phase. Section shows pronounced grain coarsening of base material in proximity of fusion face. Bright field, 10x.

Some of the more common chemical and electrolytic etching reagents for welded joints in a variety of materials are listed below.

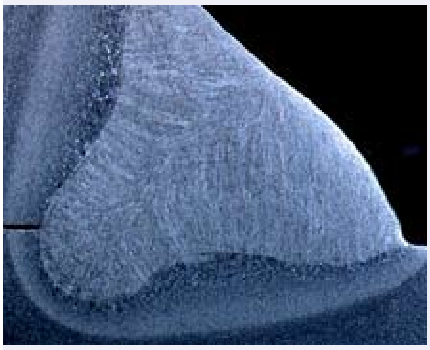
Material	Etchant	Comment
Carbon and low alloy steels	100 ml ethanol (95%) or methanol (95%) 1-5 ml nitric acid (Nital)	Good general purpose reagent; can be increased to 15 ml nitric acid for macro etching.
	100 ml distilled water 10 g ammonium persulphate	Good macro etching
Stainless steels	480 ml distilled water 120 ml hydrochloric acid (32%) 50 g iron (III) choride,	Macro etching
	100 ml distilled water 10 g oxalic acid	Electrolytic etching 4-6 volts for a few secs.
	100 ml distilled water 5 ml sulphuric acid (95-97%)	Electrolytic etching 2-4 volts for a few secs
Nickel alloys	100 ml distilled water 5 ml sulphuric acid (95-97%)	Electrolytic etching 3-6 volts for a few secs.
Copper alloys	100 ml distilled water 10 ml ammonium hydroxide (25%) with a few drops of aqueous hydrogen peroxide (3%)	Use freshly made
Aluminium alloys	100 ml distilled water 15 g sodium hydroxide	Macro etching

It is important to follow the recommended safety precautions when handling chemical reagents and when using chemical etchants.

METALLOGRAPHY

Macro sections

Etched macro sections allow the identification of the boundaries of the weld metal, heat affected zone, fusion boundary, grain growth and the individual runs in multi-run welds. In addition weld defects such as cracks, pores/voids, lack of fusion, and lack of penetration can be identified.

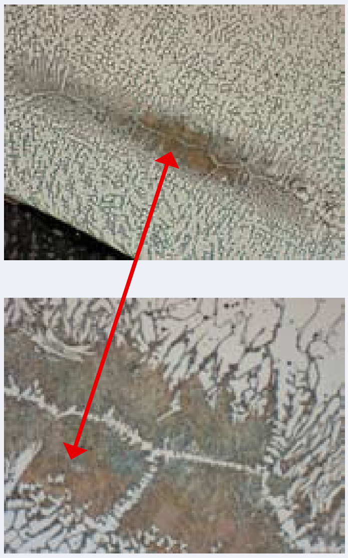


Macro section through deep penetration fillet weld in carbon steel. Section was etched with 5% Nital. Bright field, 2.5x.

Micro sections

Some of the more common metallographic tests carried out on welded joints are detailed below:

Area fraction of a constituent - identification of individual phases and determination of area fraction by point counting, e.g. delta-ferrite in austenitic stainless steel welds.



Bright field, 100x

Bright field, 500x

Polished and etched section of austenitic stainless steel weld showing islands of delta ferrite and small area of pearlite.

Grain size / grain size measurements of grain coarsened / grain refined regions in weld metal and heat affected zone.

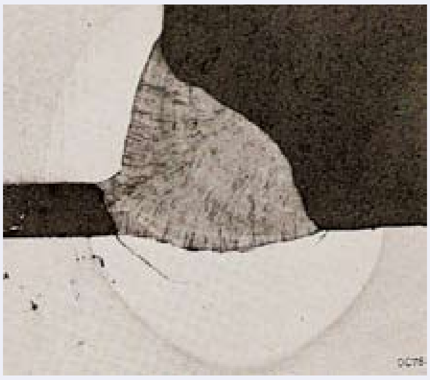
Aluminium weld showing assortment of microstructures in weld, base metal and heat affected zone. Etchant: 100 ml distilled water + 2 ml hydrofluoric acid. Bright field, 100x.

