WELDING CONSUMABLES FOR DUPLEX AND SUPERDUPLEX STAINLESS STEELS – OPTIMISING PROPERTIES AFTER HEAT TREATMENT

by

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ABSTRACT

The first 50 years of duplex stainless steel technology was dominated by cast products which were used in the chemical, marine and diverse engineering industries. During this period, a number of national specifications (eg ASTM A351, A744 – CD4MCu) and proprietary alloys (eg Ferralium 255) were developed. Upgrading using welding was inevitably required and conventional practice was to use "matching composition" consumables followed by a solution treatment plus water quench.

In recent years these practices have been extended to cover forged vessel heads and thick walled welded pipework. In order to simplify working practices, reduce inventories etc, there has been considerable development work in the use of "overmatching consumables" normally restricted for use with as-welded wrought steels and fabrications.

This paper reviews the use of this latest technology for a range of proprietary duplex and superduplex alloys. It shows that improved mechanical properties, particularly toughness, can be achieved provided the correct welding procedures and heat treatments are applied. Examples of successful welding procedures are given in an appendix to the paper.

KEYWORDS

Duplex, superduplex, welding consumables, solution anneal, toughness.

INTRODUCTION

Wrought duplex stainless steels became commercially available about 20 years ago, and their initial widespread use was in the offshore oil and gas industries – followed by more general applications which took advantage of their unique combination of corrosion resistance and excellent mechanical properties. In Europe they now represent the third most commonly used grade of stainless steel.

However, the previous 50 years of duplex stainless steel technology was dominated by cast products which were used for pump casings, valve bodies and other diverse applications in the chemical and marine industries. During this period a number of national specifications evolved, and a large number of proprietary alloys were developed. As with most alloy castings upgrading, repairs and joining using welding, was inevitably required and conventional practice was to use welding consumables with a composition closely matching that of the parent alloy, followed by a solution treatment and water quench.

In recent years these practices have been extended to weld not only castings [1], but also vessel heads [2] and thick walled process pipework [3] – all of which require full heat treatment after welding and are sufficiently substantial to avoid or minimise any distortion which might occur during heating and/or quenching. In order to simplify working practices and procedures, reduce inventories and in some cases to achieve improved toughness at sub-zero temperatures (below -50°C), there has been considerable interest in the use of overmatching consumables which are normally restricted for use as-welded on wrought steels.

The use of overmatching consumables is now considered to be a viable option which can give improved properties provided the correct welding procedures and heat treatments are applied.

MATERIALS

The steels evaluated in this programme of work have included standard 22%Cr duplex steels (UNS S31803), 25%Cr superduplex steels (UNS S32750 and S32760) together with a number of proprietary alloys with additional alloying in the form of copper and tungsten, Table 1.

Table 1: Range of typical base materials.

Standard		Product	Commercial	Typical Analysis, wt%						PRE*
UNS	EN	Form	Grades	Cr	Ni	Mo	Cu	W	N	
S31803	1.4462	Wrought	UR 45N SAF2205	22	5	3	-	-	0.15	33
S32205	1.4462	Wrought	2205 UR45N+	23	5	3	-	-	0.18	35
J92205	-	Cast	2205	22	5	3	-	-	0.18	35
S32750	1.4410	Wrought	SAF2507 UR45N+	25	5	4	-	-	0.25	41
J93404	1.4469	Cast	2507	25	7	4.5	-	-	0.25	41
S32760	1.4501	Wrought	Zeron 100	25	7	3.5	0.7	0.7	0.25	40
J93380	1.4508	Cast	Zeron 100	25	7	3.5	0.7	0.7	0.25	40
S32550	1.4507	Wrought	Ferralium 255 UR52N	25	7	3	1.5	-	0.15	38
S32550	1.4507	Wrought	Ferralium SD40 UR52N+	26	7	3.5	1.5	-	0.25	41
(J93370)	1.4515 1.4517	Cast	CD4MCuN	25	5	2	3	-	0.20	40

* PREN = %Cr + 3.3%Mo + 16%N

WELDMENTS

Welds were either single or double sided butt welds and were either produced as laboratory test pieces or as weld procedure test pieces using the SMAW process. In all cases the welding consumables used were as close a match as possible to the base material - with the exception of nickel which was overalloyed in the region of 1.5 to 2% – ie, the same consumables which would normally be used for as-welded fabrications, see Table 2. Some welds were completed with a single size of consumable whereas others were carried out using a range of sizes, eg typically in the case of SMAW, 3.2, 4.0 and 5.0mm diameters.

