DOCOL®
THE AUTOMOTIVE STEEL

Welding of AHSS/UHSS steel

A guide for the automotive industry

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SSAB

Over the past few years, we have received an increasing number of questions from the automotive industry about the welding of AHSS/UHSS steels. This is due to the rapid rise in popularity of AHSS/UHSS steels and because, in some ways, the welding of them differs from the welding of mild steels.

Since a manual for these types of highest strength steels does not exist, we at SSAB felt it necessary to develop a "Welding Guide". Its purpose is to support our automotive customers and the market itself by providing recommendations of AHSS/UHSS steel for the most common welding methods in the automotive industry. The chapters address results from tests and present recommendations, as well as suitable procedures. This "Welding Guide" shall be used as a complement to SSAB's "Sheet Steel Joining Handbook".

A QUICK GUIDE TO THE SSAB AHSS/UHSS STEELS

DOCOL is SSAB's brand product towards the automotive industry for safer and lightweight applications.

MICRO-ALLOYED STEELS (LA) Micro-alloyed cold forming steels designated according to the lowest guaranteed yield strength.

DUAL PHASE STEELS (DP) Dual Phase cold forming steels have a microstructure that contains two phases: ferrite and martensite.

COMPLEX PHASE STEELS (CP) The microstructure contains small amounts of martensite, retained austenite and pearlite within the ferrite/bainite matrix.

MARTENSITIC STEELS (M) Martensitic steels contain 100 percent martensite.

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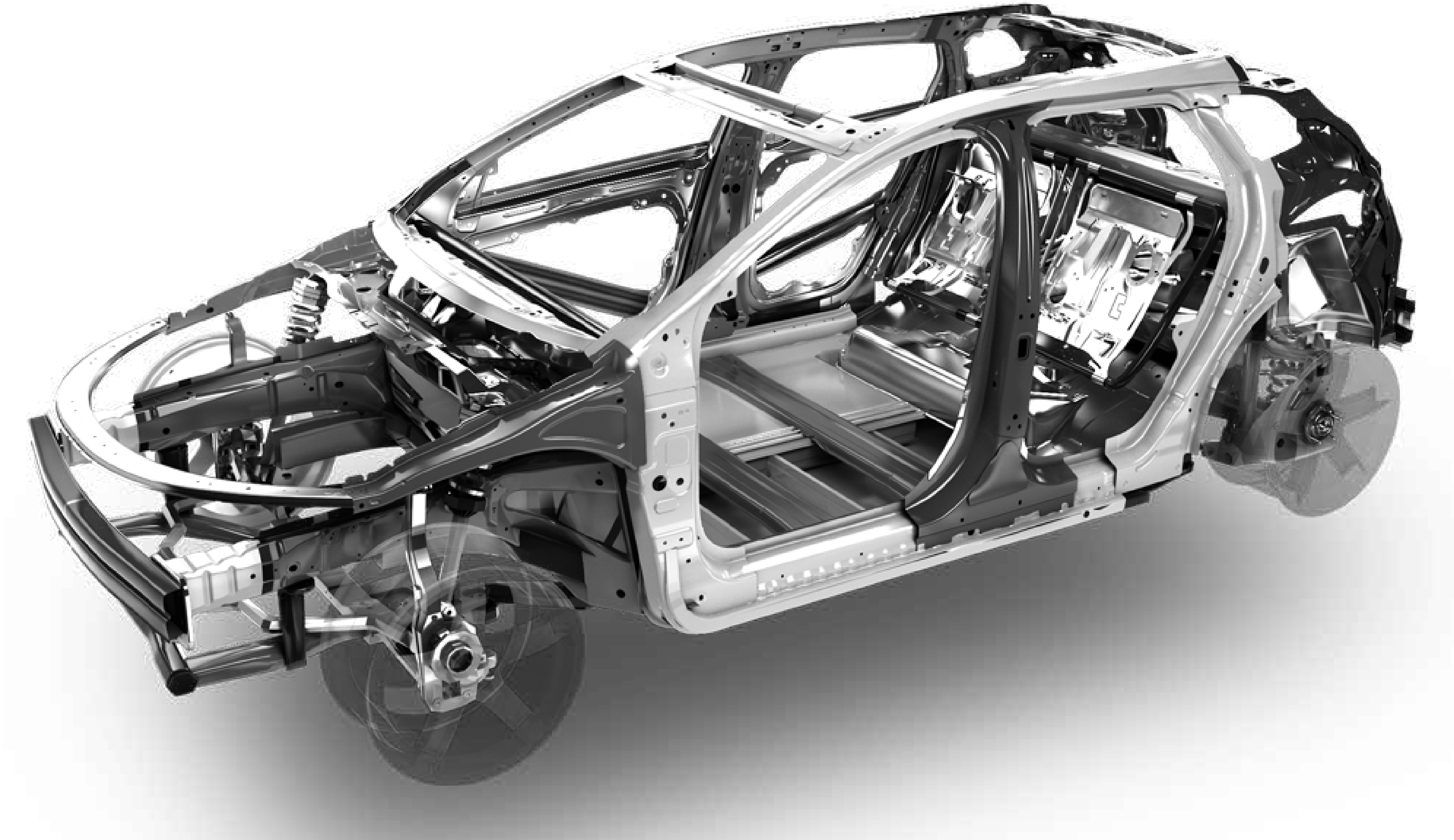


Docol AHSS/UHSS steels provide an excellent way to reduce weight and improve performance in different automotive applications.

DOCOL

The automotive steel

SSAB is a global leader for innovative Advanced and Ultra High Strength Steels (AHSS/UHSS) for the automotive industry. Our roots are based in Sweden. Our operations span the entire globe. And our more than 30 years of experience developing the strongest and highest quality AHSS/UHSS steel helps you stay ahead of competition.

We are a steel company, however, you will find that our values run much deeper. Our focus is on our customers and supporting them to develop the most innovative products on the market, right from the start of an application's development.

Our Docol branded products are Advanced and Ultra High Strength Steels for the automotive industry. They represent the highest level of competence and value added services. It is the innovative edge you need to be successful.

Docol AHSS/UHSS can be welded using all standard methods thanks to its very lean chemical composition. Complex shapes can also be formed using both stamping and roll forming techniques, using standard production equipment.

OUR EXPERIENCE

The SSAB Knowledge Service Center is an advanced technical support organization that supplies you with detailed expertise, knowledge and advice about all our steels for the automotive business. It is free of charge to our customers and is comprised of automotive experts working with specific technical skills and experience with AHSS/UHSS steels. The SSAB Knowledge Service Center gives you access to support and development, as well as problem solving on both the short and long term.

The SSAB Knowledge Service Center have competence at different technical areas including:

- Structural Technology
- Forming Technology
- Joining and Thermal Cutting Technologies.

1.

The Docol AHSS/UHSS product range

1.1 Micro-alloyed steels

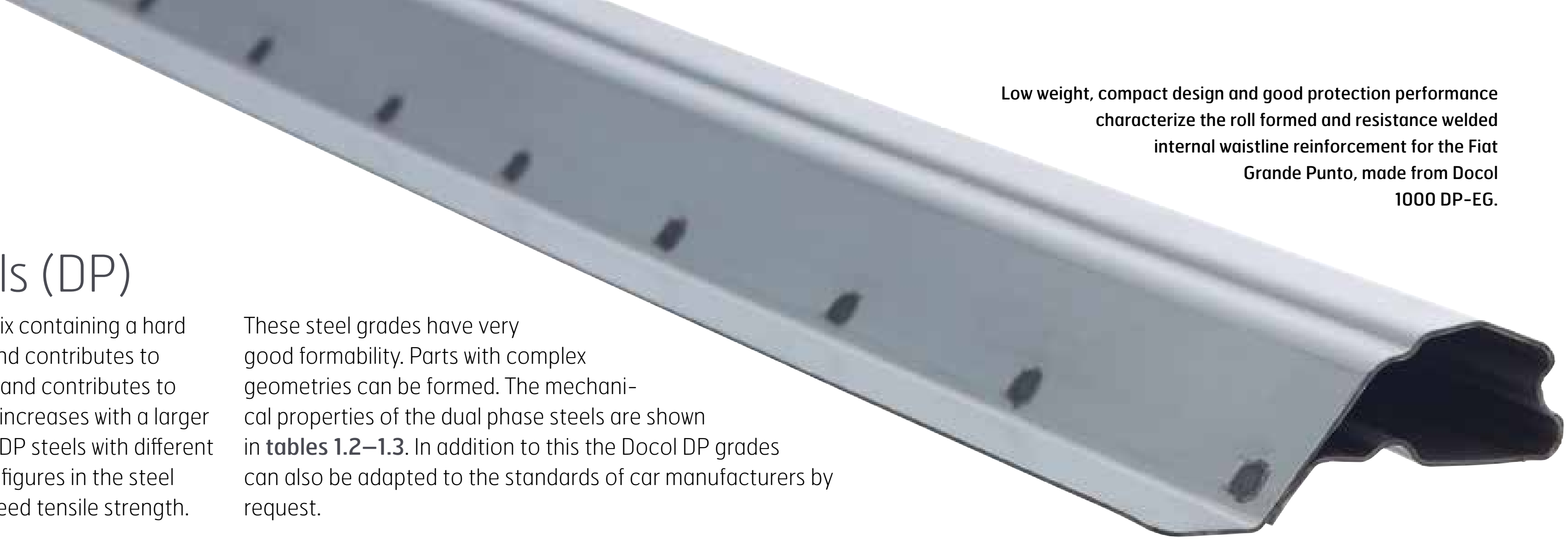
Docol micro-alloyed steels derive their high strength from the addition of very small quantities of micro-alloying elements such as niobium and titanium. These steel grades are designated according to the minimum guaranteed yield strength. The difference between their yield strength and tensile strength is small. These steel grades have excellent bendability in relation to their yield strength. The mechanical properties of the micro-alloyed steels are shown in **table 1.1**.

Table 1.1 Mechanical properties of high strength low alloy steel.

	Steel Grade	Substrate (HR/CR)	Specification	UC	EG	GI	GA	ZA	Approximate mechanical limits for material selection purposes						
									Test Direction	Yield Strength (MPa)		Tensile Strength (MPa)		Elongation (A_{80}, %)	Elongation (A_5, %)
										Min	Max	Min	Max	Min	Min
Docol 420LA	Docol CR420LA	CR	VDA 239-100:2016			●	■	■	L	420	520	480	600	17	-
	Docol HR420LA	HR	VDA 239-100:2016	●	●	■			L	420	520	480	600	18	22
	HC420LA	CR	EN 10268+A1:2013	●					T	420	520	470	600	17	-
	HX420LAD	CR/HR	EN 10346:2015			●	●	●	T	420	520	470	590	17	-
Docol 460LA	Docol CR460LA	CR	VDA 239-100:2016	●		●	■	■	L	460	580	520	680	15	-
	Docol HR460LA	HR	VDA 239-100:2016	●					L	460	560	520	640	16	20
	HC460LA	CR	EN 10268+A1:2013	●					T	460	580	510	660	13	-
	HX460LAD	CR/HR	EN 10346:2015			●	■	■	T	460	560	500	640	15	-
Docol 500LA	Docol HR500LA	HR	VDA 239-100:2016	●					L	500	620	560	700	14	17
	HC500LA	CR	EN 10268+A1:2013	●					T	500	620	550	710	12	-
	HX500LAD	CR/HR	EN 10346:2015			●	■	■	T	500	620	530	690	13	-
Docol 550LA	Docol HR550LA	HR	VDA 239-100:2016	●		■			L	550	670	610	750	12	16
Docol 600LA	Docol HR600LA	HR	SSAB	●					L	600	730	650	820	13	16
Docol 650LA	Docol HR650LA	HR	SSAB	●					L	650	780	700	880	12	14
Docol 700LA	Docol HR700LA	HR	VDA 239-100:2016	●		■			L	700	850	750	950	10	13
Docol 800LA	Docol CR800LA	CR	SSAB	■					L	800	950	800	950	9	-

Mechanical properties for information only. Coating and thickness-specific restrictions exist. Check specifications for exact requirements.

EXPLANATIONS: **UC** = Uncoated **EG** = Electro Galvanized (ZE in EN standard) **GI** = Hot Dip Galvanized (Z in EN standard) **GA** = Galvannealed (ZF in EN standard) **ZA** = Galfan
● = open in product program ■ = available upon request ▲ = under development



Low weight, compact design and good protection performance characterize the roll formed and resistance welded internal waistline reinforcement for the Fiat Grande Punto, made from Docol 1000 DP-EG.

1.2 Dual phase steels (DP)

Dual phase steels consist of a ferritic matrix containing a hard martensitic second phase. Ferrite is soft and contributes to good formability, whilst martensite is hard and contributes to the strength of the material. The strength increases with a larger proportion of the hard martensitic phase. DP steels with different yield ratios (YS/TS) can be produced. The figures in the steel designation specify the minimum guaranteed tensile strength.

These steel grades have very good formability. Parts with complex geometries can be formed. The mechanical properties of the dual phase steels are shown in **tables 1.2–1.3**. In addition to this the Docol DP grades can also be adapted to the standards of car manufacturers by request.

Table 1.2 Mechanical properties of dual phase steels.

	Steel Grade	Substrate (HR/CR)	Specification	UC	EG	GI	GA	ZA	Approximate mechanical limits for material selection purposes						
									Test Direction	Yield Strength (MPa)		Tensile Strength (MPa)		Elongation (A_{80}, %)	Elongation (A_5, %)
										Min	Max	Min	Max	Min	Min
Docol 500DP	Docol CR290Y490T-DP	CR	VDA 239-100:2016	●		●	■	●	L	290	380	490	600	24	-
	HCT490X	CR	EN 10338:2015	●					L	290	380	490	-	24	-
	HCT490X	CR	EN 10346:2015			●	■	●	L	290	380	490	-	24	-
	Docol CR230Y500T-DL	CR	SSAB	●					T	230	300	500	600	24	-
	Docol CR290Y500T-DP	CR	SSAB	●					T	290	370	500	600	20	-
Docol 600DP	Docol CR330Y590T-DP	CR	VDA 239-100:2016	●		●	●	●	L	330	430	590	700	20	-
	HCT590X	CR	EN 10338:2015	●					L	330	430	590	-	20	-
	HCT590X	CR	EN 10346:2015			●	●	●	L	330	430	590	-	20	-
	Docol CR280Y600T-DL	CR	SSAB	●					T	280	360	600	700	20	-
	Docol CR350Y600T-DP	CR	SSAB	●					T	350	450	600	700	16	-

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	Steel Grade	Substrate (HR/CR)	Specification	UC	EG	GI	GA	ZA	Approximate mechanical limits for material selection purposes						
									Test Direction	Yield Strength (MPa)		Tensile Strength (MPa)		Elongation (A_{80}, %)	Elongation (A_5, %)
										Min	Max	Min	Max	Min	Min
Docol 800DP	Docol CR440Y780T-DP	CR	VDA 239-100:2016	●		●	●	■	L	440	550	780	900	14	-
	HCT780X	CR	EN 10338:2015	●					L	440	550	780	-	14	-
	HCT780X	CR	EN 10346:2015			●	●	■	L	440	550	780	-	14	-
	Docol CR450Y780T-DP	CR	SSAB	●					L	450	550	780	900	15	-
	Docol CR390Y800T-DL	CR	SSAB	●					T	390	-	800	950	13	-
	Docol CR500Y800T-DP	CR	SSAB	●					T	500	650	800	950	10	-
	Docol 800DPX	CR	SSAB			●	■		T	620	770	800	950	10	-
Docol 1000DP	Docol CR590Y980T-DP	CR	VDA 239-100:2016	●	●	●	■	■	L	590	740	980	1130	10	-
	Docol CR700Y980T-DP	CR	VDA 239-100:2016	●	●	●	■	■	L	700	850	980	1130	8	-
	HCT980X	CR	EN 10338:2015	●	●				L	590	740	980	-	10	-
	HCT980X	CR	EN 10346:2015			●	■	■	L	590	740	980	-	10	-
	HCT980XG	CR	EN 10338:2015	●	●				L	700	850	980	-	8	-
	HCT980XG	CR	EN 10346:2015			●	■	■	L	700	850	980	-	8	-
	Docol CR700Y980T-DP-LCE	CR	SSAB	●	●	■	▲	■	L	700	900	980	1130	8	-
	Docol CR700Y1000T-DP	CR	SSAB	●	●				T	700	950	1000	1200	7	-
	Docol 1000DPX	CR	SSAB			●	■		T	800	1000	1000	1200	6	-
Docol 1200DP	Docol CR780Y1180T-DP	CR	SSAB			▲	▲		L	780	950	1180	1350	7	-

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1.3 Complex phase steels (CP)

The microstructure of complex phase steels contains small amounts of martensite, retained austenite and pearlite within the ferrite/bainite matrix. CP steels are characterized by high yield strength, moderate strain hardening, good bendability and flangability. The figures in the steel designation specify the minimum guaranteed tensile strength. The mechanical properties of hot-dip galvanized complex phase steels are shown in **table 1.4**.

Table 1.4 Mechanical properties of complex phase steels.

	Steel Grade	Substrate (HR/CR)	Specification	UC	EG	GI	GA	ZA	Approximate mechanical limits for material selection purposes						
									Test Direction	Yield Strength (MPa)		Tensile Strength (MPa)		Elongation (A_{80}, %)	Elongation (A_5, %)
										Min	Max	Min	Max	Min	Min
Docol 600CP	Docol CR350Y600T-CP	CR	SSAB			●	●	●	L	350	500	600	740	16	-
	HCT600C	CR	EN 10346:2015			●	●	●	L	350	500	600	-	16	-
Docol 800CP	Docol CR570Y780T-CP	CR	VDA 239-100:2016	■		●	■	■	L	570	720	780	920	10	-
	Docol HR660Y760T-CP	HR	VDA 239-100:2016	●		■			L	660	820	760	960	10	13
	HCT780C	CR	EN 10338:2015	■					L	570	720	780	-	10	-
	HCT780C	CR	EN 10346:2015			●	■	■	L	570	720	780	-	10	-
	Docol Roll 800	CR	SSAB	●					T	600	750	800	950	10	-
Docol 1000CP	Docol CR780Y980T-CP	CR	VDA 239-100:2016	●	●	●			L	780	950	980	1140	6	-
	HCT980C	CR	EN 10338:2015	●	●				L	780	950	980	-	6	-
	HCT980C	CR	EN 10346:2015			●			L	780	950	980	-	6	-
	Docol HR800Y950T-CP	HR	SSAB	■	■				T	800	900	950	1050	-	9
	Docol Roll 1000	CR	SSAB	●	●				T	800	950	980	1140	6	-
	Docol Roll 1000 HY	CR	SSAB	●	●				T	850	-	1000	1200	5	-
Docol 1200CP	Docol CR900Y1180T-CP	CR	VDA 239-100:2016	●	●	▲	▲		L	900	1100	1180	1350	5	-
Docol HR800HE	Docol HR800HE	HR	SSAB	▲					-	-	-	-	-	-	-
Docol HR1000HE	Docol HR1000HE	HR	SSAB	▲					-	-	-	-	-	-	-

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1.4 Martensitic steels (M)

Martensitic steels contain 100 % martensite. Martensitic steels have very high yield and tensile strength. The figures in the steel designation specify the minimum tensile strength. Martensitic steels are most suitable for bending, roll-forming, simple pressing operations and tube forming. The mechanical properties of Docol martensitic steels are shown in **table 1.5**.

