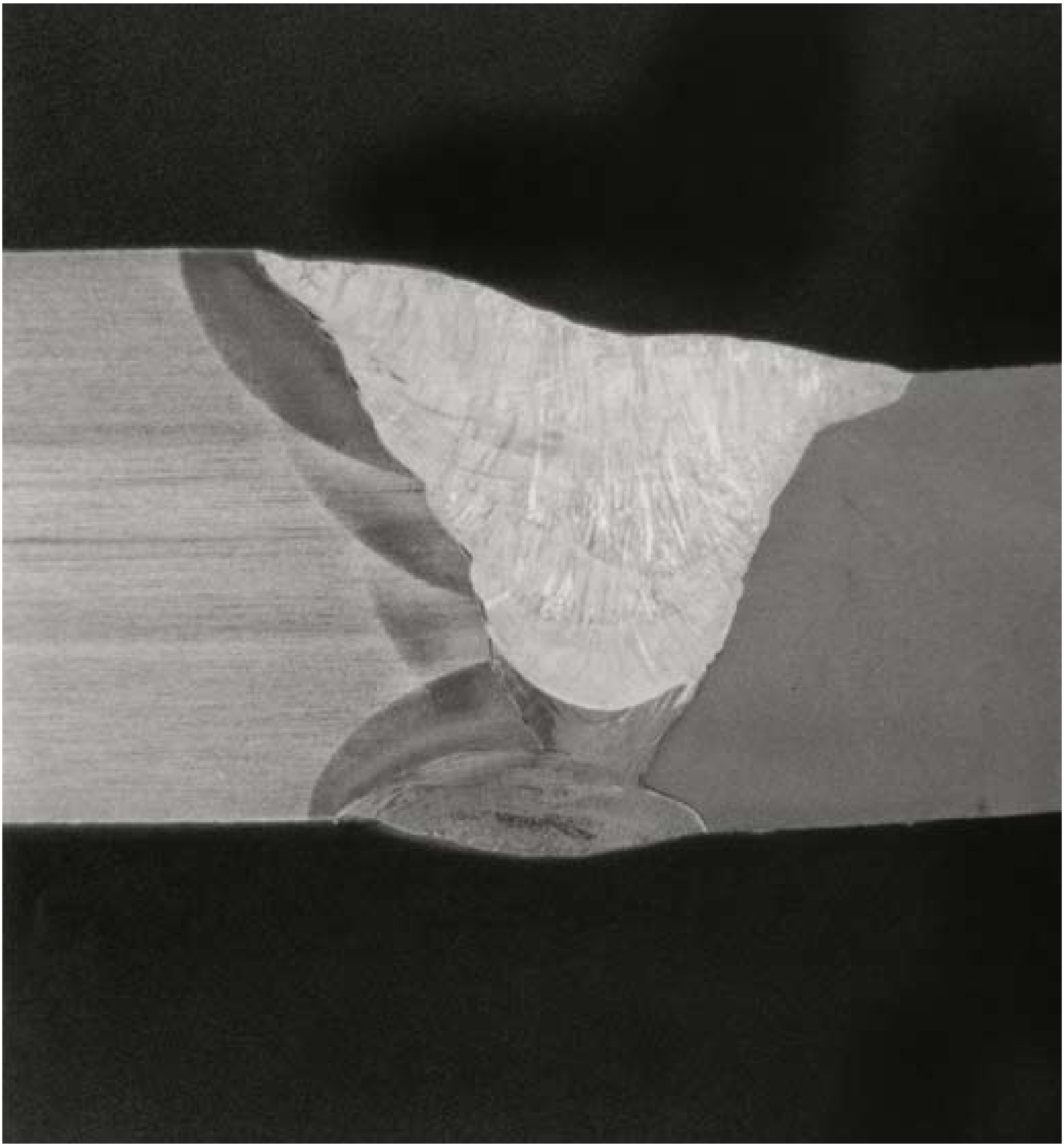
Welding guide for the joining of dissimilar metals



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Index key

		Co-alloys	Titanium alloys (Ti-alloys)	Magnesium alloys	Al-alloys	Cu-alloys					Ni-based alloys					Fe-based alloys								
						Copper-nickel	Al-bronze Si-bronze	Sn-bronze	Brass	Pure Cu	Hastelloy	Nimonic	Inconel	Monel	Pure Ni	Cast iron	Unknown comp.	Stainless steel: Ferritic-austenitic	Stainless steel: Ferritic	Stainless steel: Austenitic	Springsteel Tool steel	L. all. steel: $C_E>0.4$	L. all. steel: $C_E\leq0.4$	Carbon steel, $C_{EQ}\geq0.5$
					47	27					11					1								
Fe-based alloys	Carbon steel $C_E\leq0.4$	54	53	51	48	39	37	32	31	28	24	23	20	15	12	10	9	6	6	6	5	3	3	2
Fe-based alloys	Carbon steel $C_E>0.4$	54	53	51	48	39	37	32	31	28	24	23	20	15	12	10	9	6	6	6	5	3	3	
Fe-based alloys	L. all. steel $C_E\leq0.4$	54	53	51	48	39	37	32	31	28	24	23	20	15	12	10	9	6	6	6	5	4		
Fe-based alloys	L. all. steel $C_E>0.4$	54	53	51	48	39	37	32	31	28	24	23	20	15	12	10	9	6	6	6	5	4		
Fe-based alloys	Tool steel Springsteel	54	53	51	48	39	37	32	31	28	24	23	20	16	12	10	9	7	7	7				
Fe-based alloys	Stainless steel Austenitic	54	53	51	48	39	37	32	31	28	24	23	20	17	13	10	9	8	8					
Fe-based alloys	Stainless steel Ferritic	54	53	51	48	39	37	32	31	28	24	23	20	17	13	10	9	8						
Fe-based alloys	Stainless steel Ferritic-austenitic	54	53	51	48	39	37	32	31	28	24	23	20	17	13	10	9							
Fe-based alloys	Unknown comp.	54	53	51	48	39	37	32	31	28	24	23	20	16	12	10								
Fe-based alloys	Cast iron	54	53	51	48	40	33	33	31	29	25	21	21	18	14									
Ni-based alloys	Pure Ni	54	53	51	48	41	34	34	31	30	26	23	22	19										
Ni-based alloys	Monel	54	53	51	48	41	34	34	31	30	26	23	22											
Ni-based alloys	Inconel	54	53	51	48	42	34	34	31	30	26	23												
Ni-based alloys	Nimonic	54	53	51	48	42	34	34	31	30	26													
Ni-based alloys	Hastelloy	54	53	51	48	43	34	34	31	30														
Cu-alloys	Pure Cu	54	53	51	49	44	36	35	31															
Cu-alloys	Brass	54	53	51	49	31	36	36																
Cu-alloys	Sn-bronze	54	53	51	49	45	38																	
Cu-alloys	Al-bronze Si-bronze	54	53	51	49	46																		
Cu-alloys	Copper-nickel	54	53	51	49																			
	Al-alloys	54	53	51	50																			
	Mg-alloys	54	53	51																				
	Ti-alloys	54	52																					
	Co-alloys	54																						

This manual is divided into 55 sections, organized in an ascending order.
General comments are given in the following sections:

Section 1	Fe-based alloys
Section 11	Ni-based alloys
Section 27	Cu-based alloys
Section 47	Al-based alloys

Remaining sections give recommendations for specific material combinations.
Section 55 covers some material combinations, not covered by the index table.

Instructions for use

Example 1: 9 % Al-bronze to Copper-nickel (90/10).
First read the general comments on copper alloys in section 27.
Find the specific recommendations in section 46.

Example 2: Austenitic stainless steel to mild steel.
First read the general comments on Fe-based alloys in section 1.
Find the specific recommendations in section 6.

Introduction

This booklet will provide information on process choice for electric arc welding (MMA, GTAW and GMAW) and consumable choice for joints between dissimilar metals and/or alloys only. For joints between similar metals/alloys, see information given in the ESAB Welding Handbook.

Consider the following when welding dissimilar metals:

- The weld metal in a dissimilar joint must not create brittle intermediate phases. The recommendations given in this booklet are made keeping this in mind. As a result a number of recommendations involve a buttering technique described under each such combination.
- A joint between dissimilar metals will not result in better strength and corrosion properties than, in this respect, the "weaker" side. The recommendations are given with respect to strength and therefore corrosion aspects must be considered before using them.
- To avoid hydrogen cracks, e.g. on the steel side, mostly basic coated electrodes are recommended in such cases.
- When welding dissimilar joints, both surfaces must be preheated according to their own prescription. (See further chapter 1, 11, 27 and 47).
- When using the GTAW process, straightened, well cleaned GMAW consumables of the same composition may be used. As an emergency solution, even thoroughly cleaned strips from the plate itself may sometimes be used. However, this may cause brittle intermediate phases and therefore the use of it must be based on experience.

Abbreviation key:

MMA:	Manual Metal Arc welding with coated electrodes
SAW:	Submerged Arc Welding
GTAW:	Gas Tungsten Arc Welding (Also TIG=Tungsten Inert Gas)
GMAW:	Gas Metal Arc Welding (Also MIG=Metal Inert Gas or MAG=Metal Active Gas)

The consumables mentioned in this booklet are selcted to fit its purpose. For information on the full ESAB-range, contact your nearest ESAB-office or consult the ESAB handbook. Further details on the consumables, e.g. chemical analysis and current recommendations, are also given in the handbook.

1. Read this before welding steel and cast iron

1.1 Carbon steel, low alloy steel, tool steel and steel of unknown composition.

The weldability of steel decreases with increasing hardenability. It is therefore of great importance to evaluate this carefully. The most common way is to calculate the so called "Carbon-Equivalent" (C_E):

$$C_E = \%\,C + \frac{\%\,Mn}{6} + \frac{\%\,(Cr+Mo+V)}{5} + \frac{\%\,(Ni+Cu)}{15}$$

When welding steels with different C_E values, the welding parameters are determined by the steel with the higher C_E and the consumables are decided by the steel with the lower C_E. It is important to avoid consumables with too high C_E values, since this increases the risk of cracking. With the correct choice of consumables and welding parameters, the hardenability and the mechanical properties of the weld metal will be between those for the different steels.

The Carbon-equivalent will also influence the required preheating temperature. When welding steels with different, C_E values, the preheating level should be chosen according to the steel with the highest C_E.

C_E	Recommended preheating temperature
<0.4	<100°C
0.4–0.6	150–200°C
>0.6	250–300°C
Tool steel, Spring steel, Steel with unknown composition	~300°C

Stress annealing should be performed if possible often welding steels with greatly differing C_E values. Controlled or slow cooling will also decrease the risk of cracking on such steel combinations.

1.2 Stainless to mild steel

The mixing of these materials will lead to formation of hard brittle structures. Fig 1 shows how the formation of these structures depend upon the chemical composition of the weld metal. The Stainless steel can also be welded to unalloyed or low alloyed steel with excellent results. Some care and consideration is nonetheless needed, since the many possible steel combinations make it difficult to formulate generally applicable rules which always guarantee a perfect result. A good welding result can nearly always be obtained if the steel has a reasonable degree of weldability and certain straightforward guidelines for the avoidance of cracking are followed. However, one frequently encounters cases where these guidelines have been ignored.

The welding of stainless steel to unalloyed and low alloyed steel should normally be performed with *over-alloyed* (more highly alloyed than the *stainless steel*) stainless consumables. The three most common types of consumables are (wt. %):

23-25Cr 11-15Ni (with or without Mo.)
29Cr 9Ni and 18Cr 8Ni 6Mn.

High-temperature strength structures designed for application of over 200°C, such as the joining of creep resistant Cr-Mo steel to stainless steel should, however, be welded using *Ni-based consumables.*

Use of a Ni-based consumable prevents the higher carbon content of Cr-Mo steel from causing the carbon atoms to "migrate" from the Cr-Mo steel to the weld metal (known as "carbon migration"). This occurs when stainless consumables are used, wherein is formed a brittle, carburised weld junction area and a decarburised zone in the Cr-Mo steel resulting in a reduction in creep strength.