Table 2: Welding consumables investigated with specifications and typical analysis.

Electrode	AWS	BS EN	Typical Analysis, wt%						PRE
			Cr	Ni	Mo	Cu	W	N	
UM2205	E2209-16	E 22 9 3 NLR	23	9	3	-	-	0.17	36
2205XKS	E2209-15	E 22 9 3 NLB	23	9	3	-	-	0.17	36
SM2205	-	-	25	9.5	3.5	-	-	0.20	38
2507XKS	-	E 25 9 4 NLB	25	9.5	4	-	-	0.25	42
Z100XW	-	E 25 9 4 NLR	25	9.5	3.5	0.7	0.7	0.23	41
Z100XKS	-	E 25 9 4 NLB	25	9.5	3.5	0.7	0.7	0.23	41
SM2506Cu	E2553-16	(E 25 9 3 CuNLR)	25	7.5	3	2	-	0.18	37
UM B2553	E2553-15	E 25 9 3CuNLB	25	8	3.5	2	-	0.20	41

On completion of welding, some of the assemblies were divided into two pieces along the weld length. One part was tested as-welded, whereas the other part was solution heat treated and quenched, generally in accordance with the requirements of ASTM A890 [4]. In other cases, different test pieces were produced for the as-welded and post weld heat treated (PWHT) conditions. Details of all the weldments tested are given in Table 3 and two successful commercial weld procedures are given in the Appendix.

Table 3: Range of tests carried out.

Weld Code	Parent Material	Electrode	As-Welded	PWHT
A	2205	UM2205	Yes	1150°C for 3 hours + WQ
B	2205	UM2205	Yes	1110°C for 4 hours + WQ
C1 & C2	2205	2205XKS	Yes	1135°C for 2 hours + WQ
D	2205	SM2205	Yes	1120°C for 2-3 hours + WQ
E	Zeron 100	2507XKS	Yes	1120°C for 8 hours + WQ
F	Zeron 100	Z100XW	Yes	1120 °C for 3 hours + WQ
G	Zeron 100	Z100XKS	Yes	1120 °C for 3 hours + WQ
H	Ferralium 255	SM2506Cu	Yes	1120 °C for 3 hours + WQ
J	Ferralium SD40	UM B2553	Yes	1120 °C for 3 hours + WQ

TESTING

Wherever possible the following tests were carried out:

1. Charpy impact tests at one or more temperatures.

2. All-weld metal tensile tests; on some test assemblies transverse tests were carried out.

3. A hardness survey.

4. Measurement of weld metal ferrite number (FN) using a Fischer Ferritescope calibrated and used in accordance with the IIW recommendations [5] or point counting according to ASTM E562 [6].

RESULTS

Impact Properties

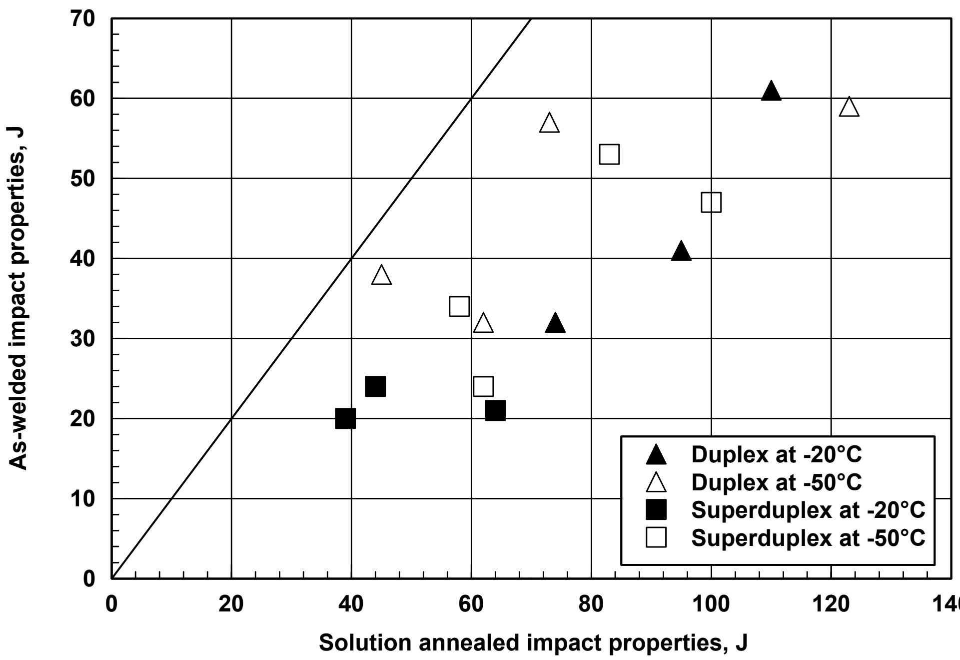
The charpy impact properties of the weld metals were without exception improved by carrying out a solution anneal, the data is summarised in Table 4. The as-welded versus solution annealed properties are plotted in Figure 1 and show that the percentage increase in impact properties at –20°C and –50°C is in the region of 50-120%.