Round tube made from Docol 1400 M, produced by roll forming together with high frequency welding. It makes a strong, lightweight and cost-effective solution.

Table 1.5 Mechanical properties of martensitic steels.

	Steel Grade	Substrate (HR/CR)	Specification	UC	EG	GI	GA	ZA	Approximate mechanical limits for material selection purposes						
									Test Direction	Yield Strength (MPa)		Tensile Strength (MPa)		Elongation (A_{80}, %)	Elongation (A_5, %)
										Min	Max	Min	Max	Min	Min
Docol 900M	Docol CR700Y900T-MS	CR	SSAB	●	●				L	700	1000	900	1100	3	
Docol 1100M	Docol CR860Y1100T-MS	CR	SSAB	●	●				L	860	1100	1100	1300	3	-
Docol 1200M	Docol CR950Y1200T-MS	CR	SSAB	●	●				T	950	-	1200	1400	3	-
	Docol HR900Y1180T-MS	HR	VDA 239-100:2016	●					L	900	1150	1180	1400	5	8
Docol 1300M	Docol CR1030Y1300T-MS	CR	VDA 239-100:2016	●	●				L	1030	1330	1300	1550	3	-
Docol 1400M	Docol CR1150Y1400T-MS	CR	SSAB	●	●				T	1150	-	1400	1600	3	-
Docol 1500M	Docol CR1220Y1500T-MS	CR	VDA 239-100:2016	●	●				L	1220	1520	1500	1750	3	-
Docol 1700M	Docol CR1350Y1700T-MS	CR	VDA 239-100:2016	●	▲				L	1350	1700	1700	2000	3	-

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2.

Resistance spot welding of Docol AHSS/UHSS

2.1 General about resistance spot welding

Resistance spot welding is the most common welding method for sheet steels. This method has several benefits including, low distortion of welded sheets, energy efficiency, no filler material and high cost effectiveness.

Heat input in resistance spot welding is defined as:

Heat input = $I^2 \cdot R \cdot t$

Where I = *Welding current*
R = *Interfacial and bulk resistance between the sheets*
t = *Welding time*

This formula is essential for the understanding of how different factors influence the welding result. Compared to a soft deep drawing steel grade, AHSS/UHSS steel of the same sheet thickness will need a lower welding current. The reason for the lower welding current for AHSS/UHSS steels in comparison with soft steels is the higher electrical resistance of the AHSS/UHSS steel. When resistance spot welding is conducted for zinc coated steels the welding current has to be raised due to the lower electrical resistance of the zinc coating in comparison with the base metal.

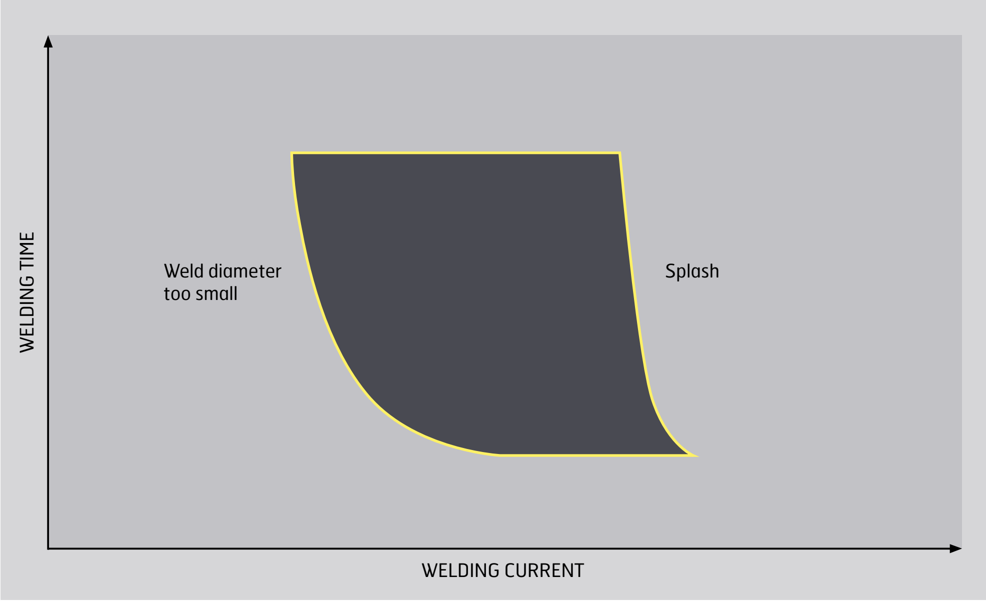
In resistance spot welding there are different tests available for assessing the weldability of a steel. The most common of these tests are:

- Width of the weldability lobe (welding range)
- Strength of the weld
- Metallographic examination
- Type of failure
- Electrode life

Weld growth curves (weld size vs. welding current) and weldability lobes form the basis of weldability studies. These give a means of comparing the available welding current range ("welding range") capable of producing acceptable welds for a particular welding schedule (electrode force/weld time combination) for different steels. The width of the weldability lobe gives information of the anticipated tolerance of a particular welding schedule in production. The aim is to maximise the welding range to achieve the greatest safety margin on weld quality.

The weldability lobe in **figure 2.1.1** shows that splash will occur if the welding current is too high, which will result in poor weld quality. If the welding current is too low, the weld diameter will be too small (which results in reduced weld strength). For measuring of the weld diameter destructive tests are used, for example peel testing (EN ISO 14270) or cross tension testing (EN ISO 14272).

Figure 2.1.1 Weldability lobe for resistance spot welding.



After the destructive test, measurements of the weld diameter are made on broken specimens according to EN ISO 14329.

The minimum weld diameter (d_{min}) which can be accepted often differs between different companies and also between different standards. However, a very common requirement for the minimum weld diameter in a two sheet joint is:

$d_{min} = 4\sqrt{t}$

Where d_{min} = *Minimum weld diameter*
t = *Sheet thickness of the single sheet (if different sheet thicknesses it is the thickness of the thinner sheet)*

EN ISO 18278-2 and SEP 1220-2 are some examples of where the assessment of the available welding current range is described in more detail.

STRENGTH

Shear tension testing (**figure 2.1.3**) and cross tension testing (**figure 2.1.2**) are normally used for determining the strength of a spot weld. The energy absorbed during the tests is also often determined. Information about these tests are given in EN ISO 14273 (shear tension) and EN ISO 14272 (cross tension).

METALLOGRAPHIC EXAMINATION

Metallographic examination of the weld is often carried out by taking a section through the spot weld. After grinding, polishing and etching, the test specimen is examined with a microscope to determine if there are any defects such as cracks or large pores. Other things being measured are indentation depth from the electrodes and penetration depth of the nugget. In conjunction with the metallographic examination, the hardness profile across the weld is often measured in order to determine the hardness of different zones in the weld. Due to the high cooling rate in resistance spot welding, the hardness of the nugget is often higher than the hardness of the base metal.

TYPE OF FAILURE

In destructive testing of resistance spot welds (e.g. peel testing or cross tension testing) different types of failure on the broken specimens may be obtained (**figure 2.1.4**):

A. Plug failure
B. Partial plug failure
C. Interface failure

If the materials fails all around the weld, this will result in plug failure (picture A in **figure 2.1.4**). With such a plug (button) on one of the sheets, it is very easy for quality control to measure the weld diameter. The weld diameter in this case is the same as the plug diameter.

Figure 2.1.2 Destructive testing of resistance spot welds.

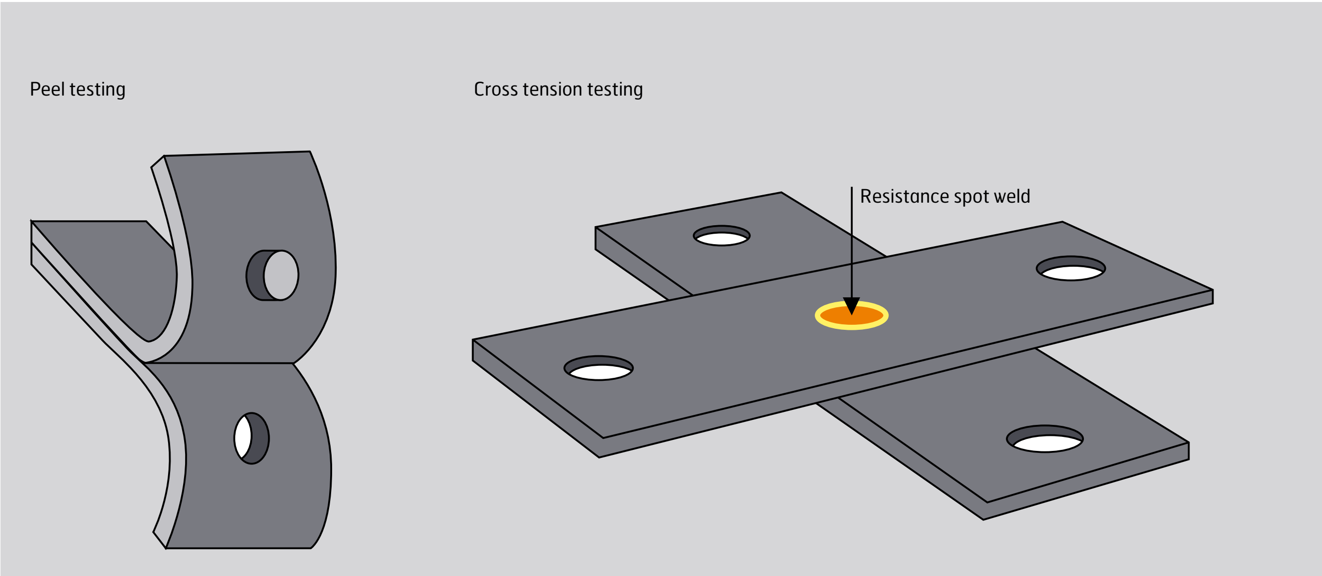
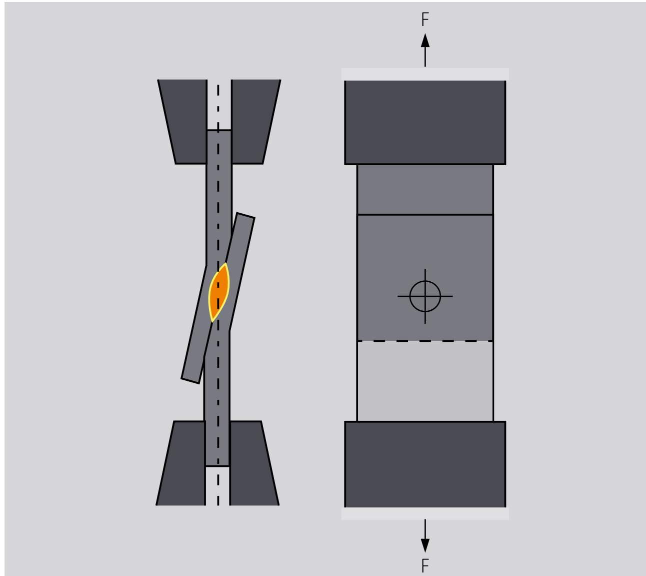


Figure 2.1.3 Shear tension testing of a spot weld.



In some cases, failure may partially occur in the interface between the two sheets, which will result in a plug, part of which is missing as shown in picture B in **figure 2.1.4**. This type of failure is called partial plug failure and may occur if the AHSS/UHSS steel being welded has a high content of carbon or other alloying elements, or if inappropriate welding parameters have been used.

If the failure is entirely located within the interface between the sheets, this is known as "interface failure". This type of failure may occur in AHSS/UHSS steel with a very high content of alloying elements or if the welding parameters are not optimized.

The definition of weld diameter in the case of partial plug failure and interface failure is described in the standard EN ISO 14329. The fused zone also has to be included when measuring the weld diameter in this case.

It is not only the chemical composition of the steel and the welding parameters which determines the type of failure on broken specimens in destructive testing. The type of destructive testing and thicknesses of tested sheets are also important factors. With peel testing and cross tension testing it is easier to obtain a plug failure in comparison with tensile shear testing and thin sheets tends to obtain a plug failure easier than thicker sheets.

There are some relationships that are used to predict the type of failure. The most common relationship is

$$CE = C + \frac{Mn}{20} + \frac{Si}{30} + 2 \cdot P + 4 \cdot S$$

$CE \leq 0.24\,\%$ plug failure
$CE > 0.24\,\%$ partial plug failure or interface failure

This relationship predicts rather well the type of failure for most grades of AHSS/UHSS steel. However, for one type of steel grade, the predicted type of failure does not work so well. Namely for UHSS steels with a very low carbon content ($C \leq 0.10\,\%$) in combination with a high manganese content ($Mn \geq 2.0\,\%$). Even if $CE > 0.24\,\%$ for this type of steel, plug failures are normally observed.

Whether partial plug failure and interface failure are accepted or not differs between companies. Some companies have very strict requirements that do not accept these types of failures and other companies do not have such requirements. Regarding the mechanical properties of the weld, high strength values are normally achieved, for example, in tensile shear testing, even if the broken specimens show partial plug failure or interface failure. So from this point of view there is no reason to disapprove resistance spot welds with these types of failure.

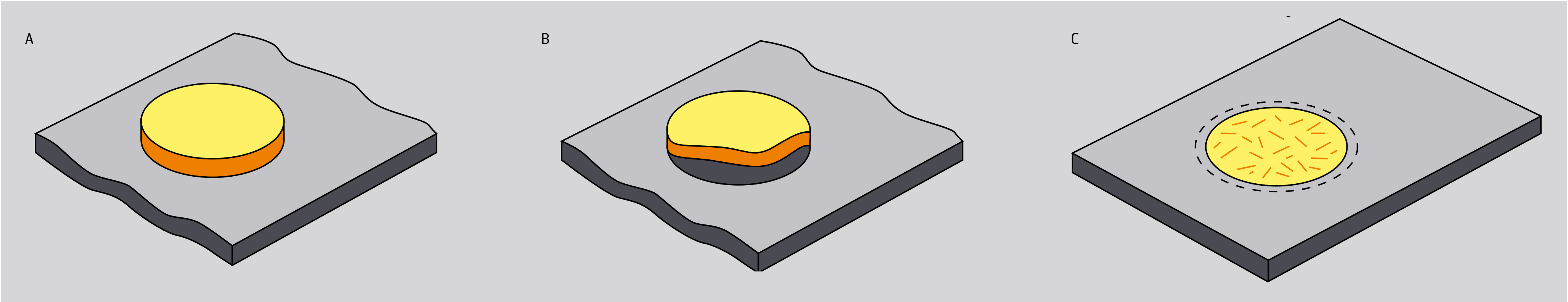
ELECTRODE LIFE

In resistance spot welding it is important to know how many welds can be made before a re-dressing of the electrodes is needed. Besides the sheet material being welded, there are many other factors that have a significant influence on the electrode life i.e. type of electrode (material, design, geometry), welding equipment (AC, MFDC, type of welding gun), welding parameters, welding rate and water cooling parameters (flow rate, temperature).

Regarding the influence of sheet material on the electrode life, it can be mentioned that:

- The electrode life of uncoated sheets is much longer than for metal coated sheets.
- Electro-galvanized is better than hot-dip galvanized.
- A thicker zinc coating reduces the electrode life.
- Thick sheets have a shorter electrode life than thin sheets (due to higher electrode forces).

Figure 2.1.4 Different types of failure in a resistance spot welded joint. A=plug failure, B=partial plug failure, C=interface failure.



2.2 Recommendations for resistance spot welding of Docol AHSS/UHSS

Docol AHSS/UHSS can be welded to other AHSS/UHSS and also to other mild steels. To obtain good welding results for Docol AHSS/UHSS, it is recommended to change the welding parameters somewhat. For Docol AHSS/UHSS it is recommended to increase the electrode force and to use longer welding times in comparison to soft deep drawing steel grades. For zinc coated Docol AHSS/UHSS the welding times and welding currents need to be increased in comparison with uncoated Docol AHSS/UHSS, in order to compensate for the narrowing of the welding range due to the zinc coating. With increased electrode forces and longer welding times, large welding current ranges can be obtained both for uncoated and zinc coated Docol AHSS/UHSS.

Both single pulse welding and multi-pulse welding can be used for Docol AHSS/UHSS. It is beneficial to use multi-pulse welding, especially for thick sheets.

Regarding welding current modes, Docol AHSS/UHSS can be welded with both AC and MFDC. The current mode has no significant effect on weld quality. Both AC (50 Hz) and MFDC (1000 Hz) can easily produce acceptable welds for Docol AHSS/UHSS sheets. For MFDC there is an additional benefit as adaptive welding can be used. This type of welding is often used for Docol AHSS/UHSS. However, adaptive welding is not suitable for the assessment of the welding current range of a steel. In this case conventional resistance spot welding in constant current mode is recommended.

When spot welding Docol AHSS/UHSS the use of sturdy welding guns with high force reserves is recommended. This is also a benefit when spot welding thicker sheets and also in the case of fit-up problems due to, for example, springback problems in the forming operation.

For resistance spot welding of Docol AHSS/UHSS an electrode material of type A2/2 or A2/3 (EN ISO 5182) is recommended. This type of CuCrZr material has a good combination of electrical/thermal conductivity and strength at elevated temperatures. There are many electrodes and electrode caps of different geometries available on the market. The size and geometry of the electrode tip is important for the obtained welding result (weld size, welding range, indentation depth on the sheet surface). For resistance spot welding of Docol AHSS/UHSS, it is recommended to use a domed electrode tip. One reason is that a flat electrode tip needs higher electrode forces than a domed electrode tip to achieve welds of acceptable quality. Electrodes with a domed tip are also beneficial when spot welding zinc coated sheets.

In EN ISO 5821 some examples of electrode caps are given that can be used for the welding of Docol AHSS/UHSS. The most common of these electrode caps are type B, E and F.

2.3 Results from resistance spot welding of Docol AHSS/UHSS

2.3.1 DOCOL MICRO-ALLOYED STEELS (LA/LAD)

Resistance spot welding of Docol micro-alloyed steels is easy due to the lean chemical composition of these steels. Welding problems due to the steel's composition do not normally arise. The failure type when testing these steels is normally plug failure.

Tables 2.3.1–2.3.2 show examples of results measured in resistance spot welding tests of Docol micro-alloyed steels. The examples show that it is possible to obtain wide welding current ranges for these steels. A minimum weld diameter of 4√t mm has been used in the evaluation of the welding current range. The test of the thick sheet in **table 2.3.2** (Docol HR 550 LA-GI 2.5 mm) show that with multi pulse welding it is possible to increase the welding current range in comparison with single pulse welding.

2.3.2 DOCOL DUAL PHASE STEELS (DP)

Docol dual phase steels are available in a broad range of strength levels. All of these DP steels can be resistance spot welded.

Tables 2.3.3 show some examples of results from resistance spot welding tests of dual phase steels of medium strength levels (up to tensile strength of 800 MPa). The obtained values show that it is possible to obtain large welding current ranges for these steels. A minimum weld diameter of 4√t mm has been used in the evaluation of the welding current range. The failure type for all these DP steels is normally plug failure due to the low content of alloying elements for these steels. In **figure 2.3.1** a cross section of a spot weld for the hot-dip galvanized steel Docol 780 DP-GI (GI60/60, sheet thickness 1.5 mm) is shown together with the corresponding hardness profile.