Two different methods can be used for welding stainless steel to unalloyed and low alloyed steel. The entire groove can be filled with the over-alloyed stainless steel or Ni-based consumable. Alternatively the low-alloyed or the unalloyed groove surface can be buttered with over-alloyed stainless weld metal, after which the groove is filled with a consumable suitable to the stainless base material.

1.2.1 Cracks in the weld metal

If consumables of the types mentioned above are used, a good welding result can normally be obtained. Unfortunately cases are found where cracks have appeared because unsuitable consumables have been used.

Cracks in the welded joint between the stainless and the unalloyed or low alloyed steel can almost always be classified as hydrogen-induced cracks or solidification cracks. In both cases the choice of consumable is the decisive factor when considering the probability of crack occurence.

Hydrogen-induced cracks are usually caused by the use of electrodes with a high moisture content or because the welding has been performed on groove surfaces which have not been cleaned properly (dirt, moisture, rust). Welding in unsuitable external conditions can also contribrute to the formation of this type of crack.

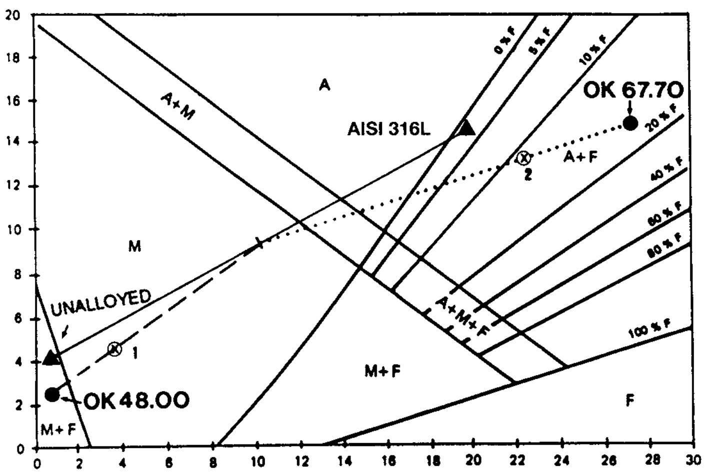
The probability that the above-mentioned factors will result in hydrogen-induced crack formation has, nonetheless large dependence on the structure of the weld metal, i.e. the choice of consumable.

During welding there occurs a dilution of the consumable by the melted unalloy or low alloyed base material. If an unalloyed, low alloyed or insufficiently alloyed stainless consumable has been used, a partly or wholly martensitic weld metal can therefore be formed (Fig 1, point 1). The weld can then be extremely hard and have a pronounced tendency to crack, especially if hydrogen is present (Fig 2).

The risk of hydrogen-induced cracks caused by the presence of martensite in the weld metal can be radically reduced by the use of a suitable consumable. If an over-alloyed stainless or Ni-based consumable is used, it is possible to compensate for the dilution by unalloyed or low alloyed base materials. (Fig 1, point 2). The formation of martensite is thus limited to a very narrow zone at the fusion line (Fig. 3) However, this zone is normally so small that it is of no significance when considering crack resistance.

The heat affected zone of the unalloyed or low alloyed basic material can contain varying amounts of martensite depending

Ni-equivalent = % Ni+30% C+0.5% Mn+30% N



Cr-equivalent = % Cr+1.5% Si+% Mo+0.5% Nb

A = Austenite, M = Martensite, F = Ferrite

Fig. 1. The Schaeffler-de-Long diagram. The definition of the composition of the weld metal when welding stainless steel to unalloyed steel. In the derivation of these compositions (point 1 and 2) has been assumed that the weld metal is diluted by equal amounts of each of the base materials. (AISI 316L and unalloyed steel) and that 70% of the weld metal is made up of the consumable. Point 1 illustrates the use of an unalloyed consumable (OK48.00) and point 2 illustrates the use of a suitable over-alloyed stainless consumable (OK 67.70).

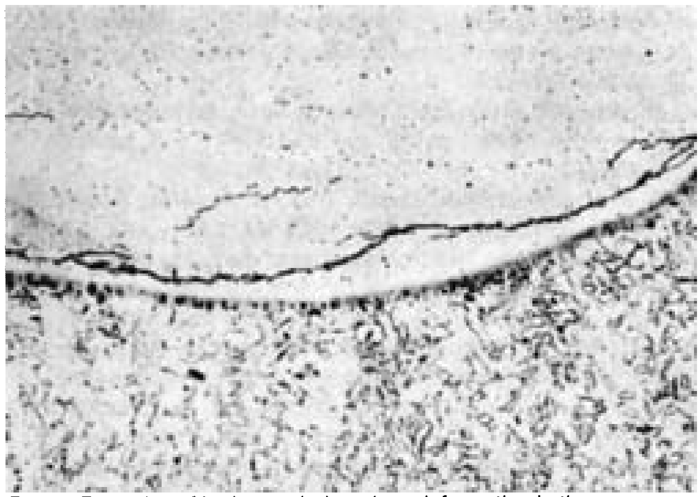


Fig. 2. Examples of hydrogen-induced crack formation in the martensite in the weld metal (above) between unalloyed steel (below) and stainless. Magnification 100x

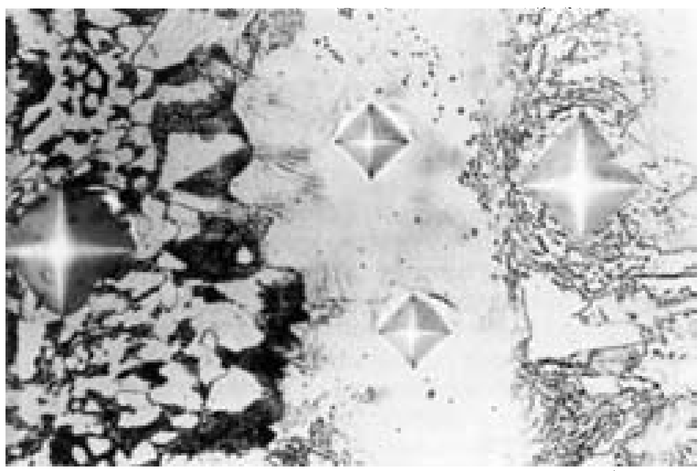


Fig. 3. Welding mild steel with a 308 L electrode. Note the hardness increase (smaller impression from measuring tool) close to the mild steel side.

on its chemical composition, the thickness of the base material, the welding parameters and so on. This zone normally presents no particular risks when it comes to cracking, provided that the above-mentioned risk of hydrogen contamination is taken into account. It the welding is performed using a suitable consumable the weld metal should in fact be wholly or partly austenitic (see Fig 1, point 2, for example). Austenite has a good hydrogen dissolving capacity. The hydrogen which is present in dissolved form in the HAZ (Heat Affected Zone) of the base material can therefore be absorbed by the austenite in the weld metal and rendered harmless.
Solidification cracks are caused by impurities, normally originating from the melted unalloyed or low alloyed base material, which concentrate between the crystals as the weld solidifies. These areas are thus weakened and crack easily due to stress build up which occurs in conjunction with cooling.
Austenite is normally more susceptible to solidification cracking than ferrite and this is why weld metals containing some ferrite are often preferred. It is, however, also possible to substantially increase the crack resistance of fully austenitic weld metals by increasing the Mn content. This has been done in consumables of the 18 Cr 8Ni 6Mn type (OK 67.45 and OK Autrod /Tigrod 16.95) and produces a highly crack-resistant weld metal.

1.2.2 Recommendations for welding stainless to unalloyed or low alloyed steel

- Use over-alloyed stainless or Ni-based consumables.
- Use dry electrodes and make sure that the groove surfaces are clean.
- Welding can usually be performed without preheating. Follow, however, the recommendations which apply to the particular steels in use.

For applications which do not require Ni-based consumables, stainless consumables of the type 23-25Cr 11-15Ni (with or without Mo). (OK 67.70, OK 67.75 and OK Autrod/Tigrod 16.53) are most commonly used. There is, however, a trend towards the increased use of the 18Cr 8Ni 6Mn type (OK 67.45 or OK Autrod/Tigrod 16.95). This type of consumable normally produces a fully austenitic weld metal of comparatively lower strength but with extremely good resistance to solidification cracking. This relatively soft weld metal reduces the stress on any martensite which may be present and thus reduces the risk of formation of hydrogen-induced cracks. Consumables of the 18Cr 8Ni 6Mn type can therefore be said in many ways to be a better choice generally than other types in those cases where somewhat lower strength can be accepted.
Finally, it should be noted that when a more difficulty welded stainless steel, particularly the martensitic, ferritic and high carbon content types, is used in the welded joint, the recommendations applying to the steel in question should also be taken into account when selecting the consumables.
However, the more common austenitic and also ferritic-austenitic steels generally cause no problems in conjunction with welding to unalloyed steel if the above guidelines are followed.

1.3 Cast iron to steel

The choice of both consumables and welding parameters are in this combination determined by the limited weldability of the cast iron. Only Ni-based filler metal can be used if any amount of strength is required from the weld metal. Weld processes that incur high heat inputs or large weld pools are unsuitable. Some cast irons, like carbide rich white irons, are not at all weldable, because of their cracking tendency. It is possible for many purposes to weld cast iron directly to steel, using a Ni-based filler metal designed for the welding of cast iron. However for critical welds ductility and strength may not be sufficient. In these cases buttering of the cast iron with a Ni-based filler metal must be performed prior to welding (see fig 4).

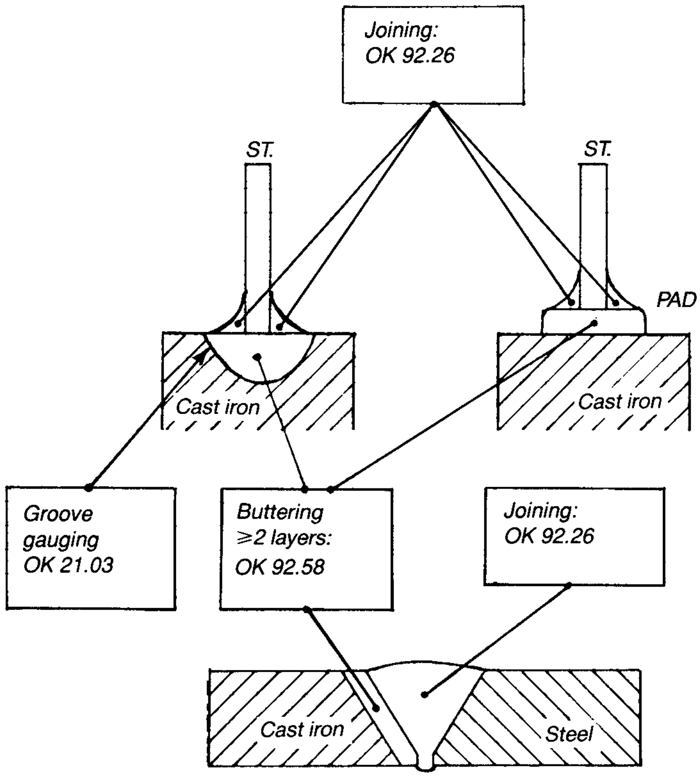


Fig. 4. Welding cast iron to steel.

Welding of cast iron can be performed without preheating, but a working temperature of about 300 °C is preferred when possible. Smaller workpieces are completely heated while larger workpieces are heated locally around the weld area.
Since cast iron shows a low ductility together with a low thermal expansion, it is essential to diminish the shrinkage stresses in the weld metal. This is best achieved by peening the weld metal with a rounded tool directly after welding. Also the use of thin electrodes and short stringer beads (3–5 cm) will work in the same way. During welding it is also essential to direct the arc towards the previous bead and not towards the base metal for the same reason.
In general these welds are made by the MMA process, but for larger series GMAW can also be used.

2. Hardenable steel to mild steel

Recommended consumables

MMA:	OK 48.XX, OK 53.18*, OK Femax 38.XX
SAW:	OK Autrod 12.10/OK Flux 10.61 or 10.62 OK Autrod 12.10/OK Flux 10.71
GMAW:	OK Autrod 12.51

* OK 53.18 is an extremely mild alloy (% C ≤0.03), which makes it especially useful as a bufferlayer on the more hardenable steel.