Microstructure type / morphology / identification of microstructural transformation products in weld metal and heat affected zone.

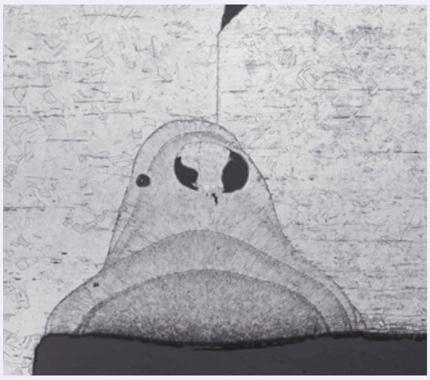
Heat affected zone in duplex stainless steel weld. Etched electrolytically with 40% aqueous sodium hydroxide solution. Bright field, 200x.

Defect analysis / identification and characterisation of indigenous weld defects.

Sub surface gas porosity in automatically MAG (Metal Active Gas) welded steel components. Ground and etched with 10% Nital. Bright field, 2x.

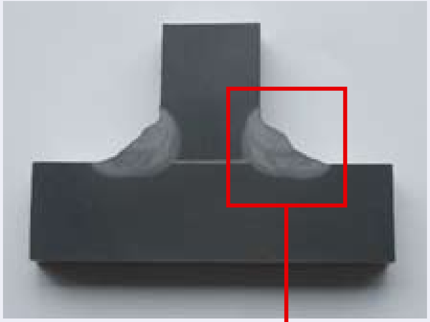


Heat affected zone crack below fillet weld in low alloy steel. Bright field, 5x.

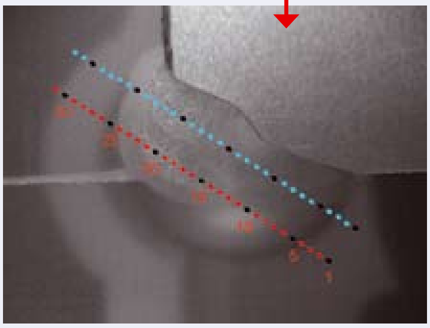


Pores in an austenitic stainless steel weld. Bright field, 100x.

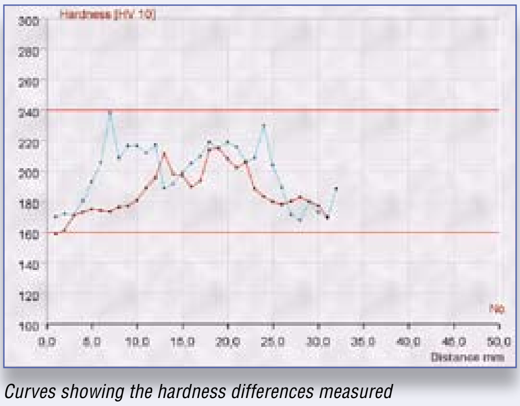
Hardness survey - normally a hardness / microhardness traverse across parent material heat affected zone and weld metal is carried out to ensure whether weld and heat affected zone properties are satisfactory.



Steel welds



Weld with hardness indentations (according to standard DIN EN 1043).



Curves showing the hardness differences measured on Duramin-A300.

Summary

The application of good metallographic practices as applied to welded joints has been outlined. An appropriate preparation method needs to be selected according to the physical properties of weld material(s). It is important that care is taken at all stages of the preparation process to obtain a correct analysis of the microstructure and properties in the weld region.

Application Note

Metallography of Welds

Bill Taylor, Anne Guesnier, Struers A/S
Copenhagen, Denmark

Acknowledgements

We wish to thank Mrs Erika Weck and Mrs Elisabeth Leistner for permission to reproduce the fourth picture on the front page "Polished and colour etched section through a multi pass austenitic stainless steel weld. Colour etched according to Lichtenberger and Bloech. Bright field, 6.5x".

We thank Mrs Brigitte Duclos, Struers S.A.S. for three micrographs on page 7:

Aluminium weld showing assortment of microstructures in weld, base metal and heat affected zone.

Heat affected zone in duplex stainless steel weld.

Pores in an austenitic stainless steel weld.