Table 2.3.1 Examples of measured welding current ranges in resistance spot welding of uncoated micro-alloyed steels (LA).

Steel 1/ Steel 2 (thickness mm)	Welding data 1)	Welding current range 2)		Type of failure	Remarks
		△I (kA)	min–max (kA)		
Docol CR 420LA (1.5) / Docol 420LA (1.5)	6/3.5/18/10	2.3	5.8-8.1	Plug	Peel test
Docol CR 420LA (2.0) / Docol 420LA (2.0)	8/5.6/21/10	4.0	7.9–11.9	Plug	Peel test
Docol CR 500LA (1.0) /Docol CR 500LA (1.0)	6.4/3.5/11/10	1.9	5.8–7.7	Plug	Peel test
Docol CR 500LA (2.0) /Docol CR 500LA (2.0)	8/5.0/440/200	3.0	6.2–9.2	Plug	Peel test

1) Cap type B; tip dia. (mm)/force(kN)/weld time (ms, cyc)/hold time (ms/cyc).
2) Minimum weld diameter = 4√t mm.

Table 2.3.2 Examples of measured welding current range in resistance spot welding of hot-dip galvanized micro-alloyed steels (LA-GI).

Steel 1/ Steel 2 (thickness mm)	Welding data 1)	Welding current range 2)		Type of failure	Remarks
		△I (kA)	min–max (kA)		
Docol CR 500LA-GI (1.2)3) / Docol CR 500LA-GI (1.2)3)	6/4.0/16/10	1.5	5.7–7.2	Plug	Peel test
Docol HR 550LA-GI (2.5)3) / Docol CR 500LA-GI (2.5)3)	8/6.0/540 4)/400	2.5	8.5–11.0	Plug	Peel test
Docol HR 550LA-GI (2.5)3) / Docol CR 500LA-GI (2.5)3)	8/6.0/5x180 5)/400	3.0	8.2–11.2	Plug	Peel test

1) Cap type B; tip dia. (mm)/force (kN)/weld time (ms, cyc)/hold time (ms/cyc).
2) Minimum weld diameter = 4√t mm.
3) Coat thickness GI50/50 (7 µm on both sides).
4) Single pulse.
5) Multiple pulse 5x180 ms.

Table 2.3.3 Examples of measured welding current ranges in resistance spot welding of DP steels of medium strength levels.

Steel 1/ Steel 2 (thickness mm)	Welding data [1]	Welding current range [2]		Type of failure	Remarks
		△I (kA)	min–max (kA)		
Docol 600 DL (1.8) / Docol 600 DL (1.8)	6/3.2/400/100	1.5	5.8–7.3	Plug	Peel
Docol 600 DP-GI[3] (1.0) / Docol 600 DP-GI[3] (1.0)	6/3.0/240/200	2.0	5.9–7.9	Plug	Peel
Docol 600 DP-GI[3] (1.0) / Docol 600 DP-GI[3] (1.0)	6/3.5/240/200	3.1	6.0–9.1	Plug	Peel
Docol 800 DL (1.5) / Docol 800 DL (1.5)	6/3.5/20/5	2.0	5.0–7.0	Plug	Peel
Docol 780 DP-GI[4] (1.3) / Docol 780 DP-GI[4] (1.3)	6/3.0/320/200	1.6	6.6–8.2	Plug	Peel
Docol 800 DP-GI[3] (1.5) / Docol 800 DP-GI[3] (1.5)	6/4.5/15/10	1.7	5.8–7.5	Plug	Peel

1) Cap type B; tip dia. (mm)/force (kN)/weld time (ms, cyc)/hold time (ms/cyc).
2) Minimum weld diameter = 4√t mm.
3) Coat thickness GI50/50 (7 µm on both sides).
4) Coat thickness GI60/60 /10 µm on both sides.

MICRO-ALLOYED STEELS (LA)
Micro-alloyed cold forming steels designated according to the lowest guaranteed yield strength.

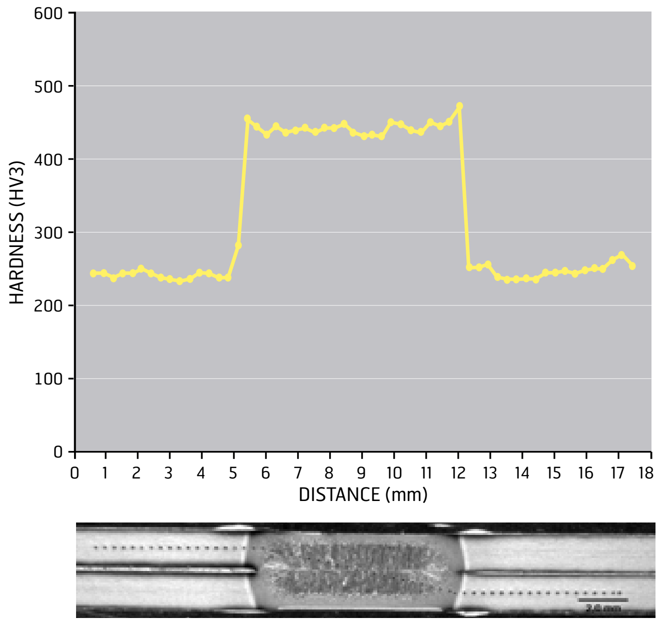
DUAL PHAS E STEELS (DP)
Dual Phase cold forming steels have a microstructure that contains two phases: ferrite and martensite.

COMPLEX PHASE STEELS (CP)
The microstructure contains small amounts of martensite, retained austenite and pearlite within the ferrite/bainite matrix.

MARTENSITIC STEELS (M)
Martensitic steels contain 100 percent martensite.

Figure 2.3.1 Cross section and hardness profile across spot weld for Docol 780 DP-GI (GI60/60, sheet thickness 1.3 mm) spot welded to itself. Welding data: Cap type B 16/6, electrode force 3.0 kN, welding time 320 ms, hold time 200 ms, welding current 7.30 kA.

HARDNESS PROFILE ACROSS WELD. DOCOL 780 DP-GI (GI60/60, t=1.3 mm).



To obtain good welding results for DP steels with tensile strength ≥ 980 MPa, it is important to use high electrode forces and long welding times. This is shown in **figures 2.3.2–2.3.3** for an AHSS steel grade (Docol 1000 DP sheet thickness 1.5 mm). **Figure 2.3.2** also shows that the increased electrode force requires a higher welding current since the contact resistance between the sheets decreases as the electrode force increases.

Table 2.3.4 shows some more welding range results for DP steels with a minimum tensile strength of 1000 MPa (uncoated, electro-galvanized and hot-dip galvanized). These examples show that it is possible to obtain wide welding current ranges for these steels if the welding parameters are changed in an appropriate manner. In **figure 2.3.4** a cross section of a spot weld for Docol 1000 DP-EG (1.5 mm thick) is shown together with the corresponding hardness profile.

Figure 2.3.2 Influence of electrode force on welding range in resistance spot welding of Docol 1000 DP (1.5 mm thickness) to itself.

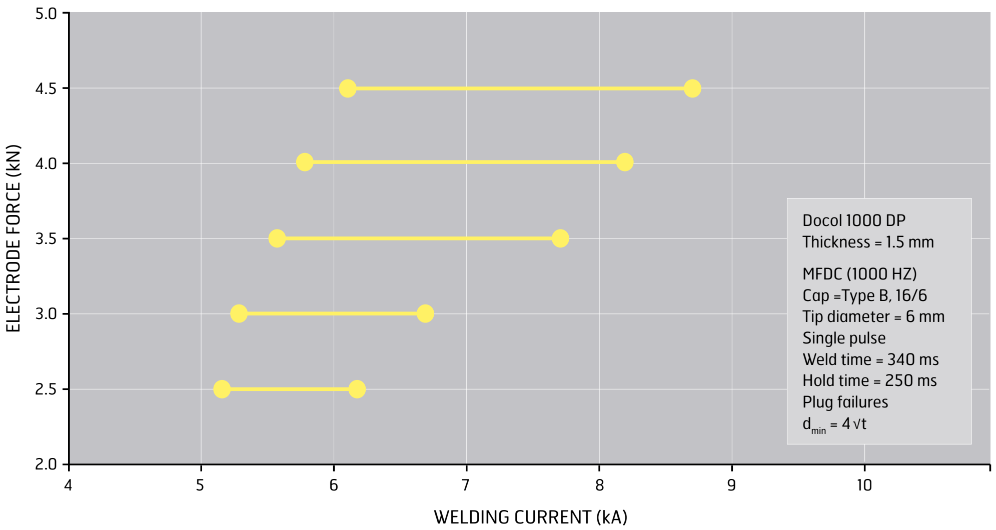
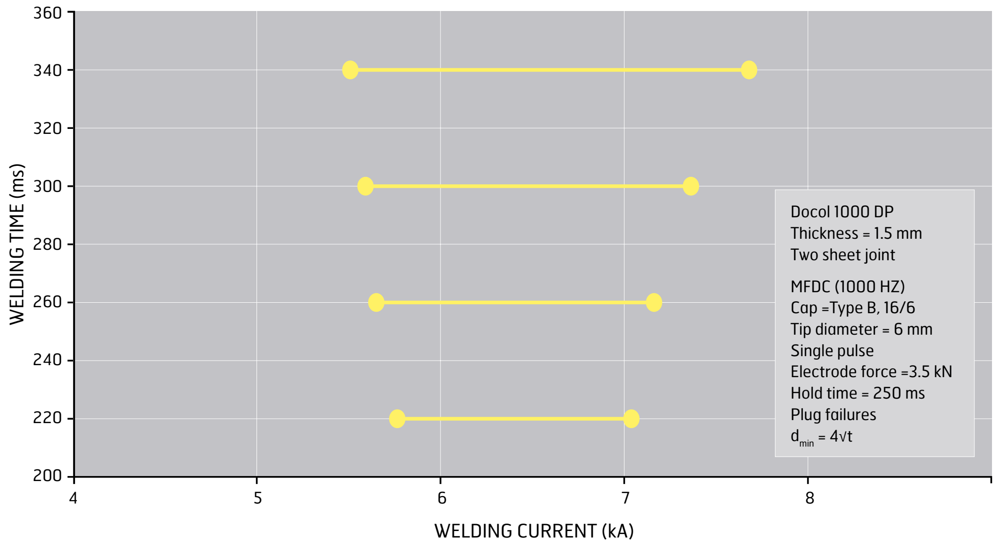


Figure 2.3.3 Influence of welding time on welding range in resistance spot welding of Docol 1000 DP (1.5 mm thickness) to itself.



The type of failure obtained for the steels in **table 2.3.4** is normally plug failures, but in some cases, and especially for thick sheets (1.8–2.0 mm), partial plug failures are often obtained. The reason for this type of failure is that Docol 1000 DP/DP-EG have a higher amount of alloying elements in comparison with DP steels of lower strength.

Docol 1000 (uncoated and electro-galvanized) has a different steel composition in comparison with Docol 1000 DP/DP-EG. The main difference is a lower carbon content for Docol 1000. Due to this changed steel composition the failure type for Docol 1000 is always plug failure. For some companies, it is very important to always obtain plug failures when spot welds are tested. Some examples of obtained welding ranges for Docol 1000 (sheet thickness 1.0 mm) are shown in **figure 2.3.5**. As mentioned before, a high electrode force is beneficial for obtaining a large welding range.

Docol 1180 DP is a newly developed dual phase steel. Despite the very high strength of this steel, it is also possible to use resistance spot welding for this steel. Some examples of obtained welding ranges for Docol 1180 DP (sheet thickness 1.0 mm and 2.0 mm) are shown in **figure 2.3.6**. The failure type for this steel is often plug failures, but in some cases also partial plug failures occur. The reason for this is a higher amount of alloying elements used for this steel in comparison with DP steels of lower strength. A minimum nugget diameter of 4√t mm has been used in the evaluation of the welding current range.

Table 2.3.4 Examples of measured welding current ranges for resistance spot welding of Docol 1000 DP/DP-EG and Docol 1000 DP-X.

Steel 1/ Steel 2 (thickness mm)	Welding data [1)]	Welding current range [2)]		Type of failure	Remarks
		△I (kA)	min–max (kA)		
Docol CR 1000 DP (1.0) / Docol CR 1000 DP (1.0)	6/3.5/220/120	2.5	5.6–8.1	Plug	Peel testing
Docol CR 1000 DP-EG[3)] (1.0) / Docol CR 1000 DP-EG[3)] (1.0)	6/3.5/12/10	2.3	5.6–7.9	Plug	Peel testing
Docol CR 1000DPX-GI (1.1)4) / Docol CR 1000DPX-GI (1.1)4)	6/3.0/18/10	1.8	5.3–7.1	Plug	Cross tension
Docol CR 1000 DP (1.5) / Docol CR 1000 DP (1.5)	6/3.5/340/250	2.1	5.6–7.7	Plug	Peel testing
Docol CR 1000 DP-EG[3)] (1.5) / Docol CR 1000 DP-EG[3)] (1.5)	6/3.5/380/300	2.0	6.0–8.0	Plug	Peel testing
Docol CR 1000 DPX-GI[4)] (1.5) / Docol CR 1000 DPX-GI[4)] (1.5)	6/4.0/400/200	2.0	5.5–8.5	Partial plug	Peel testing

1) Cap type B; tip dia. (mm)/force (kN)/weld time (ms, cyc)/hold time (ms/cyc).
2) Minimum weld diameter = 4√t mm.
3) Coat thickness EG 75/75.
4) Coat thickness GI50/50 (7 μm on both sides).

Figure 2.3.4 Cross section and hardness profile across spot weld for Docol 1000 DP-EG 75/75 (sheet thickness 1.5 mm) spot welded to itself. Welding data: Cap type B 16/6, electrode force 3.5 kN, welding time 380 ms, hold time 300 ms.

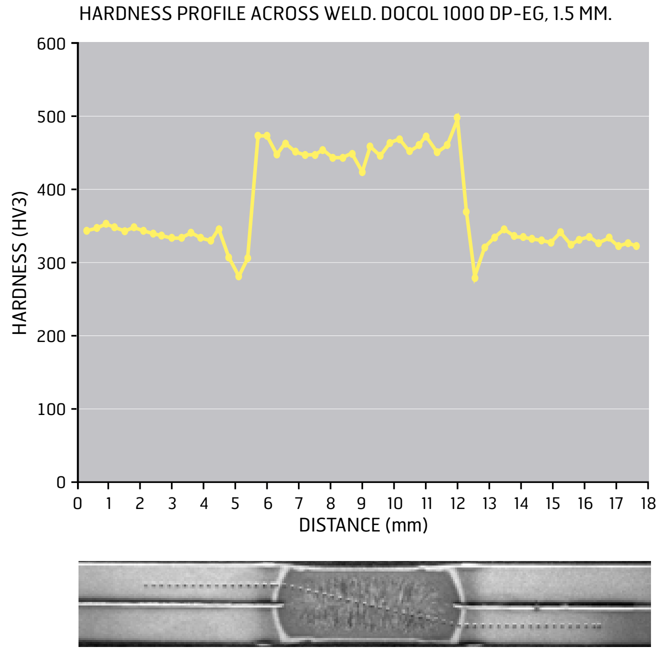


Figure 2.3.5 Influence of electrode force on welding range in resistance spot welding of Docol 1000 (1.0 mm thickness) to itself.

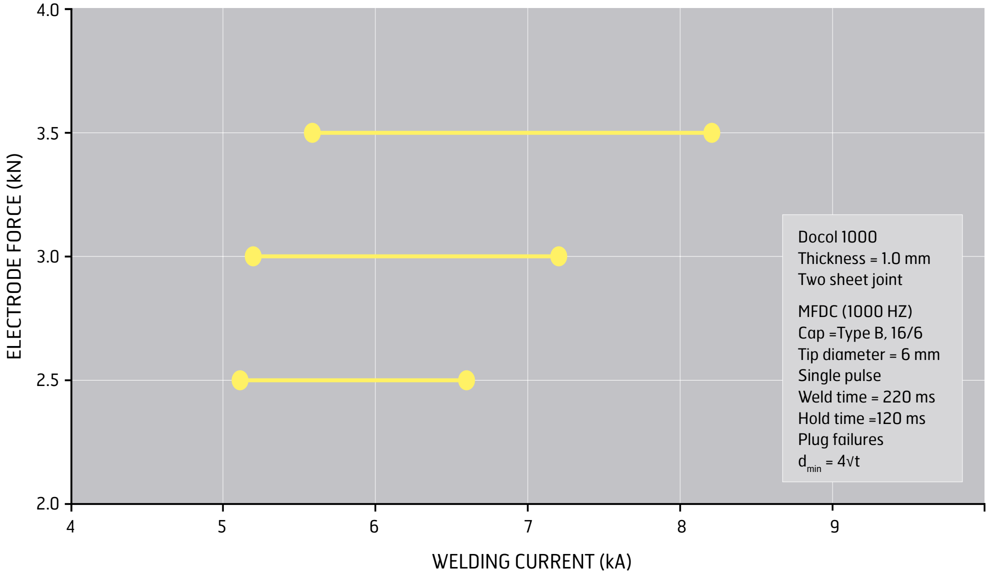
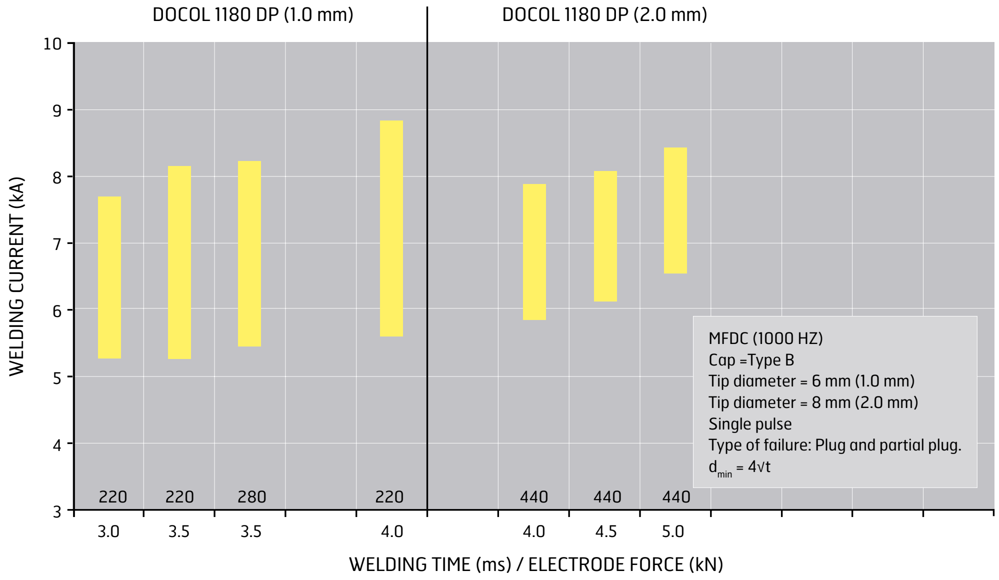


Figure 2.3.6 Welding ranges obtained for Docol 1180 DP in MFDC resistance spot welding.