3. Low alloyed steel to mild steel

The welding parameters shall be chosen according to the low alloyed steel and the consumables according to the mild steel. The limited contribution of alloying elements coming from the low alloyed steel during welding, will generally not increase the hardenability of the weld metal in any substantial manner. Consequently, low alloyed consumables of a suitable composition can perfectly well be used for this combination. However, they will have no positive influence on the strength of the joint.

Recommended consumables

Carbon steel with C_E ≤0.4 to low alloyed steel:

MMA: OK 48.XX, OK 53.18*, OK Femax 38.XX

SAW: OK Autrod 12.10/OK Flux 10.61 or 10.62

GMAW: OK Autrod 12.51

Carbon steel with C_E ≥0.5 to low alloyed steel:

MMA: OK 48.08, OK 53.18*, OK 55.00

SAW: OK Autrod 12.22/OK Flux 10.71
OK Autrod 12.24/OK Flux 10.71

GMAW: OK Autrod 12.51

* OK 53.18 is an extremely mild electrode (% C ≤0.03), which makes it especially suitable for buffer layers on the low alloyed steel. It is recommended on low alloyed steel with high E_C.

4. Different low alloyed steels to each other

The term "low alloyed steel" is somewhat vague and includes numerous possible combinations. Some of these can be very difficult to weld, but if the steel on both sides of the weld is of the same main type, although with different C_E, welding is most often done without problems. Consumables of similar type to the steel should be used. If possible, the C_E of the consumable should be similar to the C_E of the less hardenable steel. The more hardenable the steel, the less suitable the use of any other welding method except MMA.
Table. 1.1, 1.2, 1.3 and 1.4 show the recommendations for such combinations where at least the main types of the low alloyed steels are known.
When the exact composition of the steels are known, there may be other more tailormade recommendations.
However, the recommendations will result in good sound welds, suitable for most situations.

The welding should be performed with limited heat input, since too high heat inputs may result in a too wide HAZ (Heat Affected Zone), thereby increasing the risk of cracking. Therefore avoid too slow a welding speed.
Very hardenable high strength CrNi (Mo)-steel, that requires high preheating, often together with stress annealing, may cause welding problems due to difficulties with the heat treatment. In these cases it is wiser to compromise and use an austenitic stainless steel electrode and a lower preheating level. Such electrodes are OK 67.70, OK Selectrode 68.81 or 68.82 for MMA and OK Autrod 16.75 or OK Autrod 16.95 for GMAW.

Table 1.1

Consumable (MMA):

		Cr Ni (Mo)-steel	Cr Mo (V)-steel	(Mn) Ni Mo-steel	≤3.5 % Ni-steel	Mn Mo-steel
Mn Mo-steel	I.	OK 74.78	OK 74.78	OK 74.78	OK 74.78	OK 74.78 (C_E≤0.4)
	II.	OK 78.12 (C_E~0.6)	OK 76.18 (C_E~0.5)	OK 73.46 (C_E~0.4)		
	III.		OK 78.16 (C_E~0.6)			
≤3.5 % Ni-steel	I.	OK 73.79	*	OK 73.79	OK 73.79 (C_E≤0.4)	
	II.	OK 73.68		OK 73.68	OK 73.68 (C_E~0.4)	
	III.	OK 78.12		OK 78.10		
(Mn) Ni Mo-steel		OK 73.46	OK 78.10	OK 73.46		
	II.	OK 78.12	OK 78.16			
Cr Mo (V)-steel	I.	OK 76.18	OK 76.18			
	II.	OK 78.12	OK 78.16			
Cr Ni (Mo)-steel	I.	OK 78.12				

* unusual combinations with little practical interest.

I. 1st hand choice
II. 2nd hand choice
III. 3rd hand choice

Table 1.2

Consumable (SAW):

		Cr Ni (Mo)-steel	Cr Mo (V)-steel	(Mn) Ni Mo-steel	≤3.5 % Ni-steel	Mn Mo-steel
Mn Mo-steel	I.	OK Autrod 12.24 OK Flux 10.71	OK Autrod 12.24 OK Flux 10.71	OK Autrod 12.24 OK Flux 10.71	OK Autrod 12.24 OK Flux 10.71	OK Autrod 12.24 OK Flux 10.71 ($C_E \leq 0.4$)
	II.	OK Autrod 13.41 OK Flux 10.62	OK Autrod 12.34 OK Flux 10.71	OK Autrod 13.41 OK Flux 10.62 ($C_E \sim 0.5$)	OK Autrod 13.27 OK Flux 10.62 ($C_E \leq 0.4$)	OK Autrod 12.34 OK Flux 10.71 ($C_E \sim 0.5$)
≤3.5 % Ni-steel	I.	OK Autrod 13.27 OK Flux 10.62	*	OK Autrod 13.27 OK Flux 10.62	OK Autrod 13.27 OK Flux 10.62	
	II.	OK Autrod 13.42 or 13.44 OK Flux 10.71 ($C_E \sim 0.6$)		OK Autrod 13.41 OK Flux 10.62		
	III.	OK Autrod 13.43 OK Flux 10.62 ($C_E \sim 0.7$)				
(Mn) Ni Mo-steel	I.	OK Autrod 13.41 OK Flux 10.62	OK Autrod 13.41 OK Flux 10.62	OK Autrod 13.30 OK Flux 10.71 OK Autrod 13.40 or 13.41 Flux 10.62 ($C_E \leq 0.5$)		
	II.	OK Autrod 13.42 OK Flux 10.71	OK Autrod 13.10 OK Flux 10.62 ($C_E \sim 0.5$)	OK Autrod 13.53 or 13.54 OK Flux 10.71 ($C_E \sim 0.5$)		
	III.	OK Autrod 13.43 OK Flux 10.62				
Cr Mo (V)-steel	I.	OK Autrod 13.41 OK Flux 10.62	OK Autrod 13.10 OK Flux 10.62			
	II.	OK Autrod 13.42 OK Flux 10.71				
	III.	OK Autrod 13.43 OK Flux 10.62				
Cr Ni (Mo)-steel	I.	OK Autrod 13.21 OK Flux 10.71 ($C_E \leq 0.6$)				
	II.	OK Autrod 13.44 OK Flux 10.71 ($C_E \sim 0.6$)				
	III.	OK Autrod 13.43 OK Flux 10.62				

* unusual combinations with little practical interest.

I. 1st hand choice
II. 2nd hand choice
III. 3rd hand choice

Table 1.3

Consumable (GTAW):

	Cr Ni (Mo)-steel	Cr Mo (V)-steel	(Mn) Ni Mo-steel	≤3.5 % Ni-steel	Mn Mo-steel
Mn Mo-steel	OK Tigrod 13.09	OK Tigrod 13.09	OK Tigrod 13.09	OK Tigrod 13.09	OK Tigrod 13.09 (C_E~0.4)
≤3,5 % Ni-steel	OK Tigrod 13.13	*	OK Tigrod 13.09		
(Mn) Ni Mo-steel	OK Tigrod 13.29 (C_E~0,5)	OK Tigrod 13.13 (C_E≤0,5)			
Cr Mo (V)-steel	OK Tigrod 13.29	OK Tigrod 13.12 (C_E~0,6)			
Cr NI (Mo)-steel	OK Tigrod 13.13				

Table 1.4

Consumable (GMAW):

	Cr Ni (Mo)-steel	Cr Mo (V)-steel	(Mn) Ni Mo-steel	≤3.5 % Ni-steel	Mn Mo-steel
Mn Mo-steel	OK Autrod 13.09 OK Tubrod 14.02	OK Autro 13.09 OK Tubrod 14.02	OK Autrod 13.09 OK Tubrod 14.02	OK Autrod 13.09 OK Tubrod 14.02	OK Autrod 13.09 (C_E~0.4) OK Tubrod 14.02 (C_E≤0,4)
≤3,5 % Ni-steel	OK Autrod 13.13 (C_E≤0,5)	*	OK Tubrod 14.04 (C_E≤0,4) OK Tubrod 15.25	OK Tubrod 14.04 OK Tubrod 15.25 (C_E~0,3)	
(Mn) Ni Mo-steel	OK Autrod 13.13	OK Autrod 13.29 (C_E~0,5)	OK Tubrod 14.03 (C_E~0,5)		
Cr Mo (V)-steel	OK Autrod 13.29 OK Autrod 13.13	OK Autrod 13.12 (C_E~0,6)			
Cr Ni (Mo)-steel	OK Autrod 13.29 OK Autrod 13.13				

* unusual combinations with little practical interest.

I. 1st hand choice
II. 2nd hand choice
III. 3rd hand choice

5. Tool steel, spring steel, etc. to mild or low alloyed steel

These steel can be very difficult to weld, since phase transformations during heating or cooling increase the risk of distortion, cracking etc. The welding may sometimes involve special treatments that are difficult and sometimes impossible to perform on dissimilar joints (e.g. step-welding). However, reasonably good welds can often be achieved with the following recommendations:

Recommended consumables:

MMA:	OK 68.81 or 68.82 OK 67.45
FCW:	OK Tubrodur 15.34
GTAW:	OK Tigrod 16.95
GMAW:	OK Autrod 16.75 OK Autrod 16.95

In some cases (e.g. manual welding of thinner work pieces, ($\leq$10 mm), the welding can be performed without preheating, but for most welds a preheating temperature of around 300°C should be maintained during welding. Weld with a low heat input to limit the HAZ (Heat Affected Zone) and small weld pools to limit the dilution of the weld metal.

6. Stainless steel to mild or low alloyed steel

(N.B. See 1.2)

Even though most mild or low alloyed steel can be welded to stainless steel without preheating, it is beneficial to preheat the non-stainless side to around 150°C. Close to the fusion line on the non-stainless side of the weld a small amount of martensite will always form. This may not always cause problems, but entrapment of hydrogen from the arc atmosphere can cause increased risk of cracking. The suggested preheating accelerates the migration of hydrogen out of the weld area, thereby decreasing any cracking tendency. Preheating is most beneficial when welding with rutile electrodes.

Recommended consumables, see table 2

One particular dissimilar joint between austenitic stainless steel and low alloyed CrMo-steel that often occurs, is the welding of superheaters for boilers. The stainless steel pipes in these constructions are sometimes welded to the CrMo-steel with stainless steel electrodes. The weak point in this combination is the border line between the weld metal and the low alloyed side. Carbon migrates from the low alloyed side of the stainless steel weld metal, where it accumulates in a carbon rich border zone. Sooner or later this leads to cracking of the joint (See fig 5).
If for the same joint, a Ni-base filler metal is chosen the weld remains unaffected even after several times the lifetime using stainless steel electrodes. Long term tests have resulted in over 10 000 hours of uninterrupted working time, using Ni-based consumables (See fig 6). It is worth mentioning that the joint was undamaged when the test was interrupted.
The recommended consumables for such joints are:

MMA:	OK 92.26
GMAW:	OK Autrod 19.85

Table 2

Stainless steel to mild steel and low alloyed steel respectively

		Austenitic	Ferritic	Ferrite-austenitic
MMA: Mild steel or low alloyed steel with $C_E \leq 0.4$	I.	OK 67.70/75	OK 67.75	OK 67.50/70 OK 68.81/82
	II.	OK 63.32	OK 67.70	
	III.	OK 67.62	OK 67.45	
	IV.	OK 67.45		
Mild steel or low alloyed steel with $C_E \geq 0.5$	I.	OK 67.75	OK 67.75	OK 67.50/70
	II.	OK 63.32	OK 67.70	OK 68.81/82
	III.	OK 67.45	OK 67.45	
SAW: Mild steel or low alloyed steel		OK Autrod 16.53/86 OK Flux 10.91/92	OK Autrod 16.53/86 OK Flux 10.91/92	OK Autrod 16.53 OK Flux 10.91/92
FCW: Mild steel or low alloyed steel		OK Tubrodur 15.34 OK Tubrod 14.32 OK Tubrod 14.33	OK Tubrodur 15.34 OK Tubrod 14.32 OK Tubrod 14.33	OK Tubrodur 15.34 OK Tubrod 14.32 OK Tubrod 14.33
GTAW: Mild steel or low alloyed steel	I.	OK Tigrod 16.53	OK Tigrod 16.53	OK Tigrod 16.53
	II.	OK Tigrod 16.95	OK Tigrod 16.95	OK Tigrod 16.95
GMAW: Mild steel or low alloyed steel	I.	OK Autrod 16.52	OK Autrod 16.52	OK Autrod 16.79
	II.	OK Autrod 16.95	OK Autrod 16.95	OK Autrod 16.95