Table 4: Charpy impact properties at a range of temperatures both as-welded and solution annealed.

Code	Electrode	As-Welded Impact Properties				PWHT Impact Properties			
		+20°C	-20°C	-50°C	-75°C	+20°C	-20°C	-50°C	-75°C
A	UM2205	53	45	38	-	-	-	45	-
B	UM2205	56	-	-	-	177	-	-	-
C1 *	2205XKS	-	-	59	-	-	-	123	84
C2 *	2205XKS	-	-	57	-	-	-	73	81
D	SM2205	50	40	30	-	-	75	68	-
E	2507XKS	87	79	53	37	-	-	83	-
F	Z100XW	-	32	24	-	-	-	62	-
G	Z100XKS	89	75	47	26	-	-	100	86
H	SM2506Cu	37	21	-	-	-	64	-	-
J	UMB2553	-	61	-	-	-	110	58	-

* Current generation 2205XKS electrodes will provide typically 135J at +20°C, 90J at -50°C and 60J at –75°C as-welded and would be expected to give a comparative increase when solution annealed.

Figure 1: As-welded versus solution annealed impact properties.



Tensile

The tensile data for the welds is summarised in Table 5. The UTS (R_m) of the weld metal does show a small decrease after PWHT which is in line with the drop in the mid-weld Vickers hardness (HV) of about 5-15%. The 0.2% proof stress ($R_{p0.2}$) shows a more significant decrease, the solution annealed proof stress only being about 70% of the as-welded value, Fig 2. The solution annealed welds also show an increase in elongation (A_4).

Table 5: Tensile properties as-welded and solution annealed.

Code	Electrode	As-Welded					PWHT				
		R_m MPa	$R_{p0.2}$ MPa	A_4 %	HV	HRC	R_m MPa	$R_{p0.2}$ MPa	A_4 %	HV	HRC
A	UM2205	845	670	27	285	-	-	-	-	-	-
B	UM2205	-	-	-	-	23	-	-	-	-	17
C	2205XKS	869	679	29	281	26	792	482	41	240	17
D	SM2205	870	685	25	270	25	798	483	32	248	-
E	2507XKS	905	710	28	320	-	-	-	-	299	-
F	Z100XW	910	710	25	303	26	-	-	-	251	20
G	Z100XKS	898	722	30	305	28	842	552	35	287	25
H	SM2506Cu	947	763	24	279	-	-	-	-	250	-
J	UM B2553	1021	827	24	335	33	910	607	33	269	-

Figure 2: As-welded versus solution annealed tensile properties.