2.3.3 DOCOL MARTENSITIC STEELS (M)

Docol martensitic steels are available in a broad range of strength levels. Spot welding can be used for all of these martensitic steels. In relation to high strength levels, all martensitic steels have lean chemical compositions. Docol 900 M/M-EG in one line, have very lean chemical compositions and the spot weldability is very good for these steels. Docol martensitic steels with very high strength levels (Docol 1200 M–Docol 1700 M) can also be spot welded. To obtain acceptable welding results for these steels, it is very important that the welding parameters are adjusted to fit these steels (high electrode force, increased welding time).

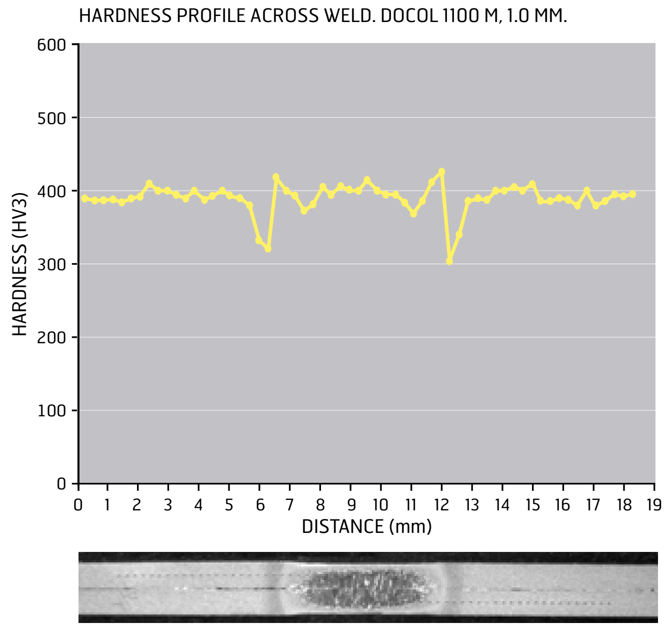
In **table 2.3.5** some examples of results from resistance spot welding of Docol 900 M/M-EG and Docol 1100 M/M-EG are shown. A minimum weld diameter of 4√t mm has been used in the evaluation of the welding current range. The obtained values show that it is possible to obtain large welding current ranges for these steels. The failure type for Docol 900 M/M-EG and Docol 1100 M/M-EG is always plug failure due to the low content of alloying elements for these steels. In **figure 2.3.7** a cross section of a spot weld for Docol 1100 M (1.0 mm thick) is shown together with the corresponding hardness profile.

Table 2.3.5 Examples of measured welding current range for resistance spot welding of Docol 900 M/M-EG and Docol 1100 M/M-EG.

Steel 1/ Steel 2 (thickness mm)	Welding data [1)]	Welding current range [2)]		Type of failure	Remarks
		△I (kA)	min–max (kA)		
Docol CR 900M (1.5) / Docol CR 900M (1.5)	6/3.5/320/200	2.1	5.8–7.9	Plug	Peel testing
Docol CR 900M-EG[3)] (1.0) / Docol CR 900M-EG[3)] (1.0)	6/3.5/300/200	1.8	6.1–7.9	Plug	Cross tension
Docol CR 900M-EG[3)] (1.2) / Docol CR 900M-EG[3)] (1.2)	6/3.5/340/200	2.0	5.9–7.9	Plug	Cross tension
Docol CR 900M-EG[3)] (1.5) / Docol CR 900M-EG[3)] (1.5)	6/3.5/320/200	2.4	6.2–8.6	Plug	Cross tension
Docol CR 1100M (1.0) / Docol CR 1100M (1.0)	6/3.0/220/120	2.6	5.4–8.0	Plug	Peel testing
Docol CR 1100M-EG[3)] (1.0) / Docol CR 1100M-EG[3)] (1.0)	6/3.0/220/120	3.2	6.5–9.7	Plug	Peel testing

1) Cap type B; tip dia. (mm)/force (kN)/weld time (ms, cyc)/hold time (ms/cyc).
2) Minimum weld diameter = 4√t mm.
3) Coat thickness EG 75/75.

Figure 2.3.7 Cross section and hardness profile across spot weld for Docol 1100 M (sheet thickness 1.0 mm) spot welded to itself. Welding data: Cap type B 16/6, electrode force 3.0 kN, welding time 220 ms, hold time 120 ms, welding current 6.19 kA.



In **table 2.3.6** and **figure 2.3.8**, some examples from resistance spot welding of Docol 1200 M/M-EG are shown. A minimum weld diameter of 4√t mm has been used in the evaluation of the welding current range. The obtained values show that it is possible to obtain large welding current ranges for Docol 1200 M/M-EG.

The failure type for Docol 1200 M/M-EG is normally plug failure, but for thick sheets (1.8–2.0 mm) partial plug failures are sometimes obtained. In **figure 2.3.9** a cross section of a spot weld for Docol 1200 M-EG (sheet thickness 2.0 mm) is shown together with the corresponding hardness profile. The hardness curve shows that there is a soft zone in the heat affected zone close to the spot weld. This is quite typical for steels of very high strength with a fully martensitic microstructure.

Table 2.3.6 Examples of measured welding current range for resistance spot welding of Docol 1200 M (sheet thickness 1.0 mm and 1.6 mm).

Steel 1/ Steel 2 (thickness, mm)	Welding data 1)	Welding current range 2)		Type of failure	Remarks
		△I (kA)	min–max (kA)		
Docol CR 1200 M (1.0) /Docol CR 1200 M (1.0)	6/3.0/220/120	2.4	5.3–7.7	Plug	Peel testing
Docol CR 1200 M (1.0) /Docol CR 1200 M (1.0)	6/3.5/220/120	2.7	5.6–8.3	Plug	Peel testing
Docol CR 1200 M (1.6) /Docol CR 1200 M (1.6)	6/3.5/20/10	2.3	5.0–7.3	Plug	Peel testing
Docol CR 1200 M (1.6) /Docol CR 1200 M (1.6)	6/4.0/20/10	2.9	5.2–8.1	Plug	Peel testing

1) Cap type B; tip dia. (mm)/force (kN)/weld time (ms, cyc)/hold time (ms/cyc). 2) Minimum weld diameter = 4√t mm.

Figure 2.3.8 Welding ranges obtained for Docol 1200 M-EG 75/75 (sheet thickness 1.0 mm and 2.0 mm) in MFDC resistance spot welding.

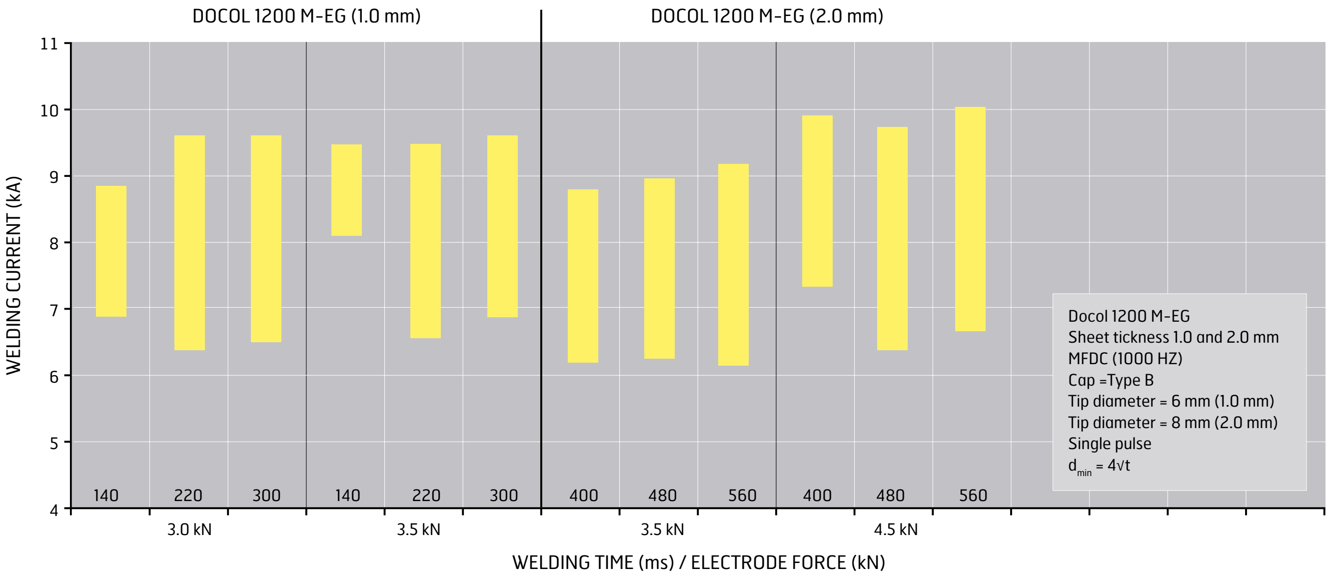
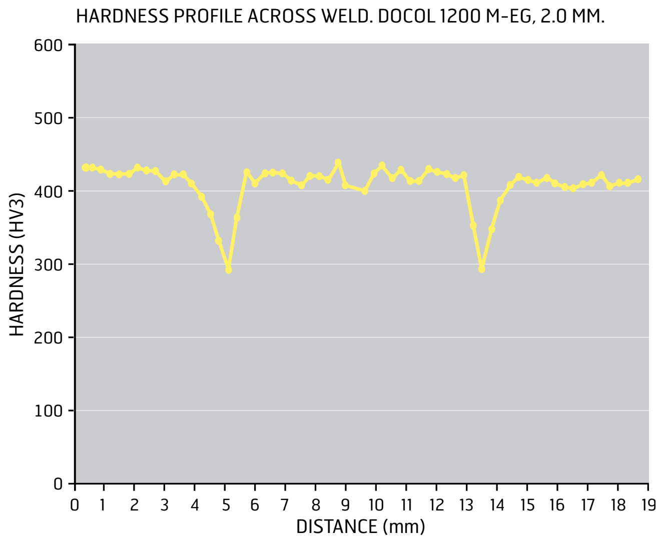
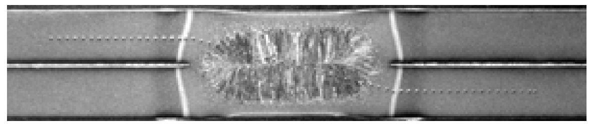


Figure 2.3.9 Cross section and hardness profile of spot weld for Docol 1200 M-EG 75/75 (sheet thickness 2.0 mm) spot welded to itself. Welding data: cap type B 20/8, electrode force 4.5 kN, welding time 480 ms, hold time 300 ms, welding current 7.54 kA.





Some examples of results from resistance spot welding of Docol 1300 M/M-EG are shown in **table 2.3.7**. Large welding current ranges are obtained for both Docol 1300 M and Docol 1300 M-EG in all tested sheet thicknesses. The failure type is mainly plug failures, but in some cases the tests result in partial plug failures. A cross section and the corresponding hardness profile of a spot weld of Docol 1300 M (sheet thickness 1.5 mm) can be observed in **figure 2.3.10**.

For Docol 1400 M it is important to use a high electrode force to obtain a good welding result (c.f. **figure 2.3.11**).

In **figure 2.3.12**, some examples from resistance spot welding of Docol 1400 M (sheet thickness 1.0 mm and 1.5 mm) are shown. The obtained values show that it is possible to obtain large welding current ranges for Docol 1400 M if a high electrode force is used. The failure type for Docol 1400 M is normally plug failure, but quite often partial plug failure is also observed in the tests.

A typical cross section and a hardness profile for a spot weld of Docol 1400 M (sheet thickness 1.0 mm) is shown in **figure 2.3.13**.

Table 2.3.7 Examples of measured welding current range for resistance spot welding of Docol 1300 M and Docol 1300 M-EG.

Steel 1/ Steel 2 (thickness, mm)	Welding data [1]	Welding current range [2]		Type of failure	Remarks
		△I (kA)	min–max (kA)		
Docol CR 1300 M (0.8) /Docol CR 1300 M (0.8)	6/3.5/13/10	2.2	5.1–7.3	Plug	Peel testing
Docol CR 1300 M (1.5) /Docol CR 1300 M (1.5)	6/3.5/20/10	1.7	4.3–6.0	Partial plug	Peel testing
Docol CR 1300 M (1.5) /Docol CR 1300 M (1.5)	6/4.0/400/200	2.0	5.4–7.4	Partial plug	Peel testing
Docol CR 1300 M-EG[3] (1.15) /Docol CR 1300 M-EG[3] (1.15)	6/2.6/270/250	3.0	5.9–8.9	Plug	Peel testing

1) Cap type B; tip dia. (mm)/force (kN)/weld time (ms, cyc)/hold time (ms/cyc).
2) Minimum weld diameter = 4√t mm.
3) Coat thickness EG 60/60.

Figure 2.3.10 Cross section and hardness profile across spot weld for Docol 1300 M (sheet thickness 1.5 mm) spot welded to itself. Welding data: Cap type B 16/6, electrode force 3.5 kN, welding time 20 cyc, hold time 10 cyc, welding current 4.98 kA.

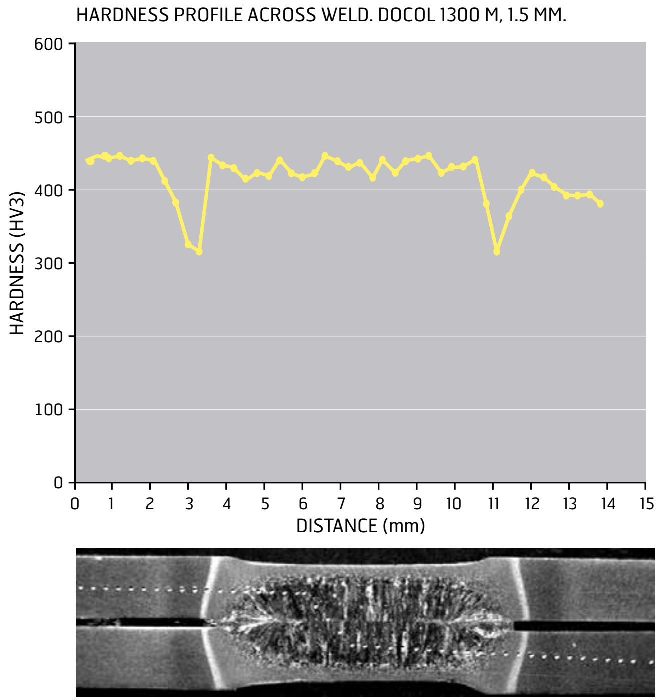


Figure 2.3.11 Influence of electrode force on welding range in resistance spot welding of Docol 1400 M (1.5 mm thickness) to itself.

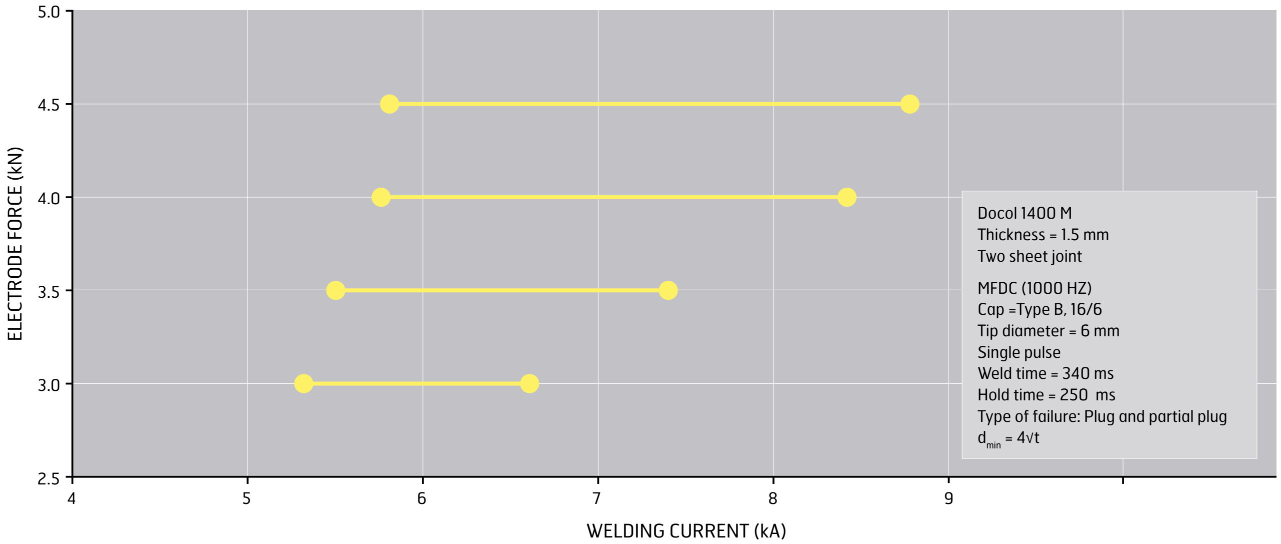


Figure 2.3.12 Welding ranges obtained for Docol 1400 M in MFDC resistance spot welding.

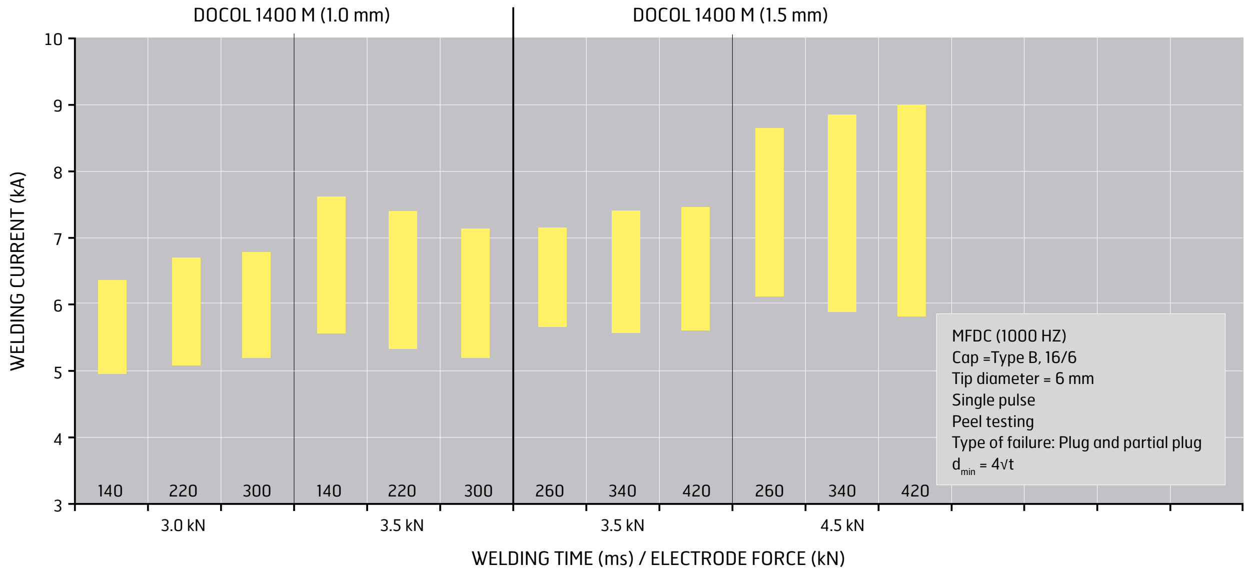
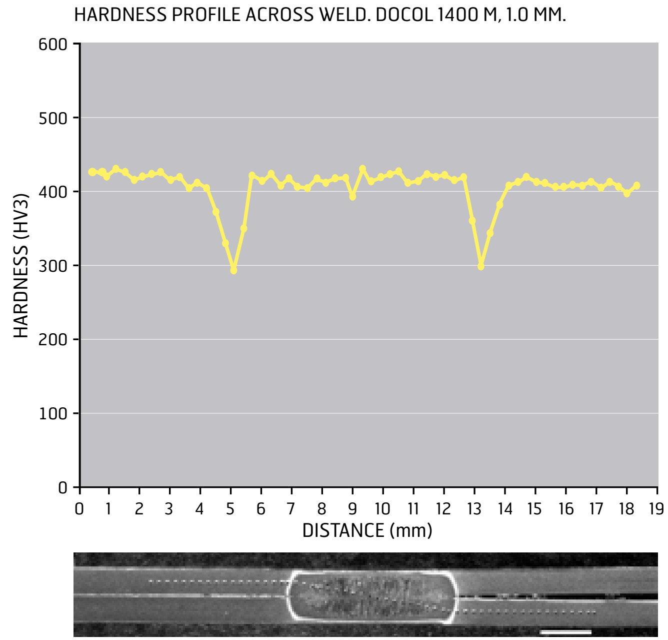


Figure 2.3.13 Cross section and hardness profile across spot weld for Docol 1400 M (sheet thickness 1.0 mm) spot welded to itself. Welding data: Cap type B 16/6, electrode force 3.5 kN, welding time 220 ms, hold time 120 ms.