I. 1st hand choice II. 2nd hand choice III. 3rd hand choice IV. 4th hand choice

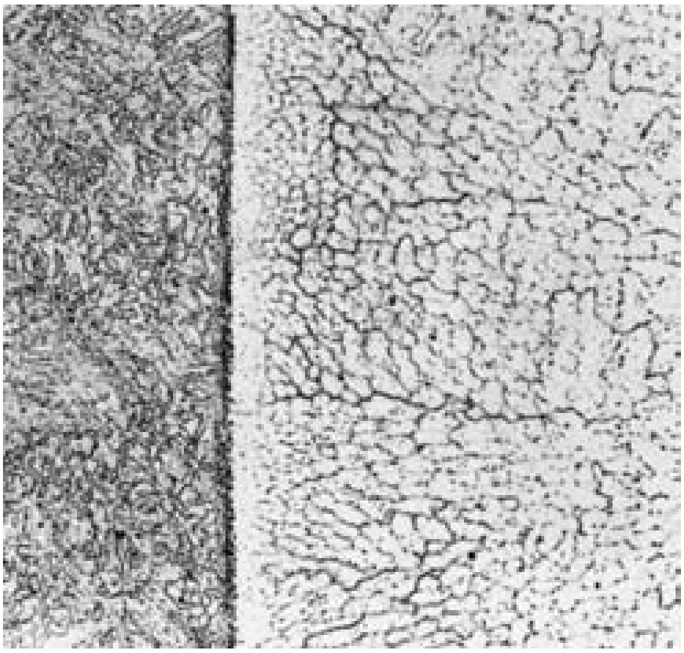


Fig. 5. Weld between 2.3 Cr 1 Mo low-alloy and 16 Cr 10 Ni Nb steels. Weld metal: 18 Cr 10 Ni Nb. Brittle carburized fusion zone boundary in the weld metal caused by carbon migration from 2.3 Cr 1 Mo material (after approx. 9 000 h at 500 to approx. 600°C). (100x).

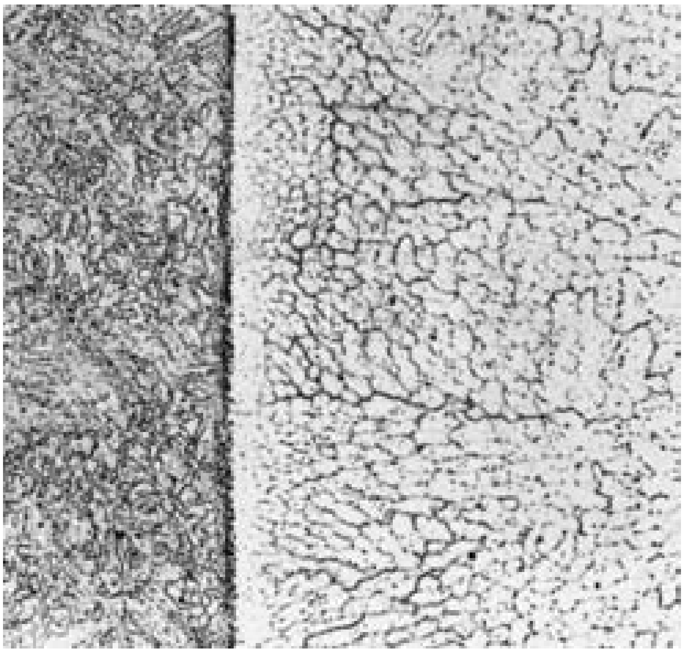


Fig. 6. Weld between 2.3 Cr 1 Mo and 16 Cr 13 Ni Nb steels. Weld metal Inconel. No carburization of weld metal fusion zone area (after approx. 9 000 h at 500 to approx. 600°C). (300x).

7. Stainless steel to tool steel, spring steel, etc.

Only non-hardenable welding consumables, not sensitive to dilution and with sufficient ductility can be used. This more or less rules out any other consumables other than austenitic stainless steel or Ni-based alloys.

Recommended consumables

	Stress annealing not performed:	*Stress annealing performed:*
MMA:	OK 68.81 OK 68.82 OK 67.75	OK 92.26 OK 67.45
FCW:	OK Tubrodur 15.34	OK Tubrodur 15.34
GTAW:	OK Tigrod 16.95	OK Tigrod 16.95
GMAW:	OK Autrod 16.75 OK Autrod 16.95	OK Autrod 19.85 OK Autrod 16.95

OK 68.81 and 68.82 and OK Autrod 16.75 are very tolerant towards dilution and are therefore superior to other consumables in the combination. However, they sensitive to cracking when heated to temperatures between 450 and 900°C due to the formation of sigma-phase. Therefore they should not be used if stressannealing is to be performed, or in thick multilayer welds. In these cases, it is better to use OK 92.26 or OK Autrod 19.85 if high strength is required or if the weld is exposed to fluctuating temperatures, and OK 67.45, OK Tubrodur 15.34 or OK Autrod 16.95 if not.

8. Dissimilar stainless steels to each other

This combination may occur in several constructions. Generally it is not too difficult to achieve sound welds.

However, some major aspects have to be considered:

- Consider the Schaeffler diagram in fig 1.
  The calculated weld metal composition must not fall into any of the areas containing martensite. If the weld metal falls into the fully austenitic area, special precautions against hot cracking have to be taken unless the weld metal is alloyed with more than 4 % manganese.
- When welding stabilized stainless steel (Alloyed with either Nb or Ti) to non-stabilized steel, the consumables should be either stabilized (Marked S in table 3) or low carbon grades (Marked L in table 3). Under no circumstances should non-stabilized high carbon grades be used!
- Welding should be performed with limited heat input.

Recommended consumables see table 3, page 10.

9. Steel with unknown or uncertain composition to other steel

This combination occurs for instance when an old steel construction is to be repaired or when the steel composition is impossible to analyse for economical or technical reasons.
Steels with unknown chemical composition should always be considered as difficult-to-weld steels, and treated as such.
For this reason the same consumables as for tool and spring steel should be chosen. The preferred weld method is manual metal arc welding (MMA).

Recommended consumables

MMA:	OK 68.81 or 68.82 OK 92.26 OK 67.45
FCW:	OK Tubrodur 15.34
GTAW:	OK Tigrod 19.85 OK Tigrod 16.95
GMAW:	OK Autrod 16.75 OK Autrod 19.85 OK Autrod 16.95

Avoid preheating of non-magnetic steel.
All other steels with uncertain chemical composition should be preheated to around 300°C!
Avoid large weld pools and keep dilution low (see chapter 7).

10. Cast iron to steel

Recommended consumables

	For buttering the cast iron side:	*For welding the steel side:*
MMA:	OK 92.60 OK 92.18 OK 92.78	OK 92.26 OK 92.60 OK 92.18
GMAW:		OK Autrod 19.85

See also chapter 1.3!

Table 3

Stainless steel

		Ferritic	Ferrite/austenitic
MMA: Austenitic stainless steel	I. II. III. IV.	OK 67.75/70^L OK 63.32	OK 63.30^L OK 63.41^L OK 63.32 OK 61.81^S/63.80^S
Ferritic stainless steel	I. II. III.		OK 67.70^L/75 OK 63.32 OK 68.81/82
SAW: Austenitic stainless steel	I.		OK Autrod 16.30^L OK Flux 10.91/92
	II.	OK Autrod 16.53^L OK Flux 10.91/10.92	OK Autrod 16.34^L OK Flux 10.91/92 OK Autrod 16.11^S/16.31^S OK Flux 10.91/10.92
Ferritic stainless steel			OK Autrod 16.53 OK Flux 10.91/10.92
GTAW: Austenitic stainless steel		OK Tigrod 16.53^L	OK Tigrod 16.30^L/16.34^L OK Tigrod 16.11^S/16.31^S
Ferritic stainless steel			OK Tigrod 16.53^L
GMAW: Austenitic stainless steel	I. II.	OK Autrod 16.52	OK Autrod 16.32^L OK Autrod 16.34^L OK Autrod 16.11^S
Ferritic stainless steel			OK Autrod 16.52

I. 1st hand choice
II. 2nd hand choice
III. 3rd hand choice
IV. 4th hand choice

L low carbon grades
S stabilized grades

11. Read this before welding Ni-based alloys!

Most Ni-based alloys are weldable, but consider the following:

- The term "Ni-based alloys" covers a wide range of materials with widely differing compositions and properties. It is therefore not possible to give an easy guide on how to weld these alloys and fully cover the issue. However, the following should be enough to avoid at least the most obvious mistakes.
- Pure nickel, Monels, Inconels and Hastelloys are generally quite weldable. Other alloys like Incoloy, Brightray, Nilo and especially Nimonic and Nimocast are so different within their group that mixed welds between these alloys cannot be easily described. Therefore, such welds should be designed in consultation with the material supplier. This is important also since some of the material trade names have been changed over the last decades, which may cause some confusion. Among these latter alloys there are some, especially the high strength ones, that have limited or no weldability. Guidelines on weldability for these alloys are given in the following.
  As a rule of thumb, the higher strength, the less weldability.

Recommended weld process for some common Nimonic alloys

Nimonic type	Typical tensile strength (MPa) (Solution treated/annealled or quenched/aged)	Weld process (To be preferred on homogenous welds)
75 PE 13 PE 16	≤850	Up to 12 mm thickness: MMA, GTAW, GMAW
86	≤870	GTAW, GMAW
80/A 90	≤900	≤~5 mm thickness* GTAW,GMAW
81	~900	≤~5 mm thickness*
101 105 120	≥1150	Not recommended

* Problems with HAZ-cracking when welding material above this thickness.

Mixed joints between most of the Nimonics should be considered as a temporary solution. In such temporary solutions OK 92.26 or OK Autrod 19.85 or OK Tigrod 19.85 may be used.

- Nickel weld metals are very sensitive to porosity during solidification. This sensitiveness decreases with increasing alloy content (Pure nickel is most sensitive). To avoid this, most Ni- or Ni-based electrodes contain some percentages of titanium.
- Some Ni-alloys, especially the Monels, are sensitive to solidification cracking when diluted with iron (see fig 7). This is effectively avoided by alloying with 4—5 % Mn. For this reason such electrodes should be used to weld dissimilar joints between Ni-based alloys and Fe-based alloys (see fig 8).
- Ni-alloys are especially sensitive to contamination from swarf, dirt, paint residuals, etc. It is therefore of the utmost importance to prepare a clean joint.
- Welding is normally done without preheating with direct current and with the electrode connected to the positive pole. (With GTAW the Tungsten-electrode should be connected to the negative pole). 10—20 seconds gas preflow and postflow should be applied in GMAW to avoid start and crater porosity. The welding should be performed with small weld pools and with low heat input.

Fig. 7. Cracks in weld metal at strongly Fe-alloyed locations in Monel weld metal with a 1.3 % Mn content. (100x)

- Shrinkage during solidification and cooling is greater with Ni-alloys than with steel. Therefore, narrow joints should be avoided and the weld surface profile should be kept convex instead of concave, to avoid cracking.
- When corrosion aspects are important, the choice of consumables should be discussed with the material supplier.

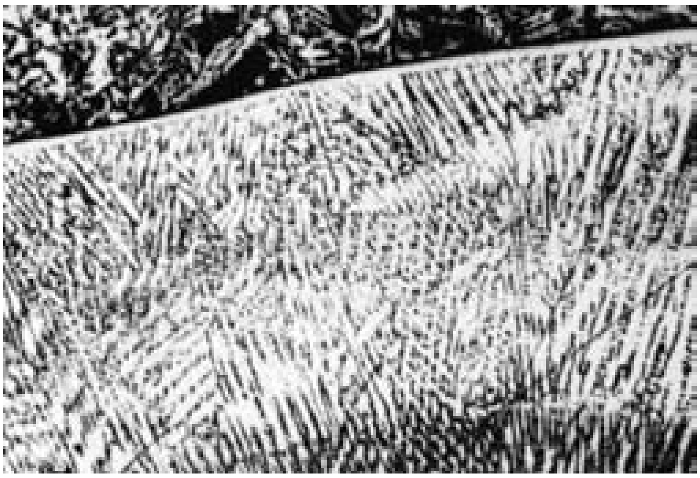


Fig. 8. Unalloyed sheet steel clad with ESAB OK 92.26. Fusion zone boundary is fault-free with no cracks. Mn content of weld metal is 5 %. (200x).