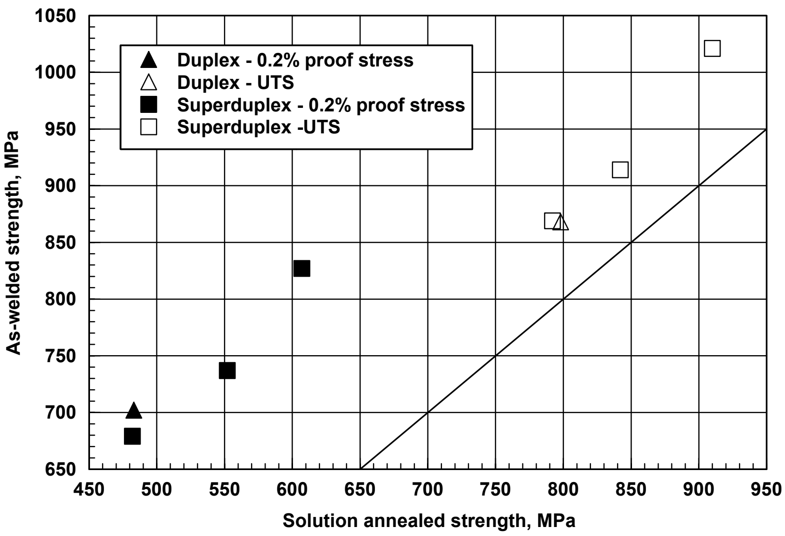


Table 6: Transverse tensile properties from weld procedure tests.

Code	Electrode	Base material	Condition	Transverse tensile strength, MPa	Failure location
B	UM2205	S31803	As welded	736, 745	Parent material
			1110°C/4hr	707, 716	
D	SM2205	J92205	As welded	775, 757	
			1120°C/3hr	715, 734	
E	2507XKS	J93380	As welded	771	
			1120°C/8hr	779	

The large reduction in proof stress does not prove to be a factor when procedure qualification tests are carried out. For procedure tests, all-weld metal tensile tests are not normally required and in a transverse tensile, the failure still occurs in the base material. Examples of some transverse tensile tests from a number of procedure qualification tests are given in Table 6.

Ferrite

The ferrite measurements made using the Fischer Ferritescope and the point count measurements are summarised in Table 7. The measurements made by ferritescope tend to show a slight decrease in FN after solution annealing but the point count measurements show very little change.

Table 7: Transverse tensile properties from weld procedure tests.

Code	Electrode	Point Count, %		Ferritescope, FN	
		AW	PWHT	AW	PWHT
A	UM2205	-	59	-	-
B	UM2205	35	35	30-45	-
C1	2205XKS	-	-	36	27
C2	2205XKS	-	-	32	31
D	SM2205	40-55	50	40	-
E	2507XKS	35	35	40-55	-
F	Z100XW	-	40	-	-
G	Z100XKS	-	-	55	46
H	SM2506Cu	-	-	48	-

DISCUSSION

Impact Properties

The as-welded toughness of duplex and superduplex weld metals is an area that has been investigated extensively, with particular reference to North Sea offshore requirements. The weld metal toughness has been found to be dependent on a number of factors, particularly alloy type and welding process. The toughness generally drops as the alloy content increases, so superduplex alloys show lower toughness than the duplex alloys. With respect to welding process the welds show a general decrease in toughness in the order GTAW, GMAW, SAW, SMAW and FCAW; this corresponds approximately to increasing oxygen content of the weld metal [7]. The as-welded impact properties shown in Table 4 do not just rank according to alloy content because the toughness decreases in the order: 2205XKS, 2507XKS, Z100XKS, UMB2553, UM2205, SM2205, Z100XW and SM2506Cu. The electrodes divide into two separate groups which cover rutile coated electrodes (UM2205, SM2205, Z100XW and SM2506Cu) and basic coated electrodes (2205XKS, 2507XKS, Z100XKS and UMB2553). The difference between the basic and rutile coated electrodes can also be explained by oxygen content, basic coated electrodes having typically 700ppm oxygen while rutile coated electrodes have approximately 1100ppm [7]. All of the welds tested showed an improvement in toughness following solution annealing Fig 1. A number of the consumables tested showed high levels of toughness (>80J) at temperatures down to –75°C. This temperature is lower than that normally considered appropriate to welded duplex structures. Although no microstructural examinations were carried out this improvement would be expected because of the homogenising effect of the heat treatment [8].

Tensile Properties

The test results reported here show that the overmatching consumables normally used for as-welded applications are capable of producing good properties in the solution annealed condition. Compared to as-welded properties, the solution annealed welds showed improved ductility combined with reduced strength and hardness. However, the substantial reduction in all-weld proof stress of the solution annealed welds does not compromise the strength of the welded joint. For weld procedure qualifications it will always be the weld joint that will be tested using a transverse tensile test rather than an all-weld test. From transverse tensile tests carried out on procedure qualifications, the tensile specimens fail in the parent material at a UTS virtually the same as tests on as-welded joints, Table 6. Although, in virtually all cases, a small reduction in tensile strength can be expected after PWHT, the resulting strength should always be greater than that specified for the parent materials.