In **table 2.3.8** some examples from resistance spot welding of Docol 1400 M in sheet thickness 2.0 mm are shown. The type of failure obtained in the tests is partial plug failure and also interfacial failure. Wide welding current ranges are obtained for all three electrode forces used. The difference in obtained welding ranges for different electrode forces is not so large, but an advantage with the highest electrode force used here (5.0 kN) is that the risk for pores in the center of the spot weld is reduced.

In **figure 2.3.14** a weld growth curve is shown for Docol 1400 M-EG 75/75 (sheet thickness 1.3 mm). The type of failure obtained in the peel testing was mainly plug failures. It was only in the lower part of the current range that some partial plug failures were also obtained.

Figure 2.3.15 shows a cross section and a hardness curve from the weld growth curve in **figure 2.3.14**. The hardness curve exhibits a soft zone in the heat affected zone close to the spot weld. As mentioned before, this is quite typical for martensitic steels.

In **table 2.3.9** some more examples from resistance spot welding of Docol 1400 M-EG are shown. A minimum weld diameter of 4√t mm has been used in the evaluation of the welding current range. Large welding current ranges were obtained in all cases.

Table 2.3.8 Examples of measured welding current range for resistance spot welding of Docol 1400 M (sheet thickness 2.0 mm).

Steel 1/ Steel 2 (thickness, mm)	Welding data [1]	Welding current range [2]		Type of failure	Remarks
		△I (kA)	min–max (kA)		
Docol CR 1400 M-EG (2.0) /Docol CR 1400 M (2.0)	8/4.0/480/300	2.2	6.0–8.2	Partial plug + interfacial	Peel testing
Docol CR 1400 M (2.0) /Docol CR 1400 M (2.0)	8/4.5/480/300	2.3	6.4–8.7	Partial plug + interfacial	Peel testing
Docol CR 1400 M (2.0) /Docol CR 1400 M (2.0)	8/5.0/480/300	2.4	6.5–8.9	Partial plug + interfacial	Peel testing

1) Cap type B; tip dia. (mm)/force (kN)/weld time (ms, cyc)/hold time (ms/cyc). 2) Minimum weld diameter = 4√t mm.

Figure 2.3.14 Weld growth curve for spot welded Docol 1400 M-EG 75/75, 1.3 mm welded to itself (peel test). Welding current range=2.7 kA for a minimum weld diameter of 4.6 mm (4√t mm).

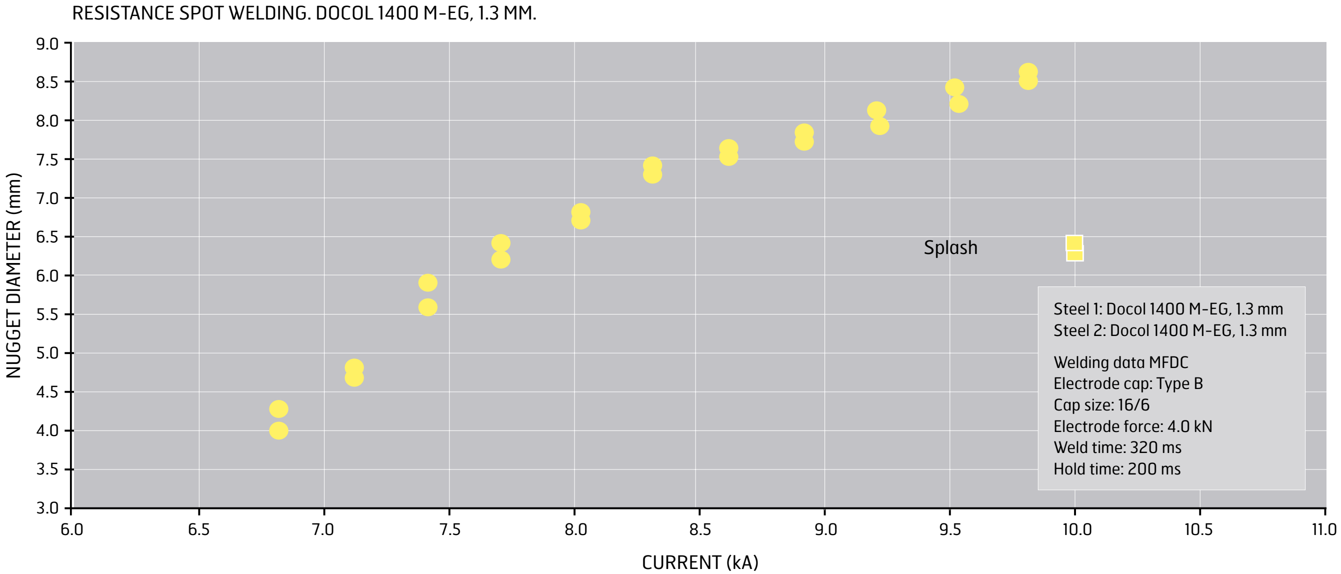


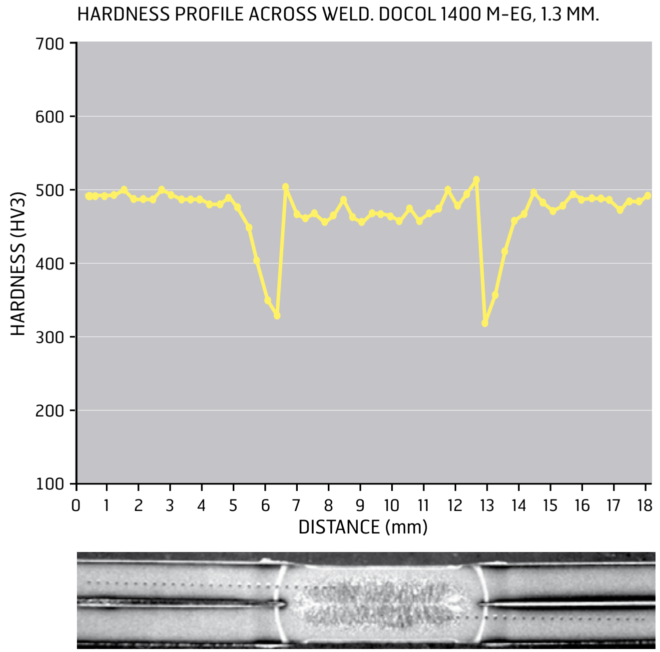
Table 2.3.9 Examples of measured welding current range for resistance spot welding of Docol 1400 M-EG.

Steel 1/ Steel 2 (thickness, mm)	Welding data [1]	Welding current range [2]		Type of failure	Remarks
		△I (kA)	min–max (kA)		
Docol CR 1400 M-EG[3] (1.2) /Docol CR 1400 M-EG[3] (1.2)	6/4.0/320/200	2.1	6.9–9.0	Partial plug	Peel testing
Docol CR 1400 M-EG[3] (1.3) /Docol CR 1400 M-EG[3] (1.3)	6/3.5/320/200	3.2	6.2–9.4	Partial plug	Peel testing
Docol CR 1400 M-EG[3] (1.3) /Docol CR 1400 M-EG[3] (1.3)	6/4.0/320/200	3.7	7.1–9.8	Partial plug	Peel testing
Docol CR 1400 M-EG[3] (1.3) /Docol CR 1400 M-EG[3] (1.3)	6/5.0/320/200	2.4	7.3–9.7	Partial plug	Peel testing

1) Cap type B; tip dia. (mm)/force (kN)/weld time (ms, cyc)/hold time (ms/cyc).
2) Minimum weld diameter = $4\sqrt{t}$ mm.
3) Coat thickness EG 75/75.

Shape's bumper beam (Power B-Section) is made from Docol 1300 M.

Figure 2.3.15 Cross section and hardness curve across spot weld for Docol 1400 M-EG 75/75 (sheet thickness 1.3 mm) resistance spot welded to itself.



In **table 2.3.10**, some examples from resistance spot welding of Docol 1500 M/M-EG are shown. The obtained values show that it is possible to obtain large welding current ranges for Docol 1500 M/M-EG despite the very high strength of this steel.

The failure type for Docol 1500 M/M-EG is often partial plug failures, but interfacial failures are also quite often obtained. The reason for these failures is due to the increased alloying content needed to reach the aimed strength level.

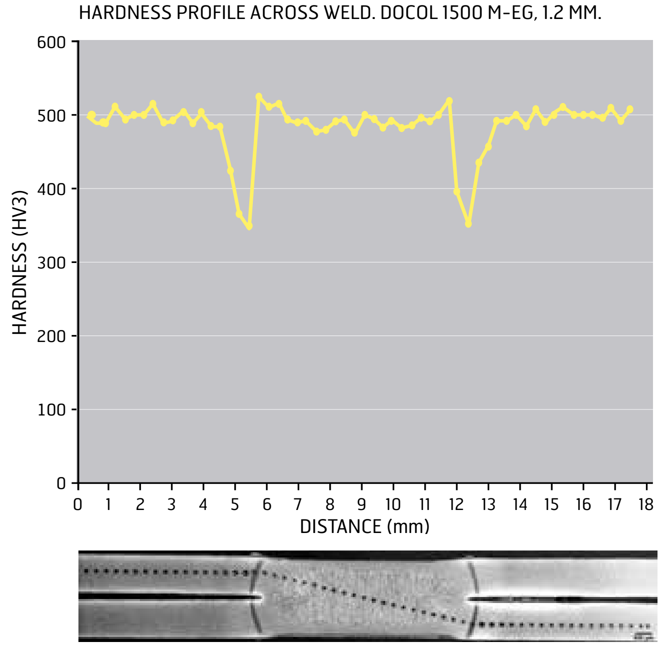
In **figure 2.3.16**, a cross section of a spot weld for Docol 1500 M-EG (sheet thickness 1.2 mm) is shown together with the corresponding hardness profile.

Table 2.3.10 Examples of measured welding current range for resistance spot welding of Docol 1500 M and Docol 1500 M-EG.

Steel 1/ Steel 2 (thickness, mm)	Welding data [1]	Welding current range [2]		Type of failure	Remarks
		△I (kA)	min–max (kA)		
Docol CR 1500 M (1.2) /Docol CR 1500 M (1.2)	6/3.5/280/200	2.7	5.4–8.1	Partial plug	Peel testing
Docol CR 1500 M (1.2) /Docol CR 1500 M (1.2)	6/4.0/280/200	3.2	5.7–8.9	Partial plug	Peel testing
Docol CR 1500 M (2.0) /Docol CR 1500 M (2.0)	8/4.0/480/300	2.0	6.1–8.1	Interfacial	Peel testing
Docol CR 1500 M (2.0) /Docol CR 1500 M (2.0)	8/5.0/480/300	2.4	6.4–8.8	Interfacial	Peel testing
Docol CR 1500 M-EG[3] (1.2) /Docol CR 1500 M-EG[3] (1.2)	6/4.0/320/200	3.0	6.7–9.7	Partial plug	Peel testing

1) Cap type B; tip dia. (mm)/force (kN)/weld time (ms, cyc)/hold time (ms/cyc).
2) Minimum weld diameter = $4\sqrt{t}$ mm.
3) Coat thickness EG 75/75.

Figure 2.3.16 Cross section and hardness curve across spot weld for Docol 1500 M-EG (sheet thickness 1.2 mm) resistance spot welded to itself. Welding data: Cap type B 16/6, electrode force 4.0 kN, welding time 320 ms, hold time 200 ms, welding current 7.31 kA.



2.3.4 STRENGTH

The strength of the spot welded joint is very important for the performance of the spot welded component. The strength of the spot weld increases with increasing sheet thickness and increasing weld size. The strength of the steel also has an influence on the strength of the spot weld. The influence of the steel strength depends on the type of loading. This is demonstrated in **figure 2.3.17** (sheet thickness 1.0 mm) and in **figure 2.3.18** (sheet thickness 1.5 mm) where the shear strength and cross tension strength are plotted vs. base metal strength for Docol AHSS/UHSS of different strength levels (Docol 800 DP, Docol 1000 DP, Docol 1200 M, Docol 1400 M). For reference, steel of lower strengths are also included, as well as a press hardened boron steel of very high strength (sheet thickness = 1.5 mm, tensile strength = 1585 N/mm^2).

The graphs show that the shear strength increases with increasing base metal strength. For the cross tension strength, the influence of base metal strength is less pronounced. The highest cross tension strength is obtained for the DP steels Docol 800 DP and Docol 1000 DP. The reason for the drop in cross tension strength for the steels with very high strength (Docol 1400 M and press hardened boron steel) is that the hardness of the spot weld (hardness in the nugget zone) is higher for these steels in comparison with DP steels and the other softer reference steels. These results demonstrate that the greatest benefit of spot welding steels with very high strength is obtained in shear loading. Peel loading and cross tension loading of spot welds, if possible, should be avoided.

Figure 2.3.17 Static strength of resistance spot weld vs. tensile strength of base metal. (Sheet thickness 1.0 mm, weld size 5.5 mm).

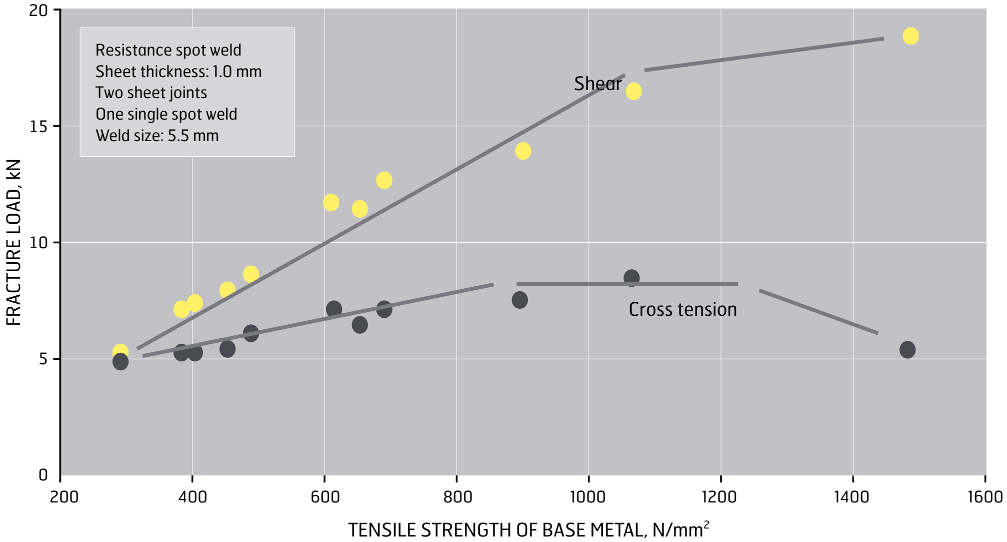
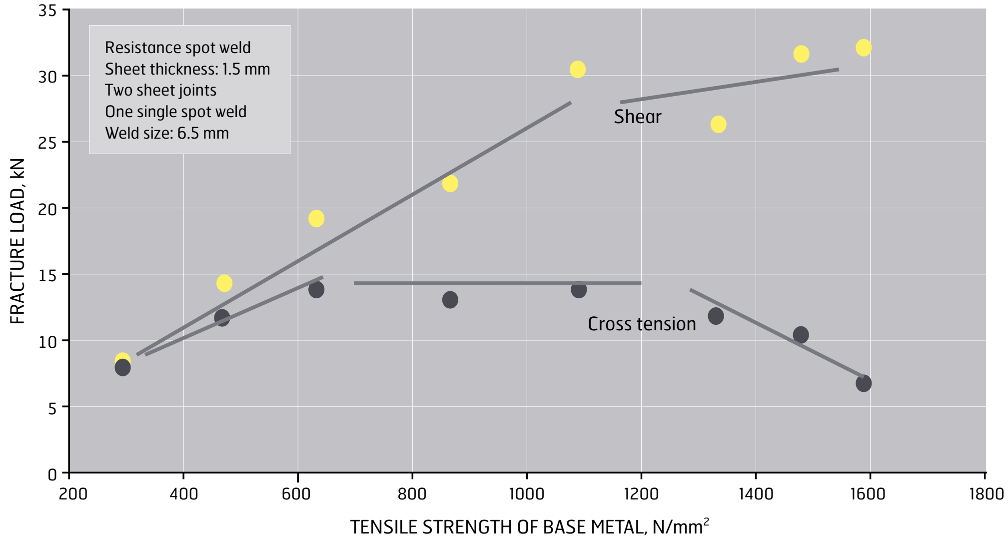


Figure 2.3.18 Static strength of resistance spot weld vs. tensile strength of base metal. (Sheet thickness 1.5 mm, weld size 6.5 mm).



3.

Laser welding of docol AHSS/UHSS

3.1 General about laser welding

Laser welding is very common within the automotive industry. This welding method has many benefits such as:

- High welding speed.
- High productivity.
- Low heat input, which minimize the deformation of the sheets.
- Access needed only from one side.
- Good mechanical properties of welded joints.

Some disadvantages of laser welding are high investment costs and the need for accurate joint preparation and, in some cases, fixturing of the sheets.

Laser butt welding is, for example, used in the production of tailor welded blanks (TWB) and in the roll forming process when closing the profile in the roll forming line. For laser butt welding, a good quality edge and a good fit-up are needed in order to obtain good results after laser welding. In assembly laser welding, different kind of lap welds are often used including a lap fillet weld (edge weld) or a conventional lap weld. Most common is laser lap welding of two sheets, but it is also possible to perform laser lap welding of more than two sheets.

In the assembly welding of different components to a roll formed profile, laser welding has a great advantage compared to gas metal arc welding (GMAW) and resistance spot welding. In comparison to GMAW, laser welding causes less deformation of the component due to the lower heat input of laser welding. Another benefit with laser welding in comparison with GMAW is less spatter. Compared to resistance spot welding, laser welding has the advantage that access is needed only from one side. Spot welding requires access from two sides and that is often not possible when assembling roll formed closed profiles to other components.