12. Pure Nickel to non-stainless steel

Welding can be performed with pure nickel electrodes or with Ni-based electrodes. The latter normally give less porosity. Dilution with some percentages of Fe is of no great importance.

Recommended consumables

MMA:	OK 92.26 OK 92.05
GTAW:	OK Tigrod 19.85
GMAW:	OK Autrod 19.85

13. Pure nickel to stainless steel

Both pure nickel and Ni-based electrode can be used to weld this combination.

Recommended consumables

MMA:	OK 92.26
GTAW:	OK Tigrod 19.85
GMAW:	OK Autrod 19.85

14. Pure nickel to cast iron

The welding conditions for this combination are similar to those described in chapter 1.3.

Recommended consumables

	For buttering of the cast iron side	*For joining to the pure Ni-side*
MMA:	OK 92.18 OK 92.78	OK 92.86

15. Monel to mild or low alloyed steel

Recommended consumables

MMA:	OK 92.86 OK 92.26
GTAW:	OK Tigrod 19.85
GMAW:	OK Autrod 19.85

Dilution with steel shall be kept as low as possible.

16. Monel to tool steel, spring steel and steel of unknown composition

The safest weld is achieved with weld metal of Inconel-type but in many cases Mn-alloyed electrodes of Monel-type are just as good.

Recommended consumables

MMA:	OK 92.26 OK 92.86
GTAW:	OK Tigrod 19.85
GMAW:	OK Autrod 19.85

Dilution with steel should be kept as low as possible.

17. Monel to stainless steel

Monel weld metal is sensitive to dilution with Fe, Cr, and some other elements and it is therefore safer to use electrodes of Inconel-type rather than of Monel-type.

Recommended consumables

MMA:	OK 92.26
GTAW:	OK Tigrod 19.85
GMAW:	OK Autrod 19.85

18. Monel to cast iron

This is a farely easy combination, since Monel-electrodes are well suited to weld cast iron. It is possible to achieve good sound welds using electrodes designed for welding of cast iron or Monel-electrodes in single-pass welds, but as described in chapter 1.3 the best result is achieved when a buttering technique is used.

Recommended consumables

	For buttering of the cast iron side:	*For joining to the Monel side:*
MMA:	OK 92.78 OK 92.18	OK 92.86

19. Monel to pure nickel

This is a rather uncomplicated combination. Both pure nickel electrodes and Monel types can be used. Monel types are mostly used.

Recommended consumables

MMA:	OK 92.86

20. Inconel-types to steel

Recommended consumables

MMA:	OK 92.26
SAW:	OK Autrod 19.85/OK Flux 10.16
GTAW:	OK Tigrod 19.85
GMAW:	OK Autrod 19.85

For welding of Inconel 625 to steel, either OK 92.45 (MMA) or OK Autrod 19.82 (GMAW) is recommended.

21. Inconel- or Nimonic-types to cast iron

This is an unusual and, at least for Nimonic-types, sometimes difficult combination. (See chapter 1.3 and 11). The cast iron side must be buttered with a suitable Ni-based electrode.

Recommended consumables

	For buttering of the cast iron side:	*For joining to of the Ni-based side:*
MMA:	OK 92.60 OK 92.18 OK 92.78	OK 92.26
GMAW:		OK Autrod 19.85

22. Inconel-types to pure nickel or Monel-types

Recommended consumables

MMA:	OK 92.26
GTAW:	OK Tigrod 19.85
GMAW	OK Autrod 19.85

23. Nimonic-types to steel, pure nickel, Monel-types and Inconel-types

Be sure to read chapter 11 before using the following instructions and remember the part about temporary solutions!

Recommended consumables

MMA:	OK 92.26
GTAW:	OK Tigrod 19.85
GMAW:	OK Autrod 19.85

24. Hastelloy-types to steel

Ni-based consumables are best suited, but some overalloyed stainless steel types can also be used.

Recommended consumables

Hastelloy B or C to steel:

MMA:	OK 92.35* OK 92.26 OK 68.82 OK 68.81
GTAW:	OK Tigrod 19.85
GMAW:	OK Autrod 19.85

* When welding Hastelloy to stainless steel, OK 92.26 is to be preferred

Welding should be performed with limited heat input. In particular, the Hastelloy side must be protected against overheating. Excess iron pick-up can be avoided by directing the arc slightly towards the Hastelloy side.

25. Hastelloy-types to cast iron

Welding of this combination has to be done with a buttering technique (See chapter 1.3). The buffer layer should be applied on the cast iron side.

Recommended consumables

	For buttering on the cast iron side:	*For joining to the Hastelloy side:*
MMA:	OK 92.18 OK 92.60	OK 92.35 OK 92.26
GMAW:		OK Autrod 19.85

26. Hastelloy-types to pure nickel and Ni-alloys

A weld metal of Hastelloy type is preferred provided it is not too much diluted by the non-Hastelloy side material. Also Inconel-types can be used.

Recommended consumables

For Hastelloy B or C:

MMA:	OK 92.35 OK 92.26
GTAW:	OK Tigrod 19.85
GMAW:	OK Autrod 19.85

When welding these types of mixed joints involving Hastelloy B, the dilution from this alloy shall be kept as low as possible.

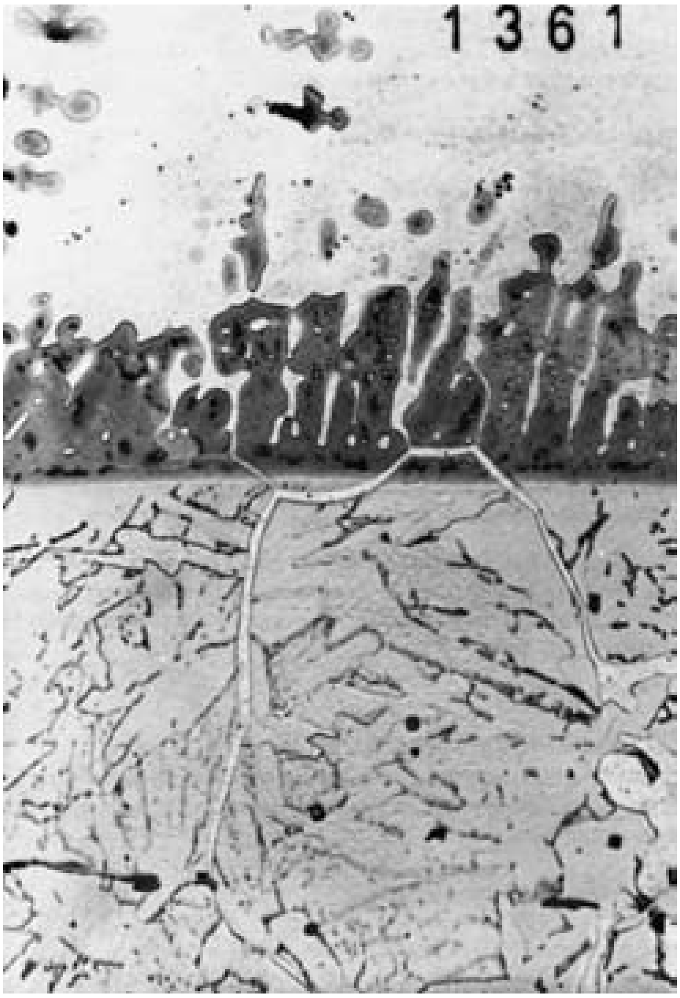


Fig. 9. Penetration of bronze melt into heat affected zone of the steel when welding with a bronze electrode. (800x).

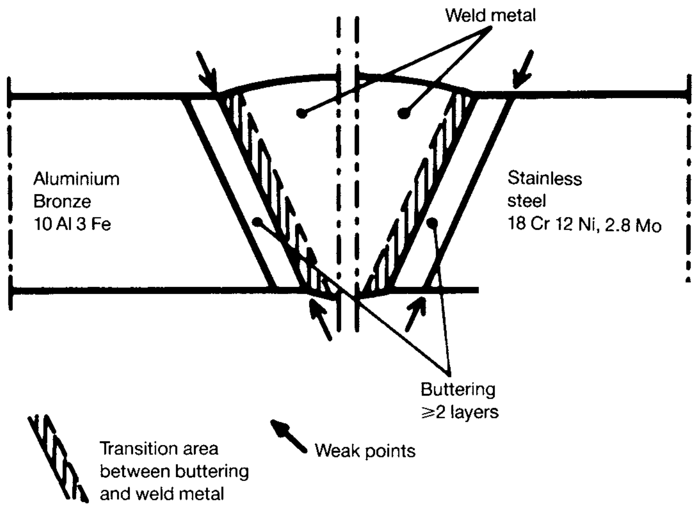
27. Read this before welding copper and its alloys to steel and Ni-based material

27.1 Pure copper and bronzes

Liquid copper and, to a somewhat smaller extent, bronze migrates into the HAZ (Heat Affected Zone) of the steel and precipitates in its grain boundaries. This phase has a melting point several hundred degrees lower than steel and its tensile strength is less than half that of steel. The penetration is fast and the penetration depth can be over 1 mm (See fig 9). This phenomenon is encouraged by tensile stresses, which are always present in welding. It can also occur in Ni-based alloys, except pure nickel and Monel-types. For this reason pure nickel or Monel can be used as a buffer layer to avoid this copper penetration.
This penetration of copper is not necessarily detrimental. It can be tolerated for instance in many surfacing applications. If however, the weld is exposed to heavy loads or particularly if it is exposed to high temperature where this grain boundary phase will cause brittleness, the copper penetration must be avoided. In multilayer welds, the repeated heat treatment caused by each weld run, accelerates the copper penetration, and cracks may occur along the fusion line. For this reason multilayer welds should be performed with a buffer layer of nickel or Monel. If pure nickel is chosen as a buffer layer, it should be placed on the copper or bronze side. Monel should be placed on the none-copper side. To minimize the detrimental effects of dilution by Fe and Cr, it is best to use Mn-alloyed Monel electrodes.
When welding the buttered joint it is essential that physical contact between the weld metal and the metal beneath the bufferlayer is avoided. This is the most important point to be made, since negligance in this respect will most certainly lead to cracking. (See fig 10: Weak points).

When buttering copper or bronze, a preheating temperature of 300—500°C should be applied. Thick workpieces are fully heated, while thinner ones only need to be heated around the starting area. Insufficient preheating may lead to disturbances in the energy balance of the arc and create an unstable arc with the possible consequences of lack of fusion, slag inclusions, etc.
When buttering the non-copper side, the preheating temperature should be chosen according to the rules valid for this material.
When welding joints buttered on the non-copper side using Cu-based electrodes, the copper side should be preheated to 150—200°C (Al-bronzes and Sn-bronzes) and ≤100 C (Si-bronzes) respectively. Joints buttered on the copper side need not to be preheated on this side, since the insulating Ni-layer effectively lowers the heat sink caused by the high thermal conductivity of copper.
Bronzes loose much of their strength and ductility in the temperature range 400—500°C. It is therefore of great importance to avoid restrained conditions or tensile stresses caused by the mass of the bronze part itself.
When welding bronzes, especially when using bronze-electrodes, it is important to avoid too slow welding speeds, thereby avoiding too long a heating time within the critical area. This is most important for Si-bronzes where a welding speed below ~20 cm/min (MMA) may cause cracking.
When using Al-bronze electrodes to weld steel, it is important to adjust the welding parameters so that sufficient base material is melted and lack of fusion is avoided. This will be achieved by slightly lowering the welding speed.