Ferrite

In the past there has been concern that the ferrite content of welds made using 'overmatching' consumables would show a significant reduction [9]. In practice, the FN measurements do show a small reduction but would still be acceptable. The point count measurements do not actually detect any variations between as-welded and solution annealed welds. The weld A, which was heat treated at 1150°C showed a fairly high ferrite content after PWHT (59%), unfortunately, there is no ferrite measurement as-weld as a comparison, but it is noticeable that this weld showed only a small increase in toughness after PWHT.

Corrosion Performance

One area not specifically examined in this work was the comparative corrosion properties of as-welded and solution annealed welds. For duplex and superduplex alloys, this is normally determined using the ASTM G48A pitting corrosion test. In the as-welded condition the G48A critical pitting temperature is dependent upon composition and increases with increasing PRE number. This trend will be followed by weld metals in the solution annealed condition but because of the homogenising effect of the heat treatment the critical pitting temperatures would be expected to be higher than in the as-welded condition [1].

Heat Treatment

All of the tests reported in this paper utilised a single stage heat treatment followed by a water quench, no investigation into the effects of the solution annealing temperature, or of two stage heat treatments, was carried out. The solution annealing temperature needs to be high enough for full dissolution of intermetallic phases formed during the heating cycle and at a temperature that will on quenching provide the optimum phase balance. For this reason two stage heat treatments are sometimes carried out with a higher temperature (e.g. 1120°C) being used to ensure intermetallics are dissolved and then cooling to a lower temperature (e.g. 1050°C) before quenching to obtain a better phase balance and minimise the risk of quench cracking [10]. Apart from the actual heat treatment temperature the quenching of the material is also very important and can have a significant effect on the properties [11].

It is interesting to note that the test weld A carried out using UM2205 electrodes which was solution annealed at 1150°C did not show such a large increase in impact properties as the other welds, only from 38J to 45J. It is possible that the heat treatment temperature selected was actually too high to achieve the optimum properties this is also reflected in the high ferrite (59%) compared to weld B.

Earlier work by Kotecki [10] carried out on S32550 looked at different heat treatment temperatures and indicated that solution temperatures in excess of ~1100°C were necessary to ensure complete solution of sigma. All the test heat treatments reported in this work were significantly above this critical temperature and it is therefore expected that the resultant microstructures would be free from sigma, even in the more highly alloyed weld metals. This is confirmed by the fact that weld metals with significant alloying of tungsten and/or copper all achieved toughness in the range 60 to 120J when tested at –50°C.

CONCLUSIONS

A number of duplex and superduplex weldments made with overmatching SMAW consumables have been tested in both the as-welded and solution annealed conditions. The following conclusions are drawn:

1. Toughness always improves after suitable solution treatment and quenching; 80J can be achieved at temperatures down to at least –75°C which could give confidence to expand the scope for sub zero applications.

2. Tensile properties, in terms of proof strength and ultimate tensile strength, are always reduced after solution annealing. However, they still overmatch the parent material requirements and weld procedure transverse tensile tests invariably fail in the parent material.

3. Weld metal ferrite contents showed very modest reductions after solution annealing. There was no evidence to support the concern that has been sometimes expressed that overmatching weld metals would contain insufficient ferrite.

4. Overmatching consumables are now considered to be a viable option which can give improved properties provided the correct welding procedures and heat treatments are applied.

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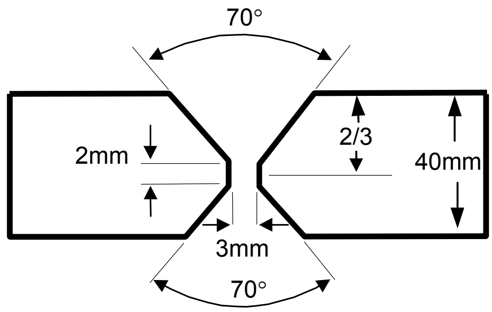
Weld Procedure Record