3.2 Recommendations for laser welding of Docol AHSS/UHSS

All Docol AHSS/UHSS steel grades can be laser welded. The risk for welding defects is very low for all of these steel grades. There is no big difference between laser welding of mild steels and laser welding of Docol AHSS/UHSS. Normally, the same welding parameters which are used for mild steels can also be used for Docol AHSS/UHSS. There are, however, certain things that should be mentioned in order to obtain optimal results in regards to the mechanical properties and performance of the welded joint.

When laser butt welding, a good quality edge and a good fit-up are needed to obtain an acceptable welding result. It is important to avoid gaps between the sheet edges. Too large of a gap between the sheet edges can give an undesirable underfill on the top side of the weld or even lack of fusion in the weld seam. Depending on the sheet thickness, the maximum allowable edge separation before the start of welding is in the order of 0.1 to 0.2 mm.

For lap welds of thin Docol AHSS/UHSS sheets, full penetration in the lower sheet is recommended due to an easy quality control process in this case. For lap welds in thick sheets full penetration is not always possible. In such a case, it is recommended to use a penetration depth of approximately 50 % in the lower sheet.

In the case of lap welds in combination with zinc coated Docol AHSS/UHSS, a small gap (0.1 – 0.2 mm) between the sheets is beneficial. This way, pores and other defects can be avoided as zinc can escape from the weld. To avoid underfill on the top side of the lap weld, an excessive gap should be avoided. Another way to avoid problems with pores is to use a laser twin-spot technique. The twin-spot welding can be created by beam splitting into two beams. The two focal spots are aligned in the welding direction and thereby create a larger keyhole. The recommended distance between the spots for thin sheets (0.8 – 1.2 mm) is approximately 0.3 – 0.5 mm. With this elongated keyhole a longer time is available for zinc to escape from the weld.

When laser welding of Docol AHSS/UHSS is conducted, an unnecessarily large amount of oil on the sheet surface should be avoided. Too much oil can result in hydrogen pick up in the weld and create weld defects. If problems related to the oil is observed, for example in a roll forming line, the oil can be effectively burnt away before welding by preheating the area close to the sheet edges with a high frequency induction device placed just before the laser welding equipment.

In some cases, it is important to produce laser welds with high strength transverse to the weld. For micro-alloyed steels (Docol LA) and dual phase steels of medium strength (e.g. Docol 600 DP and Docol 800 DP) this is normally not a problem, because the strength of the laser weld is generally higher than the strength of the base metal. However, for dual phase steels of very high strength (Docol 1000 DP, Docol 1180 DP) and Martensitic steels (Docol M), the strength of the laser welds is not always higher than the strength of the base metal. In laser butt welding of steels with very high strength, it is beneficial to use low heat inputs (high welding speeds) to decrease the soft zones. This way, high strength of the welds is obtained. For lap welds, the strength is determined by the properties in the heat affected zone and also by the width of the weld. A very narrow weld results in a small fusion area, which results in low strength. For this type of joint, optimization is required with regard to both the welding heat input and the width of the weld.

Peel loading of laser lap welds should be avoided due to the fact that the peel strength of laser lap welds is very low for all type of steels.

3.3 Results from laser welding of Docol AHSS/UHSS

Typical for the laser welding of thin sheets are the high welding speeds and the low heat inputs. The low heat inputs is a great benefit because the distortions of the sheets are reduced. The low heat input is also very important for the obtained hardness profile across the weld and the mechanical properties of the laser welded joint.

3.3.1 LASER BUTT WELDS

An example of laser butt welding is when closing a roll formed profile in the final step.

Other examples of laser butt welding are in the production of tailor welded blanks (TWB) and laser welding of tubes. For laser butt welding, a good quality edge and a good fit-up are needed to obtain good results after laser welding. The gap between the sheet edges before start of welding should be zero or close to zero. If the gap is too large, there is a risk that the requirements regarding weld quality cannot be fulfilled.

Hardness profiles and cross sections

In **figures 3.3.1–3.3.5**, some examples of hardness profiles of laser butt joints are shown for a Docol micro-alloyed steel (Docol LA), as well as some medium strength Docol DP steels. For some of the steels, the corresponding cross section is also included.

Typical to the laser butt welding of these medium strength steels are:

- the hardness of the fusion zone is higher than the hardness of the base metal.
- the hardness of the inner HAZ (the heat affected zone close to the fusion zone) is higher than the hardness of base metal.
- the drop in hardness (softening) in the outer HAZ is close to zero or very small.

Figure 3.3.1 Cross section and hardness profile across a laser butt weld of Docol 800 DP (sheet thickness 1.5 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, focal spot size 0.5 mm, welding speed 5 m/min.

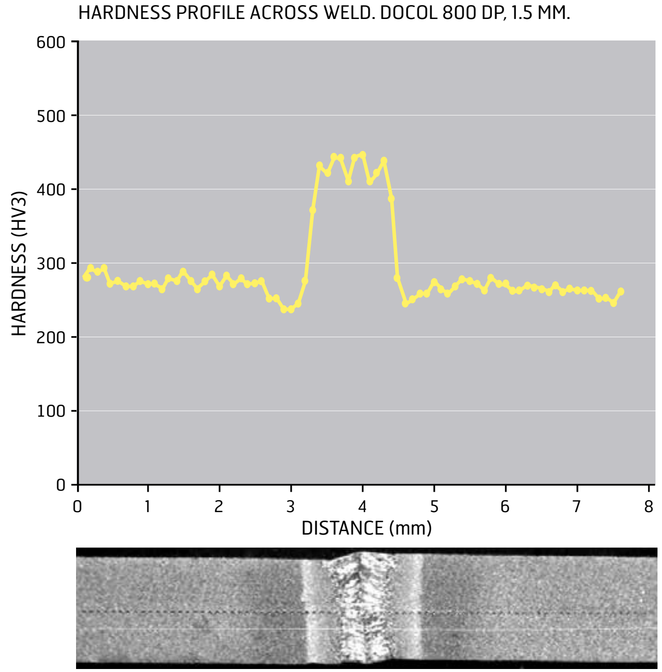


Figure 3.3.2 Hardness profile across a laser butt weld of Docol 500 LA (sheet thickness 1.25 mm).

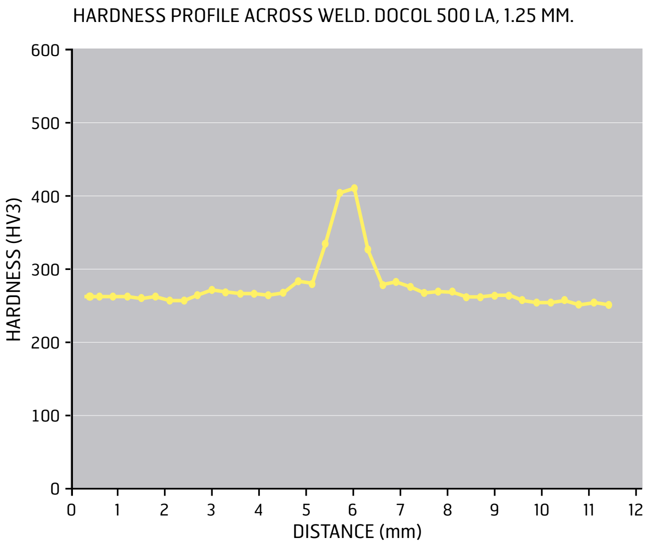


Figure 3.3.3 Hardness profile across a laser butt weld of Docol 800 DL (sheet thickness 1.5 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, focal spot size 0.5 mm, welding speed 5 m/min.

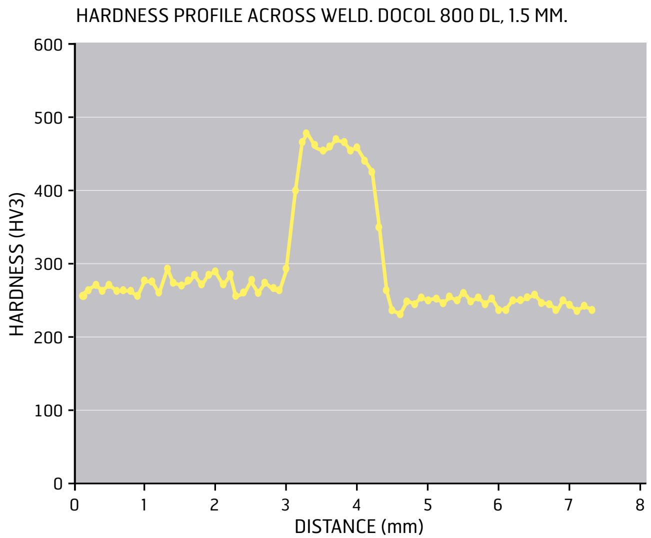


Figure 3.3.4 Hardness profile across a laser butt weld of Docol 600 DP-GI (sheet thickness 1.5 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, focal spot size 0.5 mm, welding speed 5 m/min.

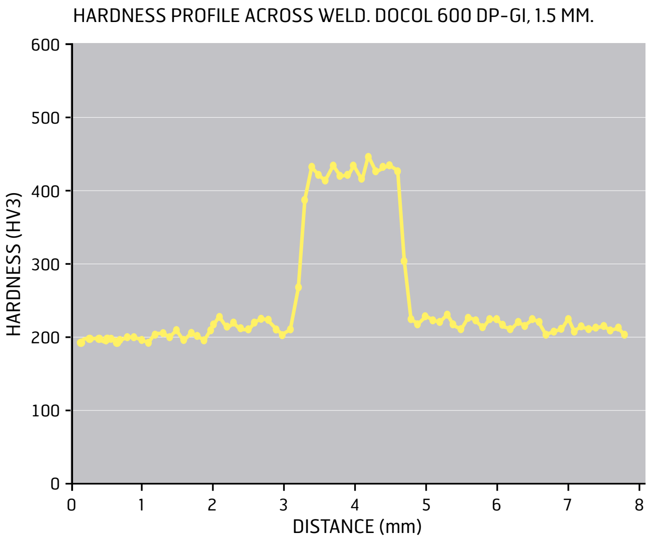
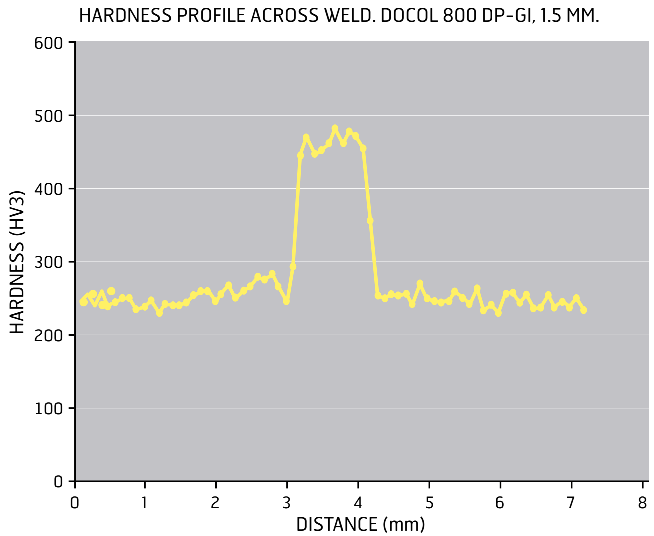


Figure 3.3.5 Hardness profile across a laser butt weld of Docol 800 DP-GI (sheet thickness 1.5 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, focal spot size 0.5 mm, welding speed 5 m/min.



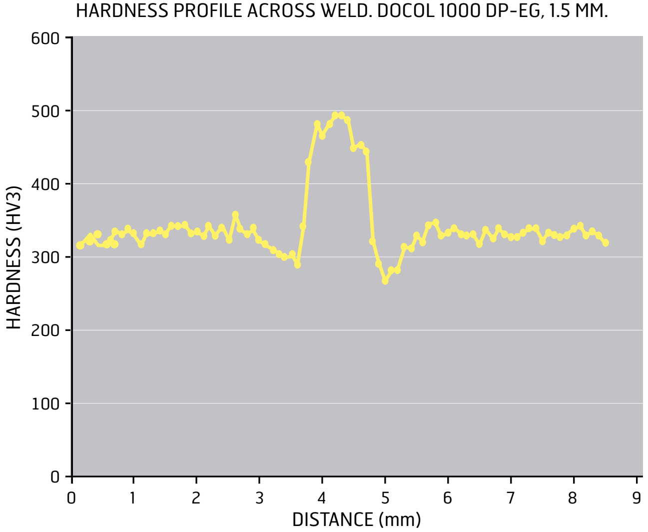
In **figures 3.3.6–3.3.8**, some examples of hardness profiles of laser butt joints are shown for Docol DP steels of high strength (Docol 1000 DP-EG, Docol 1000, Docol 1000 DPX). For Docol 1000 DP-EG, the corresponding cross section is also included.

Some typical characteristics for laser butt welds of these Docol DP steels of very high strength are:

- the hardness of the fusion zone is higher than the hardness of the base metal.
- the hardness of the inner HAZ (heat affected zone close to fusion zone) is higher than the hardness of the base metal.
- in some cases there is a softening in the outer HAZ.

For Docol 1000 DP-EG, there is a slight softening in the outer HAZ. Docol 1000 LCE has a greater softening due to the leaner chemical composition of this steel. The degree of softening is also influenced by the heat input. For low heat input, the softening is small and for high heat input, the softening is greater. For Docol 1000 DP-GI, there is no softening in HAZ. The reason for this is the higher content of alloying element for this steel in comparison with Docol 1000 DP/DP-EG.

Figure 3.3.6 Cross section and hardness profile across a laser butt weld of Docol 1000 DP-EG 75/75 (sheet thickness 1.5 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, focal spot size 0.5 mm, welding speed 5 m/min.



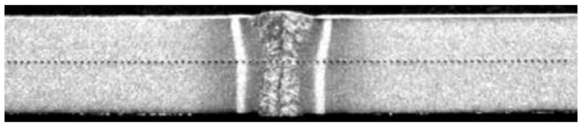


Figure 3.3.7 Hardness profile across a laser butt weld of Docol 1000 LCE (sheet thickness 1.0 mm).

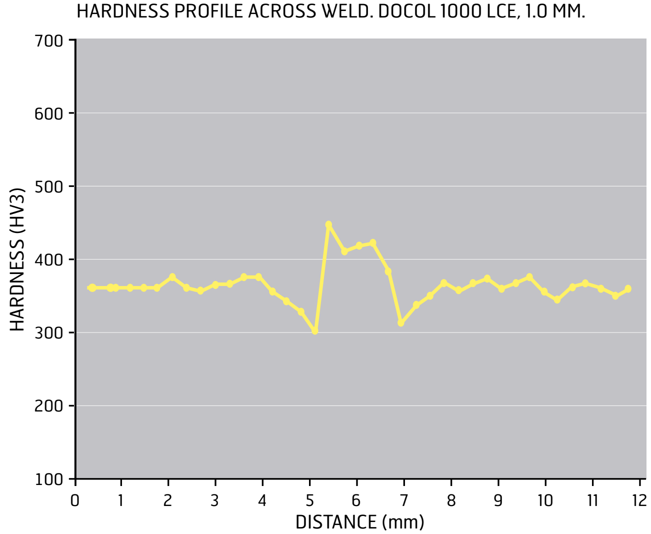
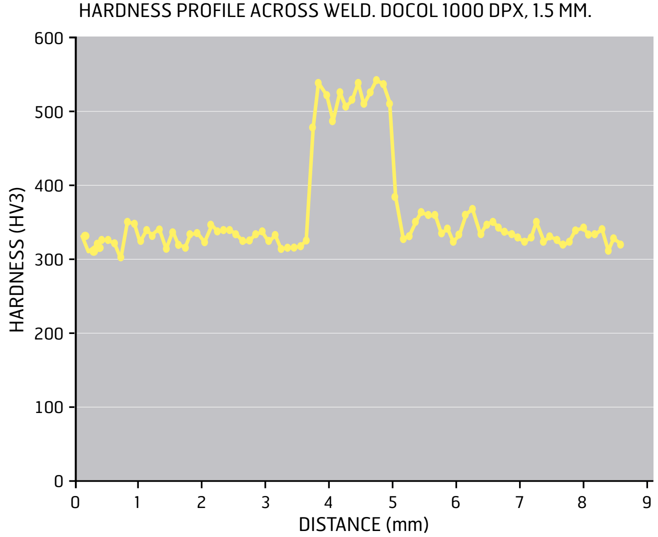


Figure 3.3.8 Hardness profile across a laser butt weld of Docol 1000 DPX (GI50/50, sheet thickness 1.5 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, focal spot size 0.5 mm, welding speed 5 m/min.



Some examples of cross sections and hardness profiles of laser butt welds for some Docol M steels (Docol 900 M-EG, Docol 1200 M, Docol 1400 M-EG and Docol 1500 M) are shown in **figures 3.3.9 – 3.3.12**.

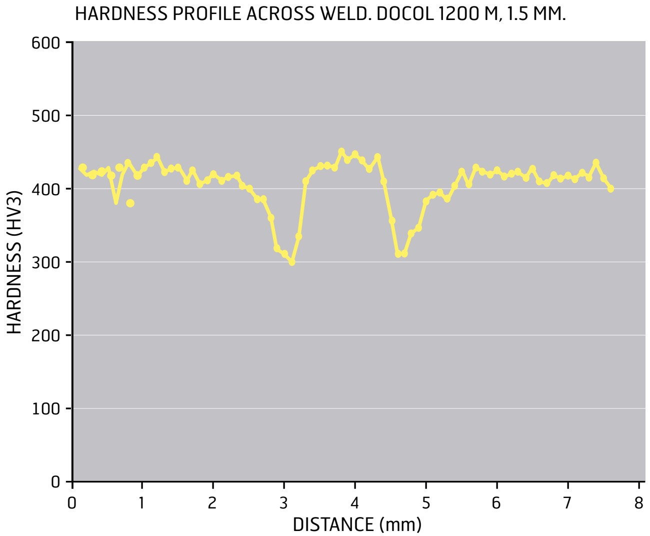
Some typical characteristics for laser butt welds of Docol M steels are:

- the hardness of the fusion zone is slightly higher or approximately the same as the hardness of the base metal.
- the hardness of the inner HAZ is approximately the same as the hardness of the base metal.
- there is a clear softening in the outer HAZ.

The softening in HAZ for Docol M steels reduces the strength of the laser butt joint.

To some degree the softening can be influenced by the welding parameters, but even if the laser welding is performed with very low heat input, it is not possible to completely avoid the softening in HAZ for the Docol M steels.

Figure 3.3.9 Cross section and hardness profile across a laser butt weld of Docol 1200 M (sheet thickness 1.5 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm,focal spot size 0.5 mm, welding speed 5 m/min.



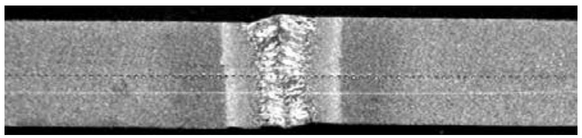


Figure 3.3.10 Hardness profile across a laser butt weld of Docol 900 M-EG (sheet thickness 1.5 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, focal spot size 0.5 mm, welding speed 5 m/min.