Welded joint
between aluminium bronze and stainless steel



	Buttering		Weld Metal	Changes in the transition area	Crack proofness
	Bronze	Steel			
	Side				
1.	Ni	—	Stainless 28 Cr 12 Ni 2.8 Mo	Ni<	Bad
	Ni	—	Ni-base 15 Cr 10 Fe 2 Nb	Ni<	Good
2.	—	Ni	Aluminium Bronze 19 Al 3 Fe	Cu>	Bad
	—	Ni +1 layer Cu		—	Fair

Fig. 10

27.2 Brasses

Electric arc welding of these Cu-Zn-alloys is not possible since Zn evaporates heavily. The concentrated heat involved in this weld process will cause excessive overheating of the weld pool which in turn will cause the partial pressure of Zn to rise over 1 atm. (See fig 11). This evaporation may cause such a porosity that no strength will be left in the weld and it is also dangerous to the welder. Therefore only oxy-acetylene welding is recommended for the welding of brasses.
There are some exceptions. The most common one is the welding of Al-brasses, which can be welded with the GTAW-process using a Cu-7 % Al filler metal provided a correct gas protection is maintained during the whole process and that both joint and filler metal surfaces are thoroughly cleaned prior to welding. (See also chapter 31 and 36).

27.3 Coppernickels

The most common types are those with 10, 20 or 30 % Ni and a balance of Cu. They are mostly used in heat exchangers, condensers and pipings for seawater. The single most common type is the one with 30 % Ni.
They show brittleness if the iron content rises above 10—12 %, so dilution with iron must therefore be kept on a lower level.
The structural similarity between coppernickels and Monels makes Monel electrodes suitable for many combinations involving coppernickels. For the welding of coppernickel to itself or other coppernickels, the most used consumable is the one with 30 % Ni.
Welding is done without preheating, with direct current and the electrode connected to the positive pole (GTAW Negative!).
The coppernickels are just as sensitive to contamination as the Ni-based alloys (See chapter 11). It is therefore very important to ensure clean joint surfaces before welding.

27.4 Welder skill—An important issue when welding dissimilar joints between copperbased alloys and other alloys

When welding these materials, especially on a larger production scale, only qualified welders should be used. If such welders are not available, be sure to train new ones, or otherwise to subcontract a qualified welding workshop.

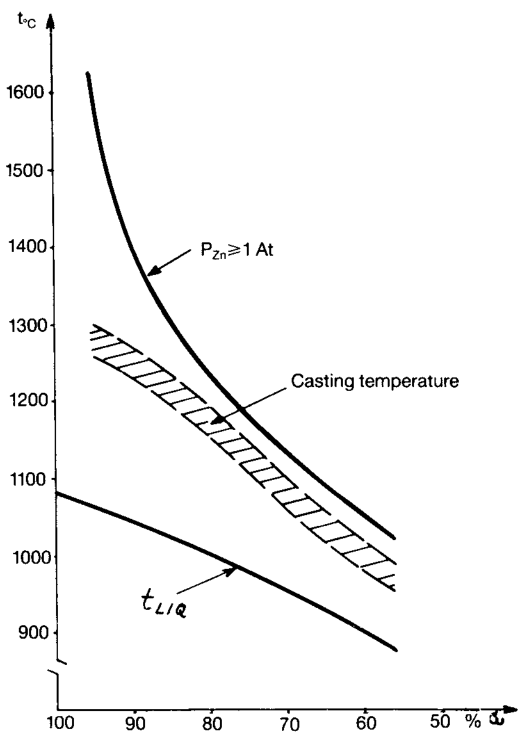


Fig. 11. Influence of temperature on partial pressure of zinc in Cu–Zn alloys.

28. Pure copper to steel.

(See also chapter 27.1)

A buttering technique must be used. The buttering can be done either on the copper side or on the steel side. In both cases a pure nickel electrode should be used. For the final welding of the joint, use electrodes of Inconel-type or bronze-type depending on which side the buttering layer is applied.

Recommended consumable

For buttering:

MMA: OK 92.05

For welding on the copper side:

MMA: OK 94.55
OK 94.25

GMAW: OK Autrod 19.40

For welding on the steel side:

MMA: OK 92.26

GTAW: OK Tigrod 19.85

GMAW: OK Autrod 19.85

29. Pure copper to cast iron

In this very unusual combination, the fairly high contents of sulphur and phosphorus in the cast iron, can (aside from other problems, see chapter 1) cause problems if they come into contact with the copper. For this reason, buttering if the cast iron side is strongly recommended.

Recommended consumables

	For buttering on the cast iron side:	*For joining to the copper side:*
MMA:	OK 92.60	OK 94.55
GTAW:		OK Tigrod 19.40
GMAW:		OK Autrod 19.40

30. Pure copper to nickel and its alloys

Insufficient information is available on the sensitivity of nickel alloys to copper penetration in the grain boundaries. However, most Ni-based alloys show a sensitivity and there has even been suggested some sensitivity regarding Monel when the temperature- and stress-conditions have proved especially unfavourable. In this specific case it is probably hotcracks, refilled with copper, more or less as in eutectic healing. Nevertheless the lower strength of the copperphase lowers the strength of the whole joint.
To avoid all problems of this kind, use the buttering technique. The buttering layer should be applied on the copper side. Final welding should then be performed with an electrode suitable to the opposite material.

Recommended consumables

For buttering of the copper side:

MMA: OK 92.05
Alt. (except joints with Hastelloy on the opposite side):
1st layer: OK 92.05
Subsequent layers: OK 92.86

For joining with pure nickel:

MMA: OK 92.05
OK 92.86

GTAW: OK Tigrod 19.85

GMAW: OK Autrod 19.85

For joining with Monel:

MMA: OK 92.86

For joining with Inconel or Nimonic:

MMA: OK 92.26

GTAW: OK Tigrod 19.85

GMAW: OK Autrod 19.85

For joining with Hastelloy B or C:

MMA: OK 92.26
OK 92.45

GTAW: OK Tigrod 19.85

GMAW: OK Autrod 19.85
OK Autrod 19.82

31. Brasses to Fe- and Ni-based alloys, pure copper or coppernickel

In view of the comments in chapter 27.2, electric arc welding is not recommended for these combinations. However, as a temporary solution Al-bronze electrodes or Si-bronze electrodes may be used. Still, even with the greatest precautions during welding, brittle structures may form in the weld metal. Apart from this there is the previous mentioned problem with porosity and the hazard to the welder.
It is therefore better to use oxy-acetylene welding or brazing.

32. Sn-bronze to steel

When welding Sn-bronze directly to steel in butt welds or fillet welds, there is a risk for lack of fusion. Aside from copper penetration (see chapter 27.1), this will reduce the strength of the joint. This is avoided if the steel side is buttered with a bronze-layer and then welded to the bronze side with the same electrode. If copper penetration cannot be allowed, the bronze side has to be buttered with a nickel electrode.

Recommended consumables

For buttering of the steel side with subsequent joinin g to the bronze side:

MMA: OK 94.25

For buttering of the bronze side: * **

MMA: OK 92.05

For joining to the steel side: *

MMA: OK 92.26

GMAW: OK Autrod 19.85

* To be preferred if the steel side is stainless steel!

** Buttering with some other Ni-base electrode, like Monel or those designed for welding of cast iron, will substantially increase the risk of cracking.

A joint angle of 90 degrees is recommended, since narrow joints may cause lack of fusion, due to the high thermal conductivity of bronzes.

33. Bronze to cast iron

Even if for instance Sn-bronze sometimes is used for repairs in cast iron, it is not recommended to weld bronze directly to cast iron with a bronze electrode. The safest way to weld is to butter both sides and then weld them together.

Recommended consumables

For buttering of the cast iron side:

MMA: OK 92.18
OK 92.78
OK 92.60

For buttering of the bronze side:

MMA: OK 92.05

For joining:

MMA: OK 92.86

As in chapter 32 a joint angle of 90 degrees is recommended.

34. Bronze to nickel and its alloys

This combination is best welded with the buttering technique. Nickel electrodes shall be used for buttering on the bronze side. It may be difficult to weld thicker layers with nickel electrodes, so therefore only the first buttering layer should be welded with nickel electrodes and subsequent layers with Monel electrodes. To use only Monel types in the buttering layer may lead to cracking.

Recommended consumables

For buttering of the bronze side:

MMA: OK 92.05

Alt. (exc. joints with Hastelloy on the opposite side):

MMA: 1st layer: OK 92.05
Subsequent layers: OK 92.86

For joining to pure Ni or Monel:

MMA: OK 92.86
OK 92.26

For joining to Inconel or Nimonic:

MMA: OK 92.26

GTAW: OK Tigrod 19.85

GMAW: OK Autrod 19.85

For joining to Hastelloy B or C:

MMA: OK 92.26
OK 92.45

GTAW: OK Tigrod 19.85
OK Tigrod 19.82

GMAW: OK Autrod 19.85
OK Autrod 19.82

35. Bronze to pure copper

In this combination it is important that the alloy content of the weld metal is not too diluted by the liquid copper during welding. (The risk of cracking increases with decreasing alloy content). Sn-bronze, Si-bronze and especially Al-bronze electrodes are satisfactorily safe in this respect.

Recommended consumables

For Sn-bronze to copper: Satisfactorily

MMA: OK 94.25
OK 94.55

For Al-bronze to copper:

MMA: OK 94.55

GTAW: OK Tigrod 19.40

GMAW: OK Autrod 19.40

For Si-bronze to copper:

MMA: OK 94.55
OK 94.65

GTAW: OK Tigrod 19.30

GMAW: OK Autrod 19.30

36. Bronze to Brass

Oxy-acetylene welding is the preferred welding process for this combination. However, with careful welding (minimal heat inputs, avoiding local heat concentrations, etc.), it is possible to get acceptable welds for most situations. At least, it is far better than welds made in pure brass joints.

Recommended consumables

MMA: OK 94.55

GTAW: OK Tigrod 19.40

GMAW: OK Autrod 19.40

Sn-bronze electrodes may also be used, but they are more sensitive to dilution with brass.
Still, it is not possible to guarantee entirely good results in this combination, especially if the brass is red brass, which is very unsuitable for electric arc welding.

37. Al-bronze or Si-bronze to steel

In constructions exposed only to low stress static loads and not too high temperatures, bronze electrodes can be used. The steel side shall then be buttered with a bronze layer and then welded to the bronze side, normally with the same electrode. Otherwise an insulating nickel layer has to be applied on the bronze side.

Recommended consumables

For welding without Ni on Al-bronze:

MMA: OK 94.55

GTAW: OK Tigrod 19.40

GMAW: OK Autrod 19.40

For welding without Ni on Si-bronze:

MMA: OK 94.55

GMAW: OK Autrod 19.40

For buttering on the bronze side:

MMA: OK 92.05

Alt. buttering technique on the bronze side:

MMA: 1st layer: OK 92.05
Subsequent layers: OK 92.86

For joining the buttered steel side to Al- or Si-bronze:

MMA: OK 92.86
OK 92.26

GTAW: OK Tigrod 19.85

GMAW: OK Autrod 19.85

38. Al-bronze or Si-bronze to Sn-bronze

Most bronze electrodes are good for welding this combination. Al-bronze consumables show the best tolerance to dilution while Sn-bronze is the most sensitive in this respect.

Recommended consumables

MMA: OK 94.55
OK 94.25

GTAW: OK Tigrod 19.40

GMAW: OK Autrod 19.40

39. Coppernickel to steel

For this combination CuNi-electrodes of 70/30-type is preferred. Monel-types may also be used.
For the welding of coppernickel to stainless steel, a buttering technique or the use of inserts (an intermediate piece of ferritic steel or Monel), with subsequent bilateral joining, must be performed. The consumable choice for welding with inserts is given in chapter 6, 15 and 41. The joint between coppernickel and steel inserts can be welded with CuNi- or Monel-electrodes.

Recommended consumables

For buttering the coppernickel side:

MMA: OK 92.86
OK 92.05

For joining to the stainless steel side:

MMA: OK 92.26

GMAW: OK Autrod 19.85

For welding coppernickel tubes to tube plate:

MMA: Inner area of tube end in connection with tube end:*

Other areas: OK 92.86

For welding coppernickel to mild steel:

MMA: OK 92.86

GMAW: OK Autrod 19.40

* GTAW with OK Tigrod 19.40 can be used.

Excess iron pickup from the steel side must be avoided. When welding coppernickel tubes to tube plate, the preferred weld process shall be GTAW. This can often be done without adding any filler metal, by melting part of the tube.

40. Coppernickel to cast iron

This is an unusual combination, that requires the use of a buttering technique.