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Struers

Struers A/S
Pederstrupvej 84
DK-2750 Ballerup, Denmark
Phone +45 44 600 800
Fax +45 44 600 801
struers@struers.dk

USA
Struers Inc.
24766 Detroit Road
Westlake, OH 44145-1598
Phone +1 440 871 0071
Fax +1 440 871 8188
info@struers.com

CANADA
Struers Ltd.
7275 West Credit Avenue
Mississauga, Ontario L5N 5M9
Phone +1 905-814-8855
Fax +1 905-814-1440
info@struers.com

SWEDEN
Struers A/S
Ekbacksvägen 22, 3 tr
P.O. Box 11085
SE-168 69 Bromma
Telefon +46 (0)8 447 53 90
Telefax +46 (0)8 447 53 99
struers@struers.dk

FRANCE
Struers S.A.S.
370, rue du Marché Rollay
F- 94507 Champigny
sur Marne Cedex
Téléphone +33 1 5509 1430
Télécopie +33 1 5509 1449
struers@struers.fr

NEDERLAND/BELGIE
Struers GmbH Nederland
Electraweg 5
NL-3144 CB Maassluis
Tel. +31 (0) 10 599 72 09
Fax +31 (0) 10 599 72 01
glen.van.vugt@struers.de

BELGIQUE (Wallonie)
Struers S.A.S.
370, rue du Marché Rollay
F- 94507 Champigny
sur Marne Cedex
Téléphone +33 1 5509 1430
Télécopie +33 1 5509 1449
struers@struers.fr

UNITED KINGDOM
Struers Ltd.
Unit 25a
Monkspath Business Park
Solihull
B90 4NZ
Phone +44 0121 745 8200
Fax +44 0121 733 6450
info@struers.co.uk

IRELAND
Struers Ltd.
Unit 25a
Monkspath Business Park
Solihull
B90 4NZ
Phone +44 (0)121 745 8200
Fax +44 (0)121 733 6450
info@struers.co.uk

JAPAN
Marumoto Struers K.K.
Takara 3rd Building
18-6, Higashi Ueno 1-chome
Taito-ku, Tokyo 110-0015
Phone +81 3 5688 2914
Fax +81 3 5688 2927
struers@struers.co.jp

CHINA
Struers Ltd.
Office 702 Hi-Shanghai
No. 970 Dalian Road
Shanghai 200092, P.R. China
Phone +86 (21) 5228 8811
Fax +86 (21) 5228 8821
struers.cn@struers.dk

DEUTSCHLAND
Struers GmbH
Karl-Arnold-Strasse 13 B
D-47877 Willich
Telefon +49(02154) 486-0
Telefax +49(02154) 486-222
verkauf.struers@struers.de

ÖSTERREICH
Struers GmbH
Zweigniederlassung Österreich
Ginzkeyplatz 10
A-5020 Salzburg
Telefon +43 662 625 711
Telefax +43 662 625 711 78
stefan.lintschinger@struers.de

SCHWEIZ
Struers GmbH
Zweigniederlassung Schweiz
Weissenbrunnenstrasse 41
CH-8903 Birmensdorf
Telefon +41 44 777 63 07
Telefax +41 44 777 63 09
rudolf.weber@struers.de

CZECH REPUBLIC
Struers GmbH
Organizační složka
Havlíčkova 361
CZ-252 63 Roztoky u Prahy
Tel: +420 233 312 625
Fax: +420 233 312 640
david.cernicky@struers.de

POLAND
Struers Sp. z.o.o.
Oddział w Polsce
ul. Lirowa 27
PL-02-387 Warszawa
Tel. +48 22 824 52 80
Fax +48 22 882 06 43
grzegorz.uszynski@struers.de

HUNGARY
Struers GmbH
Magyarországi fióktelep
Puskás Tivadar u. 4
H-2040 Budaörs
Phone +36 (23) 428-742
Fax +36 (23) 428-741
zoltan.kiss@struers.de

SINGAPORE
Struers A/S
627A Aljunied Road,
#07-08 BizTech Centre
Singapore 389842
Phone +65 6299 2268
Fax +65 6299 2661
struers.sg@struers.dk

www.struers.com

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