Solution annealed Z100XW weld

Ref: PQR-01

Material	J93380
Filler Metal	**Z100XW**
Classification	BS EN: E 25 9 4 N L R
Process	SMAW
Gas Shield	NA
Current	DC+
Position	ASME 1G
Preheat / Interpass Temperature	35 / 150°C
PWHT	1120°C 3 hours + WQ

Weld Details



Run No	ø mm	Current Amp	Arc Volts	Travel Speed mm/min	Heat Input kJ/mm
1-3	3.2	100-130	22-26	140-190	0.6-1.1
4-7	4.0	140-170	22-26	150-230	0.9-1.3
8-10	3.2	110-130	22-26	140-180	0.6-1.1
11-14	4.0	160-170	22-26	180-230	0.9-1.3
Fill	4.0	150-170	22-26	180-230	0.9-1.3
Cap	5.0	190-230	22-26	190-260	1.2-1.6

Procedural Comments

Runs 1-7 = side 1; runs 8-14 = side 2.
Filling runs balanced side 1 and 2.
Backgrind to sound metal and dye pen after run 7.

Analysis	C	Mn	Si	S	P	Cr	Ni	Mo	Cu	W	N
Parent	0.026	0.91	0.54	0.010	0.027	25.0	8.43	3.64	0.91	0.57	0.21
3.2mm	0.027	0.58	0.69	0.01	0.02	24.5	9.1	3.70	0.64	0.67	0.24
4.0mm	0.023	0.65	0.72	0.01	0.02	25.4	9.1	3.42	0.58	0.61	0.23
5.0mm	0.026	0.62	0.61	0.01	0.02	25.1	9.2	3.38	0.60	0.59	0.24

Transverse tensile:
Fail parent
743, 746MPa

Side bend:
4 off
180° bend
Pass

G48A:
+50°C pass

Ferrite:
Parent 52%
Cap side 1/2:
HAZ 50/44%
Weld 37/40%
Mid weld:
HAZ 49%
Weld 42%

Charpy Impact	-50°C J	mm	°C J	mm
Weld CL	57			
	68			
	60			
FL	80			
	71			
	92			
FL + 2mm	121			
	84			
	80			
FL + 5mm	114			
	118			
	104			

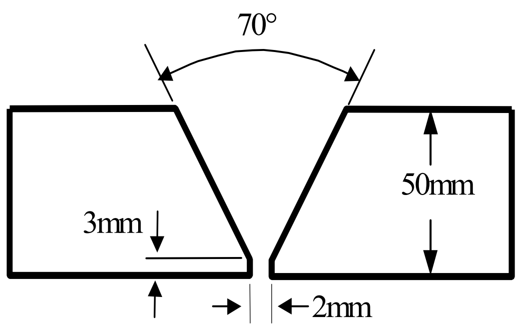
Hardness	PM	HAZ	Weld Metal
HV10	232-260	235-279	242-276
HRC	<20-21	<20-23	<20-23

Orig. GBH **Date** 27.6.00

Weld Procedure Record

Solution annealed 2507XKS weld			Ref: PQR-02
Material	J93380		
Filler Metal	**2507XKS**		
Classification	BS EN: E 25 9 4 N L R		
Process	SMAW	**Gas Shield**	NA
Current	DC+	**Position**	ASME 3G
Preheat / Interpass Temperature	20 / 150°C		
PWHT	1120°C 8 hours + WQ		

Weld Details



Run No	ø mm	Current Amp	Arc Volts	Travel Speed mm/min	Heat Input kJ/mm
1	3.2	80	28	100	1.4
2-4	3.2	85	27	75-110	1.2-1.8
5-69	4.0	145	27	120-180	1.3-2.0

Procedural Comments

Runs 1-63 side 1, runs 64-69 side 2. Backgouge to sound metal and dye pen after run 63.

Analysis											

Transverse tensile:
Fail parent
782, 777MPa

Side bend:
4 off
Pass

G48A:
+50°C pass

2.7g/m^2 wt loss

Ferrite:
ASTM E562

Parent 42%
HAZ 42%
Weld 35%

Hardness	**PM**	**HAZ**	**Weld Metal**
HV10	272-311	272-304	292-306

Charpy Impact	-50°C J	mm	°C J	mm
Weld CL	81			
	80			
	88			
FL	147			
	157			
	161			
FL +2mm	165			
	162			
	175			
FL +5mm	195			
	187			
	180			

Orig.	GBH	**Date**	27.6.00