Recommended consumables

For buttering on the cast iron side: (See chapter 1.3)

MMA: OK 92.78
OK 92.18

For joining to the coppernickel side:

MMA: OK 92.86

41. Coppernickel to pure nickel or monel

Recommended consumables

MMA: OK 92.86

42. Coppernickel to Inconel or Nimonic

Consumables of Monel-type may be used to weld this joint directly, but the safest welding is done buttering the coppernickel side with Monel and then welding it to the other side with inconel-types. This is to avoid mixing too much Cr and Fe with the Monel weld metal, which may cause cracking.

Recommended consumables

For buttering of the coppernickel side:

MMA: OK 92.86

For joining to the Ni-alloyed side:

MMA: OK 92.26

GTAW: OK Tigrod 19.85

GMAW: OK Autrod 19.85

43. Coppernickel to Hastelloy B or C

The welding difficulties are the same as described in chapter 42.

Recommended consumables

For buttering of the coppernickel side:

MMA: OK 92.86

For joining to the Ni-alloyed side:

MMA: OK 92.26
OK 92.45

GTAW: OK Tigrod 19.85

GMAW: OK Autrod 19.85

44. Coppernickel to pure copper

The best welds are made with consumables of Cu-30 % Ni-type. However, fairly safe welds can also be made with Sn-bronze electrodes.

Recommended consumables

MMA: OK 94.25

45. Coppernickel to Sn-bronze

This weld can be performed with Sn-bronze electrodes.

Recommended consumables

MMA: OK 94.25

46. Coppernickel to Al-bronze or Si-bronze

This combination may occur for instance in ship building and can be successfully welded by the buttering technique. The coppernickel side shall first be buttered with Sn-bronze and then welded to the bronze side with either Al- or Si-bronze electrodes.

Recommended consumables

For buttering of the coppernickel side:		*For joining to the bronze side:*
MMA:	OK 94.25	OK 94.65 OK 94.55
GTAW:		OK Tigrod 19.40
GMAW:		OK Autrod 19.40

47. Read this before welding aluminium and its alloys

Most aluminium alloys are well suited for electric arc welding. The following aspects however, have to be considered before welding:

- Hydrogen is the single most detrimental element to aluminium welds. Even very small concentrations will cause porosity in the solidifying weld metal (fig 12). It is not possible to dry stick electrodes down to a coating moisture level where no porosity occurs during welding without cracking the coating. These electrodes provide therefore a weld metal with finely dispersed porosity. This is normally not detrimental to mechanical properties like strength and ductility, but has to be considered when leak tight welds are required. Such welds should therefore be made with the GTAW or GMAW process.
- Beside hydrogen, organic substances may also cause porosity and therefore the joint area must be thoroughly cleaned before welding.
- Some Al-alloys cannot be mixed with each other without cracking. It is therefore of great importance to follow the consumable recommendations given in chapter 50 to avoid this problem.
- MMA and GMAW are most often done on DC with the electrode connected to the positive pole. GTAW is normally performed on AC. When using the GTAW and GMAW process the gas must be allowed to flow some seconds before and after welding to avoid porosity.
- Thinner workpieces may be welded without preheating. When welding thicknesses above 6 mm, or castings, a preheating temperature of around 200°C should be applied.

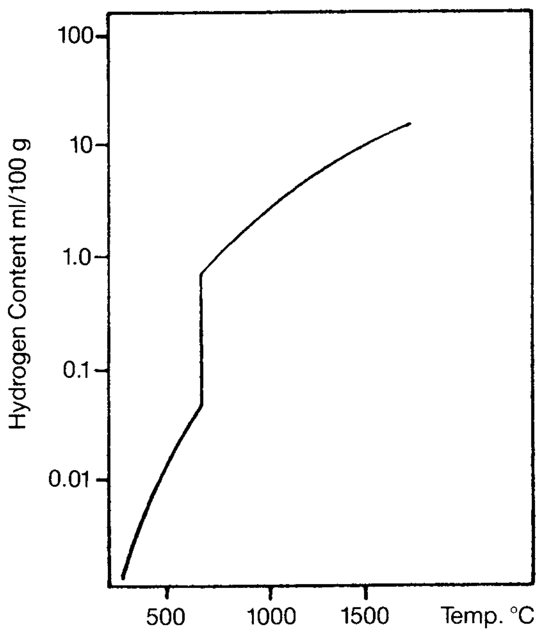


Fig. 12. Equilibrium solubility of hydrogen in aluminium. Note that liquid aluminium dissolves almost 1 ml/100 g, while solid aluminium dissolves less than 0.1 ml/100 g. Corresponding values for steel are 30 and 10 ml/ 100 g respectively.

48. Aluminium and its alloys to Fe- and Ni-based alloys

A direct joint between these materials with electric arc welding cannot be achieved with acceptable result. The main reasons for this are:

- The differences in melting points are too great (>800°C). The consequence of this is aggravated by the differences in specific heat, heat of fusion, thermal conductivity, etc.
- The wettability of aluminium on iron is poor.
- Dissolved iron in aluminium may cause embrittlement by the formation of a brittle $FeAl_3$-phase. Also AlNi-alloys shows some intermetallic phases with less suitable properties.

Dissimilar joints between these alloys are therefore usually welded with an intermediate piece of bimetal or even trimetal, so called "inserts", placed between the aluminium and the Ni- or Fe-based alloy. These inserts are generally produced by explosion welding. To avoid melting through the insert when welding on the Fe/Ni side, the insert must be thick enough. The greater the differences in melting points, the thicker the insert.
The welding is then performed with consumables suited for the chosen material combination (See appropriate chapter in this book!). The mechanical properties of the joint will be comparable to those for the aluminium side.
Good results have been reported using the GTAW process to butter the steel side with Al-bronze (OK Tigrod 19.40) and then weld it to the aluminium side using the MMA method and OK 96.50 (Al-12 % Si).
Electro plating can also be used to give a coating of Ni, Zn or Cu on the steel side (about 50 microns), but this is less safe due to the vulnerability of the coating.

49. Aluminium and its alloys to copper and its alloys

Alloys between copper and aluminium show some very brittle intermetallic phases ($CuAl_2$, CuAl, Cu3Al_2), which makes welds between these alloy very difficult to produce.
However, both the SAW and GTAW processes have been used to produce large electrical contact pieces.
The SAW process has been used for thicknesses between 12 and 20 mm. A cryolite rich flux was used together with Al-wire. The longitudinal axis of the wire was displaced towards the copper side by about 0.5 times the thickness of the copper plate.
The GTAW process was used for thinner workpieces in a tulip formed joint, using aluminium rods. The rods were fed so that a minimum of dilution from the copper side was achieved.
Electroplating of the copper side (about 50 microns) with Ag, Sn, Zn and especially Ni provides improved wettability on this side and will therefore improve the total result of the welding operation.
The safest weld though, especially when welding aluminium to bronze is to use inserts as described in chapter 48.

50. Dissimilar aluminium alloys to each other

Generally, aluminium and its alloys are not particularly difficult to weld. However, the numerous alloy-types calls for observance to the following aspects.
Some alloys, especially some of the wrought ones, can develope crack sensitive microstructures when welded. The mixed weld metal may also gain a crack sensitive composition. To avoid unnecessary risks in this respect, the most likely chemical composition of the weld metal should be calculated (This is one of the aspects taken into account in the consumable recommendations given later in this chapter!). Such calculations may be based on the following:

Weld Method	Shielding gas	Type of joint	Approx. amount of melted filler metal in the mixed weld metal (%) *
MMA:	None	Horizontal fillet	75
		Butt joint	70
		Square butt joint	65
GMAW:	Ar	Horizontal fillet	70
	75 % He+ 25 % Ar	Horizontal fillet	50
	Ar	Butt joint	60
	75 % He+ 25 % Ar	Butt joint	45
	Ar	Square butt joint	50
	75 % He+ 25 % Ar	Square butt joint	40

* Values for the GTAW process can be considered between those for MMA and GMAW.

The risk of cracking can be judged according to the following:

Alloying component	Definite risk (%)	Medium risk (%)	Low risk (%)
Mg	–	1.5–3.5	<1.5 or >3.5
Si*	0.7–4.4	0.5–0.6 or 4.5–5.0	<0.5 or >5.0
Cu	0.7–4.3	0.4–0.6 or 4.4–5.0	<0.4 or >5.0
Zn	>6.0	4.5–6.0	<<4.5

AlMgZn-alloys with Zn <3 % and Mg/Zn >1.5 show a low risk of cracking.

* In non-binary alloys, the influence of small percentages of Silicon is negligible.

When welding combinations not yet tested, it is recommended to examine their properties in a pretest before the actual welding. Table 4.1, 4,2 and 4,3. Consumable recommendations for the welding of similar and dissimilar Al-alloys to each other.

51. Magnesium and its alloys to each other or to other metals

Liquid magnesium ignites easily in air contact. It also dissolves hydrogen and above all nitrogen. Nitrides are detrimental to the mechanical properties of the weld metal. For this reason , welding is always performed in an inert gas atmosphere, usually with the GTAW process. Consumables are normally of a matching composition to the base material. Therefore strips from the actual plate to be welded can often be used.
Welds properly performed will at ambient temperature retain at least 55 % (predominantly over 70 %) of the mechanical properties possessed by the base material. The elongation will be between 20 to 65 % for wrought alloys and 30 to 125 % for castings, depending on the chosen consumable/base material combination.
Avoid too low amperages, since this will cause porosity. Castings are, with a few exceptions, welded with a preheating temperature of about 250–300°C.
GTAW is performed using DC with the electrode either on negative or positive polarity. When using DC positive, the diameter of the tungsten electrode should be increased to avoid overheating of the electrode. This will result in larger weld pools and a wider HAZ (Heat Affected Zone).
Most Mg-alloys are welded without post weld heat treatment. However, for alloys with more than 1 % Al, stress annealing is recommended. For castings this is performed for 1 hour at 500°C and for wrought alloys 1 hour at 200–250°C or 15 min at 300°C.
Electric arc welding of Mg-alloys to other metals is very unusual. It is also difficult to achieve sound welds because excessive alloying with Mg will cause cracking in most alloys. Since it is more or less impossible to avoid at least 10 % Mg in the mixed weld metal in direct joining, the welding of these combinations must be performed with inserts (see chapter 48).

52. Titanium and its alloys

Liquid titanium dissolves gases from the atmosphere. In particular oxygen and nitrogen are detrimental to the ductility. MMA welding is therefore not used for titanium, since the arc atmosphere will not protect the weld pool from such gases. Any reports on "safe" MMA-consumables should be regarded as nonsens and treated as such.
Acceptable results are achieved only in an inert gas atmosphere, using either the GTAW or GMAW process. Even welding with these processes requires special equipment like torches with auxiliary gas flow, inert root protection, etc. It is extremely important to apply a correct gas protection and to thoroughly clean the joint area.
There are three main types of Ti-alloys: α-, β- and ($\alpha+\beta$)-alloys. α-alloys can be welded to other α-alloys and β-alloys to other β-alloys. ($\alpha+\beta$)-alloys should be considered not weldable and consequently, joints between α- and β-alloys should be avoided.
The welding of titanium requires skilled and experienced welders. The necessity of cleanliness often requires specially designed premises. Inexperienced workshops should therefore perform the welding of titanium in close cooperation with a specialized workshop.

53. Titanium and its alloys to other metals

Sound welds can be made by the use of inserts (See chapter 48). Welding without inserts is very unusual. Successful welds have been reported between Ti- and Al-alloys. The plates were welded in an overlap joint with the titanium as the upper plate and aluminum as the under plate. Welding parameters were set so that the under part of the titanium plate (about 0.3–0.4 mm) remained solid and the upper part of the aluminum plate was melted. It is easy to see the difficulties in performing such welds, with the risk of burn through of the titanium plate.