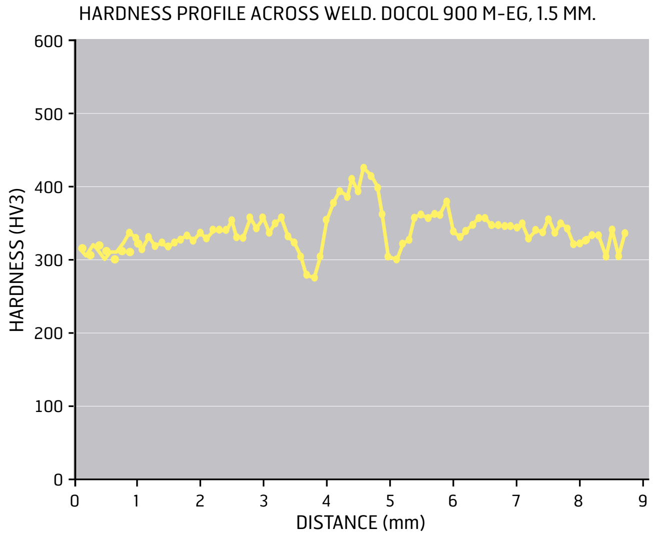


Figure 3.3.11 Cross section and hardness profile across a laser butt weld of Docol 1400 M-EG 75/75 (sheet thickness 1.5 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, focal spot size 0.5 mm, welding speed 5 m/min.

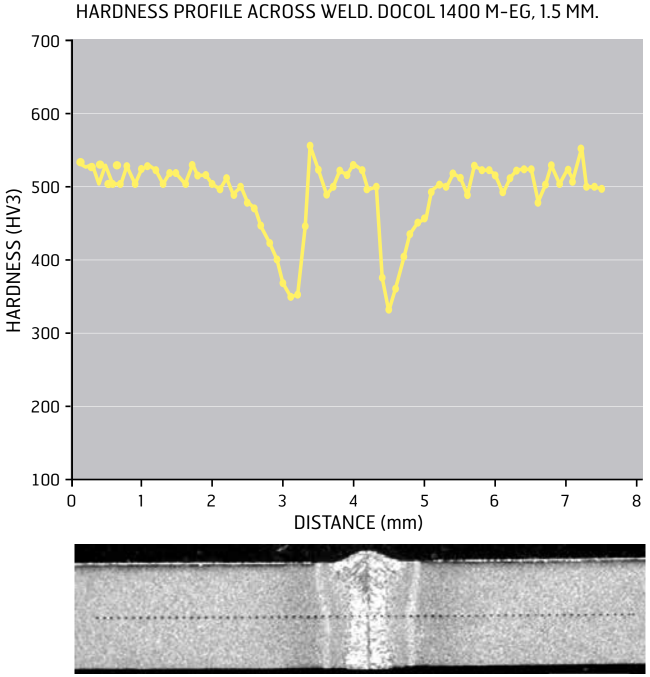
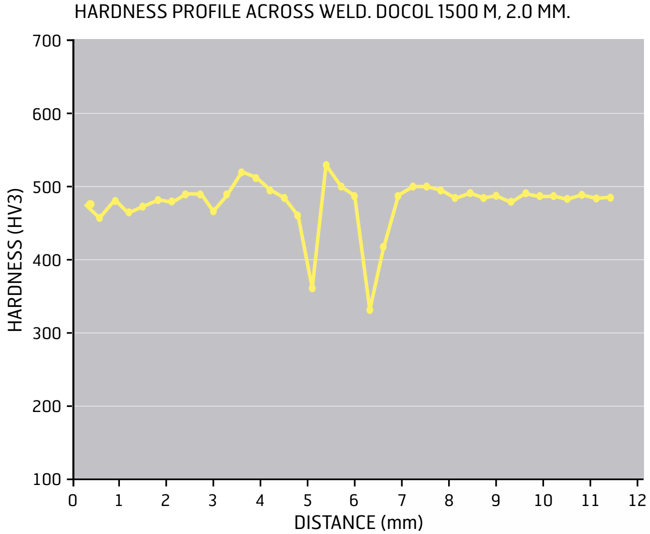
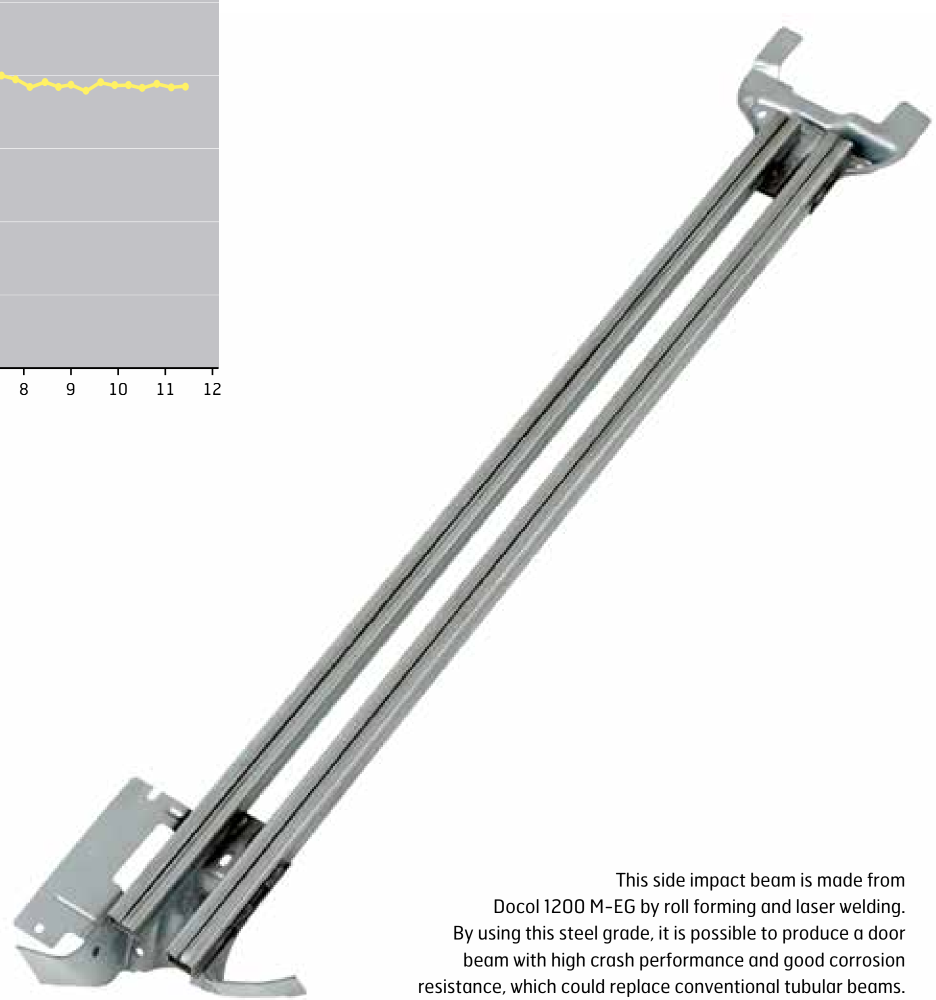


Figure 3.3.12 Hardness profile across a laser butt weld of Docol 1500 M (sheet thickness 2.0 mm).





This side impact beam is made from Docol 1200 M-EG by roll forming and laser welding. By using this steel grade, it is possible to produce a door beam with high crash performance and good corrosion resistance, which could replace conventional tubular beams.

Typical for laser welds is the high hardness in fusion zone (weld metal) and inner HAZ (heat affected zone close to fusion zone). The reason for this is the low heat input for laser welding, which results in a very high cooling rate. The steel composition and especially the carbon content is a very important factor for the obtained hardness level in the fusion zone and inner HAZ (c.f. **figure 3.3.13** Hardness vs. carbon content for laser welded sheets). As an example, it can be mentioned that Docol 1400 M-EG with a carbon content of 0.175 % exhibits a hardness value of 515 (HV0.5). Press hardened boron steels have even higher carbon content (>0.20 %) and higher weld hardness.

The hardness of the laser weld is also influenced by other factors e.g. sheet thickness and laser welding parameters, but in comparison with steel composition, the effect of sheet thickness and welding parameters are quite small.

Strength of laser butt welds

In some cases it is important to produce laser butt welds with high strength transverse to the weld. The results from laser welding tests with Docol AHSS/UHSS (sheet thickness 1.5 mm) are shown in **table 3.3.1** and in **figure 3.3.14**. A CO_2 laser was used with a power of 5.2 kW. A welding speed of 5 m/min was used for all steels. The heat input used is quite low in this case and this results in narrow welds. Examples of cross sections and hardness profiles of the welds are shown in **figures 3.3.2–3.3.11**. The obtained strength transverse to the weld is high and is on the same level as the base metal for all Docol DP/DP-EG steels. The fracture position is located on the base metal for all Docol DP-GI steels and also for most of the Docol DP/DP-EG steels. For Docol 1000 the fracture position is specific to the HAZ and this is due to the soft zones in the HAZ for this steel (c.f. hardness profile of Docol 1000 in **figure 3.3.7**).

Figure 3.3.13 Hardness of weld metal (fusion zone) vs carbon content of base metal in laser welds (sheet thickness 1.5 mm).

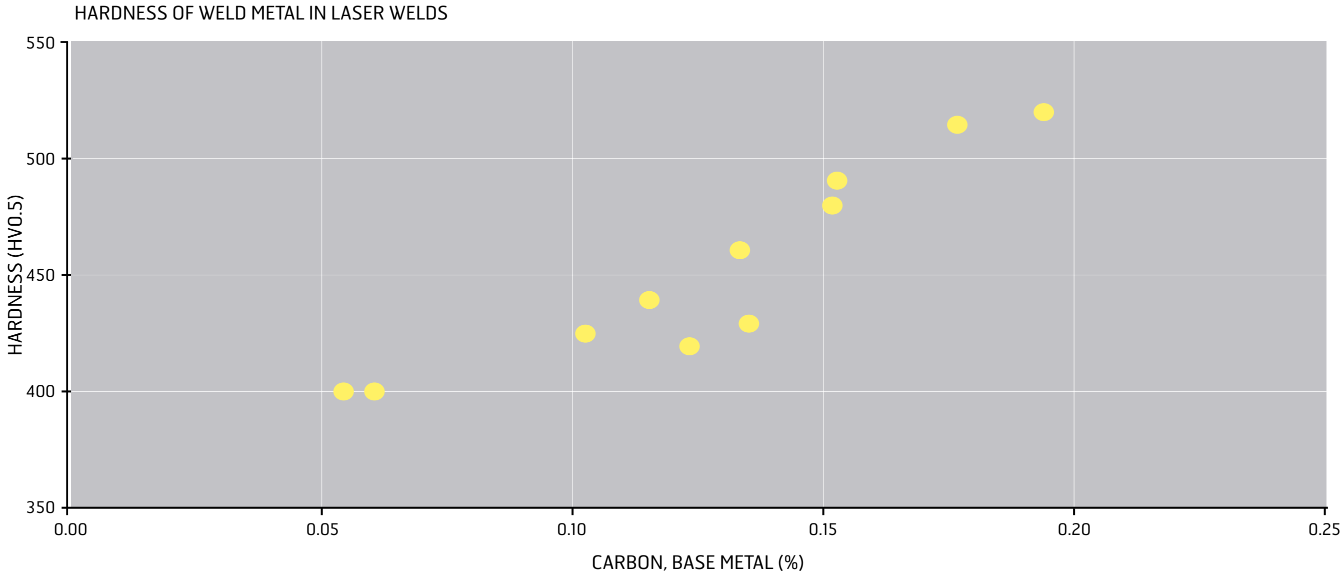
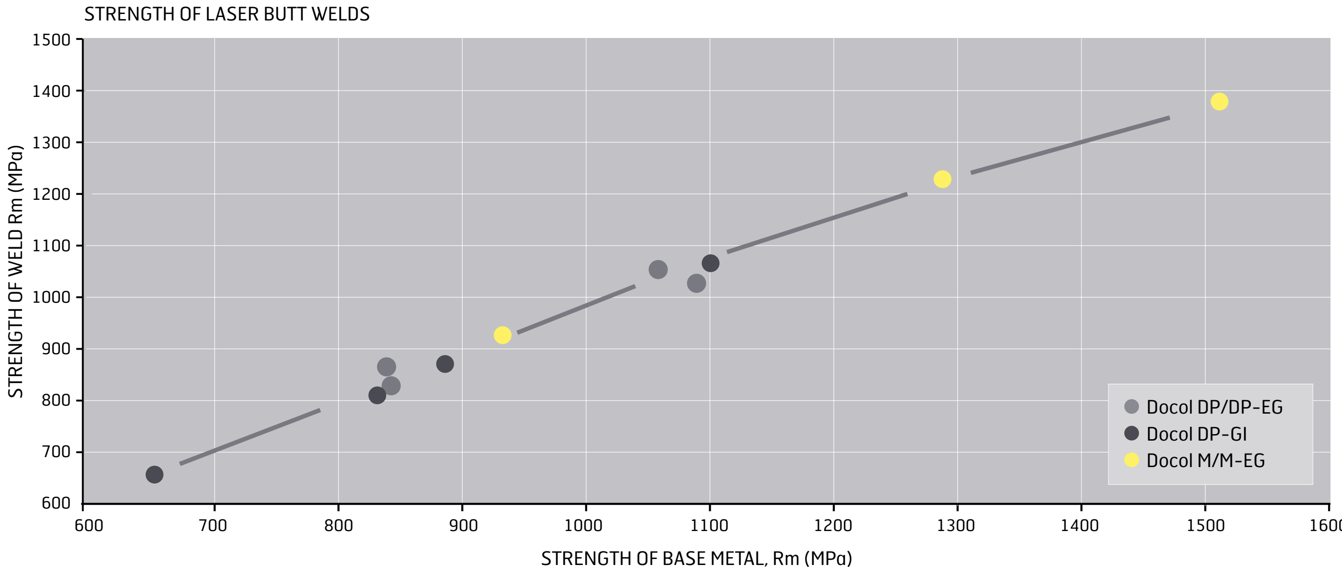


Table 3.3.1 Tensile properties of laser butt welds transverse to the weld for Docol AHSS/UHSS (sheet thickness 1.5 mm, width of tensile specimen 20 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm,spot size 0.5 mm, welding speed 5 m/min.

Steel grade	Strength - base metal		Strength - laser butt weld	
	$R_{p0.2}$ (MPa)	R_m (MPa)	R_m (MPa)	Fracture location[1)]
Docol CR 800DP	528	840	862	BM
Docol CR 800DL	435	844	831	BM
Docol CR 1000DP-EG	800	1091	1030	BM
Docol CR 1000LCE	741	1058	1054	HAZ
Docol CR 900M-EG	794	932	932	BM
Docol CR 1200M	1102	1289	1241	HAZ
Docol CR 1400M-EG	1294	1512	1386	HAZ
Docol CR 600DP	428	670	653	BM
Docol CR 800DP	519	834	808	BM
Docol CR 800DPX-GI	740	888	868	BM
Docol CR 1000DPX-GI	948	1104	1064	BM

1) BM=base metal; HAZ=heat affected zone.

Figure 3.3.14 Tensile strength of laser butt welds transverse to the weld vs strength of base metal for Docol AHSS/UHSS. Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, spot size 0.5 mm, welding speed 5 m/min.



The obtained strength for the Docol M/M-EG steels is also very high in these tests. The minimum tensile strength requirement of the base metal is also fulfilled in the welded joints for both Docol 900 M-EG and Docol 1200 M. The only case in which the base metal tensile strength requirement is not met, is for Docol 1400 M-EG. The reason for this is the soft zones in the HAZ. The fracture position is located in these zones for Docol 1400 M-EG.

To obtain high strength for laser butt welds of very high strength Docol AHSS/UHSS (Docol 1000 DP, Docol 1180 DP, Docol M steels), it is important to use low heat input as for example in the laser welding tests shown in **figure 3.3.14**. If high heat inputs are used, this will result in large soft zones, which will reduce the strength of the welds. Welding speed is an important factor for the heat input and with decreasing welding speed, the heat input is increased.

The results in **table 3.3.2** illustrate the influence of welding speed on the transverse strength of laser butt welds for Docol 1000 DP (2.0 mm sheet thickness). The higher the welding speed is, the better the transverse tensile strength value. For three of the welds (welding speed 1.8, 2.1 and 2.4 m/min) the minimum guaranteed tensile strength of this steel grade (1000 MPa) is fulfilled. However, for the two lowest welding speeds (1.2 and 1.5 m/min), the minimum guaranteed tensile strength cannot be fulfilled.

The hardness profiles of the laser butt welds for two different welding speeds are shown in **figure 3.3.15**. These results show that the maximum hardness is obtained in the weld metal and in the HAZ, there is a hardness drop (soft zone) for the laser weld with welding speed 1.2 m/min. For the laser weld with the highest welding speed (2.4 m/min), the hardness drop in HAZ is very small and the tensile strength for this laser weld is also higher.

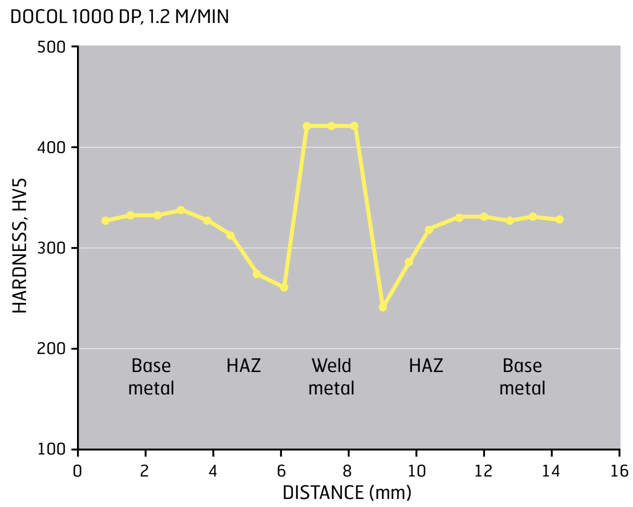
One of the benefits with laser butt welding is that the strength of the weld in Docol UHSS steels can be increased in comparison with ordinary gas metal arc welding. The reason for this is that the heat input is much lower for laser welding and the material is therefore less affected by the heat. With gas metal arc welding, there will be large soft zones in the HAZ, which is very detrimental to the strength of the weld.

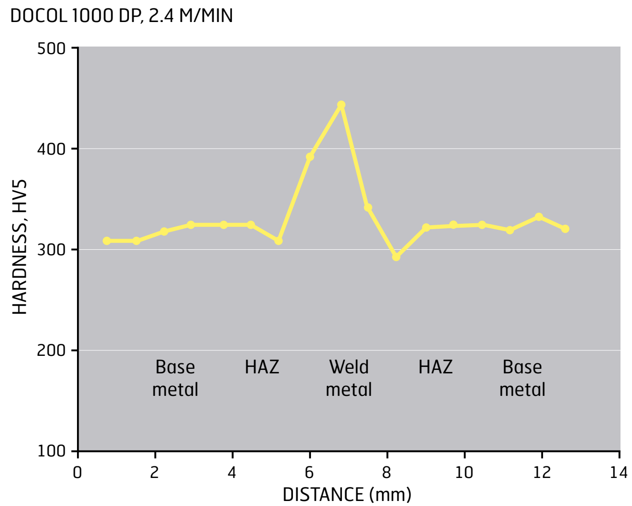
Table 3.3.2 Tensile properties of laser butt welds[1)] for Docol 1000 DP (sheet thickness 2.0 mm) welded with different weldings speeds.