Table 4.1 OK electrodes for welding of wrought aluminium alloys

		Al Cu Mg[3]	Al Zn Mg	Al Si 5	Al Mg Si (Mn, Cu)	Al Mg 3 (Mn) Al Mg 4~5 (Mn)	Al≤2 Mg (Mn)	Al Mn (Mg)	Al
Al	I.	T/A 18.05[2]			T/A 18.04	T/A 18.04[1]	T/A 18.11	T/A 18.11	T/A 18.11
	II.	S 96.50[2]	T/A 18.04	T/A 18.04	T/A 18.15/16	T/A 18.15/16	T/A 18.04	T/A 18.01	T/A 18.01
	III.	T/A 18.15/16					T/A 18.15	S 96.10/20	S 96.10/20
	IV.						T/A 18.01	T/A 18.04	T/A 18.04
Al Mn (Mg)	I.	T/A 18.05[2]	T/A 18.15/16		T/A 18.15/16	T/A 18.15/16	T/A 18.04	T/A 18.04	
	II.	S 96.50[2]	T/A 18.04	T/A 18.04	T/A 18.04	T/A 18.04	T/A 18.11	T/A 18.11	
	III.	T/A 18.15/16				T/A 18.13	T/A 18.15/16	T/A 18.15/16	
	IV.						T/A 18.01	T/A 18.01	
Al≤2 Mg (Mn)	I.	T/A 18.05[2]	T/A 18.15/16	T/A 18.04	T/A 18.04	T/A 18.15/16	T/A 18.15/16		
	II.	S 96.50[2]	T/A 18.04	T/A 18.15/16	T/A 18.15/16	T/A 18.04[1]	T/A 18.04[1]		
	III.	T/A 18.15/16			T/A 18.13	T/A 18.13	T/A 18.13		
	IV.						T/A 18.01		
Al Mg 3 (Mn) Al Mg 4~5 (Mn)	I.	T/A 18.15/16	T/A 18.15/16	T/A 18.15/16	T/A 18.15/16	T/A 18.15/16			
	II.			T/A 18.04	T/A 18.04	T/A 18.13			
	III.				T/A 18.13				
Al Mg Si (Mn, Cu)	I.	T/A 18.05[2]	T/A 18.04		T/A 18.04				
	II.	S 96.50[2]	T/A 18.15/16	T/A 18.04	T/A 18.15/16				
	III.	T/A 18.15/16	T/A 18.13		T/A 18.13				
Al Si 5	I.	T/A 18.05[2]	T/A 18.15/16						
	II.	S 96.50[2]	T/A 18.04[1]	T/A 18.04					
Al Zn Mg	I.	T/A 18.05[2]	T/A 18.15/16						
	II.	S 96.50[2]	T/A 18.04						
Al Cu Mg[3]	I.	T/A 18.05[2]							
	II.	S 96.50[2]							
	III.	T/A 18.15/16							

[1] Less suitable with respect to corrosion properties or where colourmatch is requiered (eg after anodizing).
[2] The weld metal will have a microstructure similar to castings.
[3] These alloys are generally difficult to weld.

OK Autrod/Tigrod 18.05 is not included in the ESAB standard range.

A: OK Autrod XX.XX (GMAW)
S: OK XX.XX (MMA)
T: OK Tigrod XX.XX (GTAW)

I. 1st hand choice
II. 2nd hand choice
III. 3rd hand choice
IV. 4th hand choice

Table 4.2

OK electrodes for welding of cast aluminium alloys

		Al Zn Mg	Al 5~10 Cu	Al Mg 3 (Si, Mn) Al Mg 4~5 (Si)	Al≤ 8 Si≥5 Cu	Al Si 5~8 (Mg)	Al Si 9~12
Al Si 9~12	I.	T/A 18.04	T/A 18.05	T/A 18.15/16	T/A 18.05	T/A 18.04	T/A 18.05
	II.	T/A 18.05	S 96.50	T/A 18.04	S 96.50	T/A 18.05	S 96.50
	III.	S 96.50	T/A 18.04	T/A 18.05	T/A 18.04	S 96.50	T/A 18.04
	IV.			S 96.50			
Al Si 5~8 (Mg)	I.	T/A 18.15/16	T/A 18.05	T/A 18.15/16	T/A 18.05	T/A 18.04	
	II.	T/A 18.04	S 96.50	T/A 18.04	S 96.50	T/A 18.05	
	III.	T/A 18.05		T/A 18.05	T/A 18.04	S 96.50	
	IV.	S 96.50		S 96.50			
Al≤8 Si≤5 Cu	I.	T/A 18.05	T/A 18.05	T/A 18.05	T/A 18.05		
	II.	S 96.50	S 96.50	S 96.50	S 96.50		
	III.			T/A 18.04	T/A 18.04		
Al Mg 3 (Si, Mn) Al Mg 7~5 (Si)	I.	T/A 18.15/16	T/A 18.05	T/A 18.15/16			
	II.	T/A 18.05	S 96.50	T/A 18.13			
	III.	S 96.50					
Al 5~10 Cu	I.	T/A 18.05	T/A 18.05				
	II.	S 96.50	S 96.50				
Al Zn Mg	I.	T/A 18.15/16					
	II.	T/A 18.04					
	III.	T/A 18.05					
	IV.	S 96.50					

OK Autrod/Tigrod 18.05 is not included in the ESAB standard range.

A: OK Autrod XX.XX (GMAW)
S: OK XX.XX (MMA)
T: OK Tigrod XX.XX (GTAW)

I. 1st hand choice
II. 2nd hand choice
III. 3rd hand choice
IV. 4th hand choice

Table 4.3

OK electrodes for welding of cast aluminium to wrought aluminium

Cast aluminium / Wrought aluminium		Al Zn Mg	Al 5~10 Cu	Al Mg 3 (Si) Al Mg 4~5 (Si)	Al≤8 Si≤5 Cu	Al Si 5~8 (Mg)	Al Si 9~12
Al	I.	T/A 18.04	T/A 18.05	T/A 18.04	T/A 18.05	T/A 18.04	T/A 18.04
	II.		S 96.50	T/A 18.15/16	S 96.50	T/A 18.05	T/A 18.05
	III.				T/A 18.04	S 96.50	S 96.50
Al Mn (Mg)	I.	T/A 18.15/16	T/A 18.05	T/A 18.15/16	T/A 18.05	T/A 18.04	T/A 18.04
	II.	T/A 18.04	S 96.50	T/A 18.04	S 96.50		T/A 18.05
	III.						S 96.50
Al≤2 Mg (Mg)	I.	T/A 18.15/16	T/A 18.05	T/A 18.15/16	T/A 18.05	T/A 18.04	T/A 18.04
	II.	T/A 18.04	S 96.50	T/A 18.04	S 96.50	T/A 18.15/16	T/A 18.05
	III.				T/A 18.04		S 96.50
Al Mg 3 (Mg) Al Mg 4~5 (Mg)	I.	T/A 18.15/16	T/A 18.05	T/A 18.15/16	T/A 18.05	T/A 18.15/16	T/A 18.04
	II.	T/A 18.05	S 96.50	T/A 18.13	S 96.50	T/A 18.04	T/A 18.05
	III.	S 96.50			T/A 18.04	T/A 18.05	S 96.50
	IV.					S 96.50	
Al Mg Si (Mn, Cu)	I.	T/A 18.04	T/A 18.05	T/A 18.15/16	T/A 18.05	T/A 18.04	T/A 18.05
	II.	T/A 18.15/16	S 96.50	T/A 18.04	S 96.50	T/A 18.05	S 96.50
	III.					S 96.50	T/A 18.04
Al Si 5	I.	T/A 18.15/16	T/A 18.05	T/A 18.15/16	T/A 18.05	T/A 18.04	T/A 18.04
	II.	T/A 18.04	S 96.50	T/A 18.04	S 96.50	T/A 18.05	T/A 18.05
	III.	T/A 18.05		T/A 18.05	T/A 18.04	S 96.50	S 96.50
	IV.	S 96.50		S 96.50			
Al Zn Mg	I.	T/A 18.15/16	T/A 18.05	T/A 18.15/16	T/A 18.05	T/A 18.15/16	T/A 18.05
	II.	T/A 18.04	S 96.50	T/A 18.05	S 96.50	T/A 18.04	S 96.50
	III.	T/A 18.05		S 96.50		T/A 18.05	
	IV.	S 96.50				S 96.50	
Al Cu Mg[1]	I.	T/A 18.05	T/A 18.05	T/A 18.15/16	T/A 18.05	T/A 18.05	T/A 18.05
	II.	S 96.50	S 96.50	T/A 18.04	S 96.50	S 96.50	S 96.50

[1] These alloys are generally difficult to weld.

I. 1st hand choice
II. 2nd hand choice
III. 3rd hand choice
IV. 4th hand choice

A: OK Autrod XX.XX (GMAW)
S: OK XX.XX (MMA)
T: OK Tigrod XX.XX (GTAW)

54. Cobalt alloys to other metals

Welding cobalt alloys to other metals is not very common and therefore this chapter will be restricted to welding cobalt alloys to steel and Ni-based alloys.

Cobalt alloys to steel:
Beside the normally used brazing technique, good joints with this combination can also be achieved with the electric arc welding process using specially ductile, low carbon electrodes like OK 93.07. The weld metal will be similar to the cobalt alloy. Also OK 93.06 may sometimes be used for this combination. The dilution of the weld metal with iron will decrease its hardness and thereby lower the risk of cracking. Following this, it is beneficial to achieve the greatest possible dilution with the steel side.
Both the steel and the cobalt side shall be preheated to about 350–400°C.

Recommended consumables

MMA:	OK 93.07 OK 93.06

Cobalt alloys to Ni-based alloys:
Brazing is the normal joining technique also for this combination. However, MMA-welding may be used, using OK 93.07. Also OK 93.06 may sometimes be used since Ni in the same way as iron lowers the hardness of the cobalt alloy and thereby decreases the risk of cracking.
In view of the Ni-alloys being sensitive to overheating, the applied preheating temperature shall not exceed 200°C on the nickel side. The cobalt side shall be preheated to 350–400°C.

Recommended consumables

MMA:	OK 93.07 OK 93.06

55. Material combinations not covered by the key table (page 2)

Austenitic manganese steel to other steel
Austenitic manganese steel is often used in constructions where wear resistance, especially resistance to impact, is required, like crushers, dredgers, etc. It is then often welded to ordinary steel. To use electrodes of matching composition is not recommended, unless they are alloyed with about 3 % Ni, since dilution with iron may create a very coarse grained, crack sensitive martensitic microstructure.
The most used electrodes for this joint have an austenitic stainless steel composition. (18Cr-8Ni-6Mn or 19Cr-10Ni-3Mo or 23Cr-13Ni-2Mo).

Recommended consumables

MMA:	OK 67.45 OK 63.32 OK 67.70
GMAW:	OK Autrod 16.95 OK Autrod 16.52

The welding is performed without preheating and with limited heat input. Too high heat concentrations will damage the microstructure of the manganese steel, due to carbide precipitations.

5 and 9 % Ni-steel to other steel
The use of 5 and 9 % Ni-steel is common in cryogenic constructions (designed to work at very low temperatures). Welding is performed without problems using Ni-based or special stainless steel electrodes. Electrodes of matching composition are never used, since they may cause cracking.

Recommended consumables

MMA:	OK 92.55 OK 69.46 OK 92.26
GMAW:	OK Autrod 19.85 OK Autrod 16.94

Zinc and its alloys
These materials are normally welded by the oxy-acetylene process.
However, acceptable results have been achieved using the GTAW process with an aluminum filler metal. The welding parameters and the rod/torch-movements were carefully monitored to avoid boiling of the weld pool.

Ferritic stainless ELI-steel. (Extra Low Interstitials)
These Cr-steel with low carbon and nitrogen content, are superior to other Cr-steel of similar composition, especially in terms of ductility. However, in a weld it is not possible to maintain these properties unchanged. This is particularly true for the ductility, which is dramatically lowered in the HAZ (Heat Affected Zone), due to grain growth. It is difficult to avoid this grain growth completely, but it has to be minimized. Therefore the welding should be performed with a thinner electrode than usual, no weaving and a fairly high welding speed.
The weld metal shows the same unfavourable microstructure, often with unnecessary high strength. The welding should therefore utilize electrodes of a non-matching composition. The best results are achieved using Ni-based or "over alloyed" stainless steel elecktrodes.

Recommended consumables

MMA:	OK 92.26 OK 67.70
GMAW:	OK Autrod 19.85 OK Autrod 16.52
GTAW:	OK Tigrod 19.85 OK Tigrod 16.53

ESAB reserves the right to alter specifications without prior notice.

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