Steel Grade	Welding speed (m/min)	Yield strength[2)] R_e (N/mm^2)	Tensile strength[2)] R_m (N/mm^2)	Fracture position
Docol 1000 DP (2.0 mm)	1.2	749	968	HAZ
	1.5	740	989	HAZ
	1.8	729	1022	HAZ
	2.1	746	1025	HAZ
	2.4	737	1033	Base metal

1) Welded with a Nd:YAG laser equipment. 2) Transverse to the weld.

Figure 3.3.15 Hardness profiles across laser welds of Docol 1000 DP for two laser butt welds produced with two different welding speeds (1.2 m/min and 2.4 m/min).





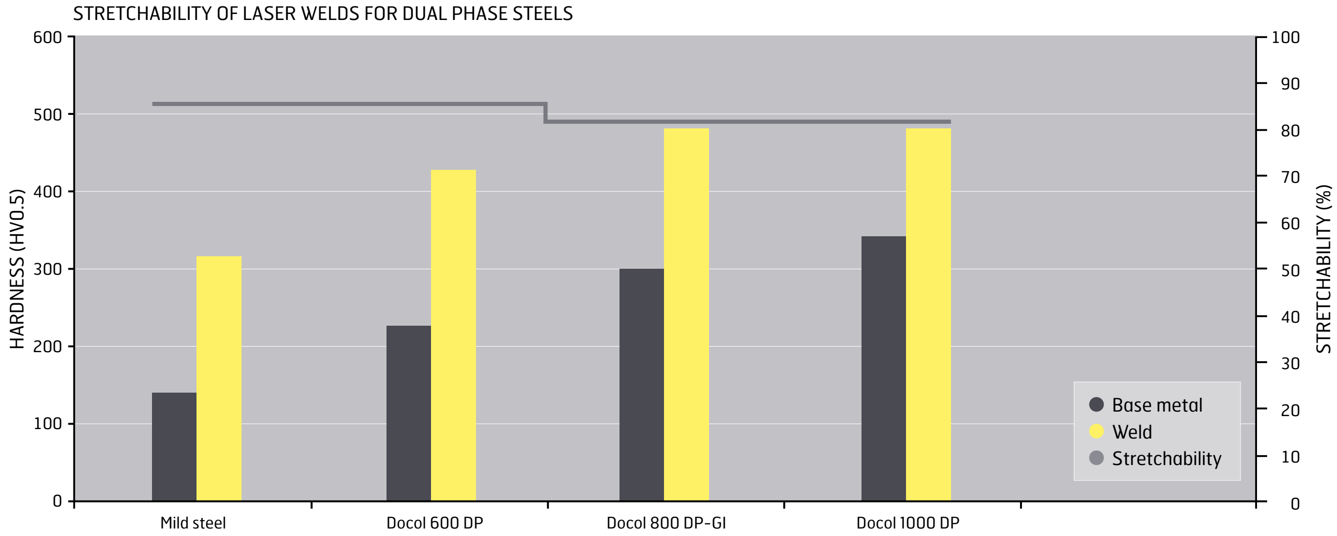
Tailored welded blanks

If a tailored welded blank product is intended for use in a forming operation, a stretchability test (Erichsen cup test) can be used for evaluation of the formability of the laser weld. For all laser butt welded Docol DP and Docol DP-GI steels, it is possible to obtain good stretchability values, c.f. results in **figure 3.3.16** (Stretchability = 100 x the ratio of stretchability of weld to stretchability of base metal). The hardness of the laser welds for DP steels is higher than for mild steels (**figure 3.3.16**), but despite this fact, good stretchability values can be achieved for the DP steels. The reason is that the factor, which mainly determines the stretchability of a laser weld, is the difference in hardness between the weld metal (fusion zone) and the base metal, and these values are not so much higher for dual phase steels compared to mild steels. To obtain such a high stretchability value for Docol 1000 DP, which is shown in **figure 3.3.16**, it is important to use a high laser welding speed to avoid soft zones in the heat affected zone.

Laser butt welded martensitic steels exhibit lower stretchability values than dual phase steels. The reason for the lower stretchability values for martensitic steels are the soft zones in the heat affected zone.

$$\text{Stretchability (\%)} = \frac{\text{Stretchability of weld}}{\text{Stretchability of base metal}} \cdot 100$$

Figure 3.3.16 Hardness and stretchability of laser butt welds for Docol DP and Docol DP-GI steels.
Butt welds with both sheets of the same thickness (1.2 mm). The Erichsen test is used for describing the stretchability.



3.3.2 LASER LAP WELDS

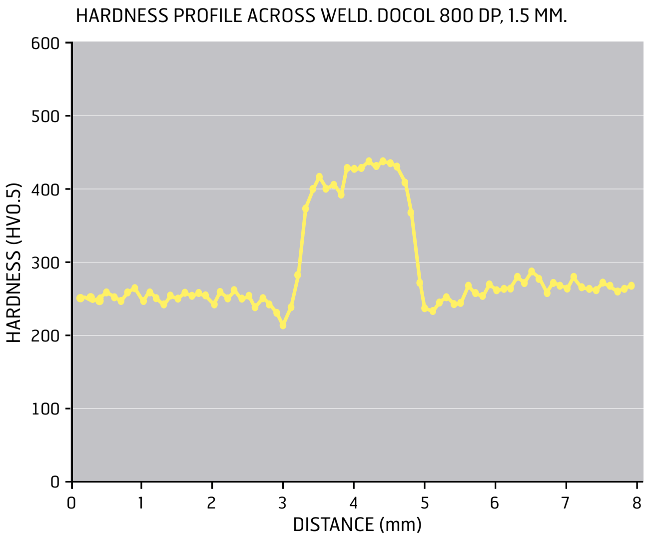
Sheets of a number of Docol AHSS/UHSS steel grades (thickness 1.5mm) have been laser lap welded. The welding was conducted with a CO_2 laser with a power of 5.2 kW. The focal length was 200 mm in combination with a spot size of 0.5 mm. For all steel grades, a travel speed of 2.5 m/min was used. For the uncoated steels there were no gaps between the sheets. To avoid welding problems for the zinc coated steel grades, shims were used to get a gap of approximately 0.1 mm between the sheets.

Hardness profiles and cross sections

The general conclusions regarding hardness profiles for laser butt welds of Docol AHSS/UHSS are also valid for lap welds. Due to the different heat inputs needed to achieve a good weld geometry between a butt weld and a lap weld, there can be some small differences in the obtained hardness values.

Some examples of hardness profiles and cross sections for the laser lap welded Docol AHSS/UHSS steel grades are shown in **figures 3.3.17 – 3.3.20**.

Figure 3.3.17 Cross section and hardness profile across a laser lap weld of Docol 800 DP (sheet thickness 1.5 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, focal spot size 0.5 mm, welding speed 2.5 m/min.



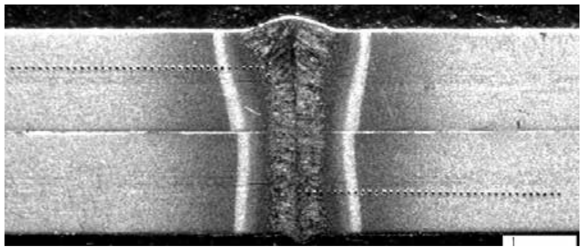
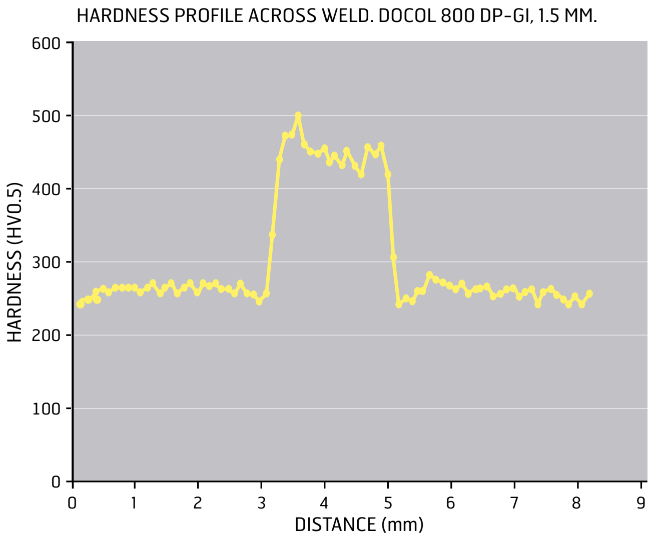


Figure 3.3.18 Cross section and hardness profile across a laser lap weld of Docol 800 DP-GI (sheet thickness 1.5 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, focal spot size 0.5 mm, welding speed 2.5 m/min.



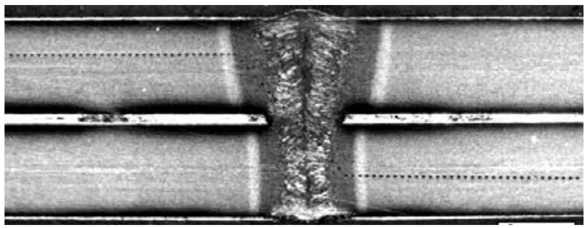


Figure 3.3.19 Cross section and hardness profile across a laser lap weld of Docol 1200 M (sheet thickness 1.5 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, focal spot size 0.5 mm, welding speed 2.5 m/min.

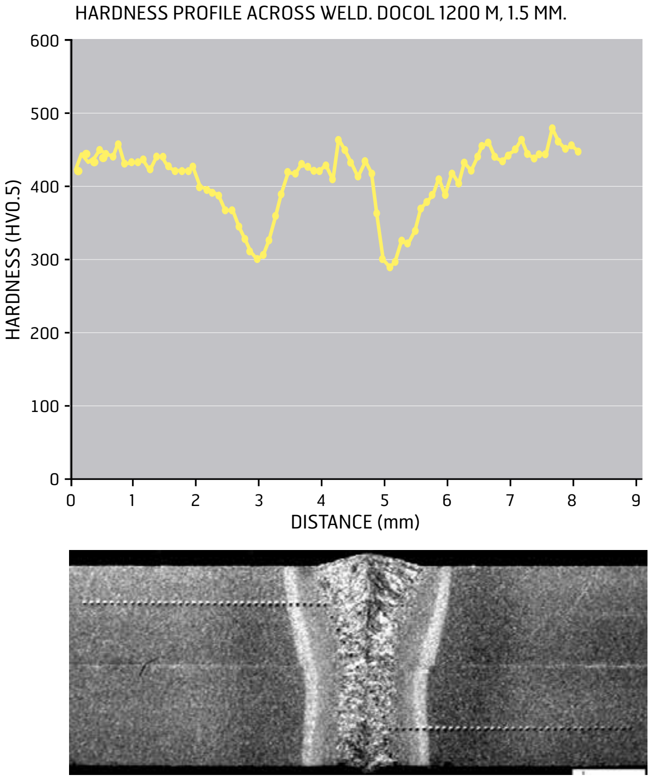
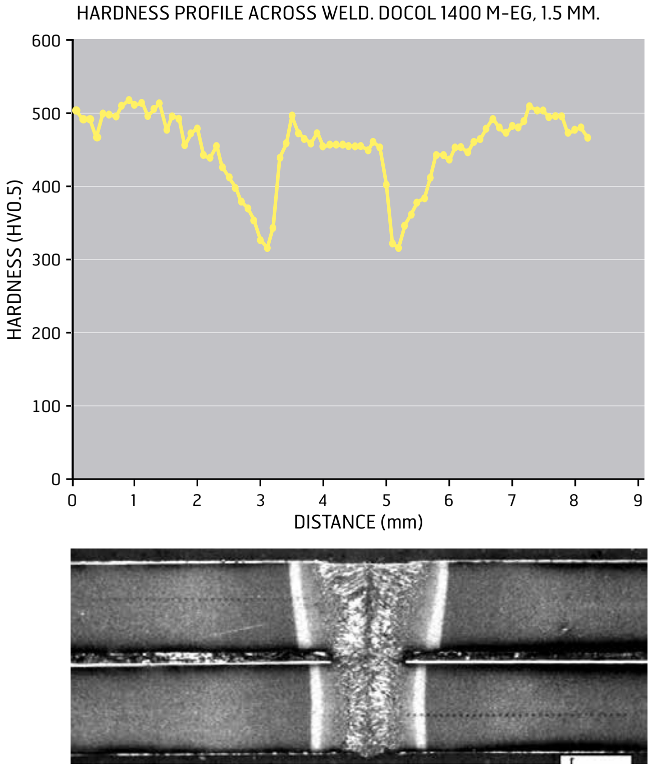


Figure 3.3.20 Cross section and hardness profile across a laser lap weld of Docol 1400 M-EG 75/75 (sheet thickness 1.5 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, focal spot size 0.5 mm, welding speed 2.5 m/min.



Strength of lap welds

Shear testing with specimens taken transverse to the weld was conducted for the laser lap welded steel grades. The width of the tensile specimen was 20 mm.

The welding parameters used in the tests resulted in rather narrow welds. Typical geometries of the welds for some of the steel grades are shown in **figures 3.3.17 – 3.3.20**. The width of the welds were 0.8 – 1.2 mm at the interface between the sheets. It was observed that the width of the welds were somewhat greater for the zinc coated steels (width 1.0 – 1.2 mm) in comparison with the uncoated steels (width 0.8 – 0.9 mm). The reason for this difference is that a gap between the sheets was used during the welding for the zinc coated sheets. Some of the melted material sank down to fill out the gap between the sheets. Due to this, the weld became wider in this area.

The results of the shear testing are shown in **table 3.3.3** and **figure 3.3.21**. The conclusions from these results are:

- The obtained shear strength is lower than the tensile strength of the base metal for all tested steels.
- For the main part of the steels, the fracture is located on the weld metal. The weld has fractured by shearing off of the weld metal at the interface between the sheets (c.f. cross section in **figure 3.3.22**).
- The zinc coated steels exhibit higher strength than the uncoated steels. This is due to the greater weld width for the zinc coated steels.
- There is no evident influence of the strength of the steels. The reason for this is that it is mainly the width of the weld that determines the shear strength in this case.

If an increased shear strength of a laser lap weld is needed, the width of the weld has to be increased. This can be done by changing the laser welding parameters (for example by reducing the welding speed). Another way to increase the strength transverse to the weld line would be to use an additional weld near the first weld.

Table 3.3.3 Shear tensile tests of laser lap welds transverse to the weld for Docol AHSS/UHSS (sheet thickness 1.5 mm, width of tensile specimen 20 mm). Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, spot size 0.5 mm, welding speed 2.5 m/min.

Steel grade	Strength - base metal		Shear strength - lap weld	
	$R_{p0.2}$ (MPa)	R_m (MPa)	R_m (MPa)	Fracture location[1)]
Docol CR 800DP	528	840	424	WM
Docol CR 800DL	435	844	442	WM
Docol CR 1000DP-EG	800	1091	639	WM
Docol CR 1000LCE	741	1058	431	WM
Docol CR 900M-EG	794	932	582	HAZ
Docol CR 1200M	1102	1289	405	WM
Docol CR 1400M-EG	1294	1512	631	WM
Docol CR 600DP	428	670	579	WM
Docol CR 800DP	519	834	527	WM
Docol CR 800DPX-GI	740	888	529	WM
Docol CR 1000DPX-GI	948	1104	657	HAZ

1) WM=weld metal; HAZ=heat affected zone.

Figure 3.3.21 Shear strength of laser lap welds transverse to the weld vs strength of base metal for Docol AHSS/UHSS. Welding data: CO_2 laser, power 5.2 kW, focal length 200 mm, spot size 0.5 mm,welding speed 2.5 m/min.

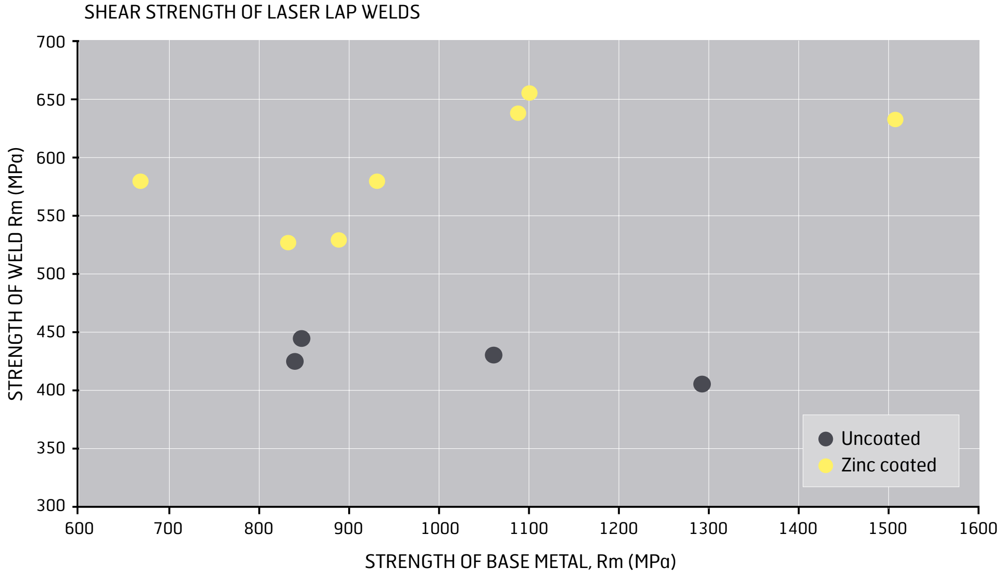
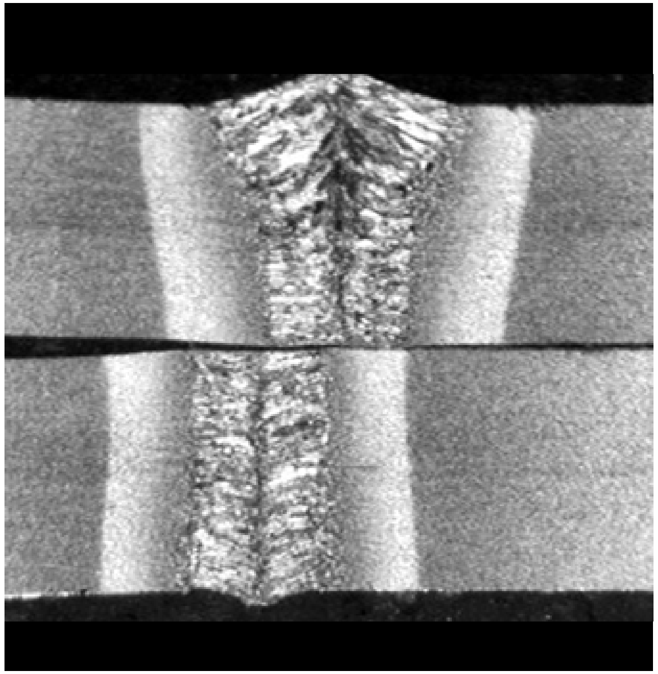


Figure 3.3.22 Cross section of fractured tensile shear specimen for a laser lap weld. The weld has fractured by shearing of the weld metal at the interface between the sheets.



4.

Arc welding of docol AHSS/UHSS

4.1 General about arc welding

Different arc welding methods can be used for the welding of Docol AHSS/UHSS. The most common method is gas metal arc welding (GMAW, MAG, MIG). Other methods used are tungsten inert gas (TIG) and submerged arc welding (SAW).

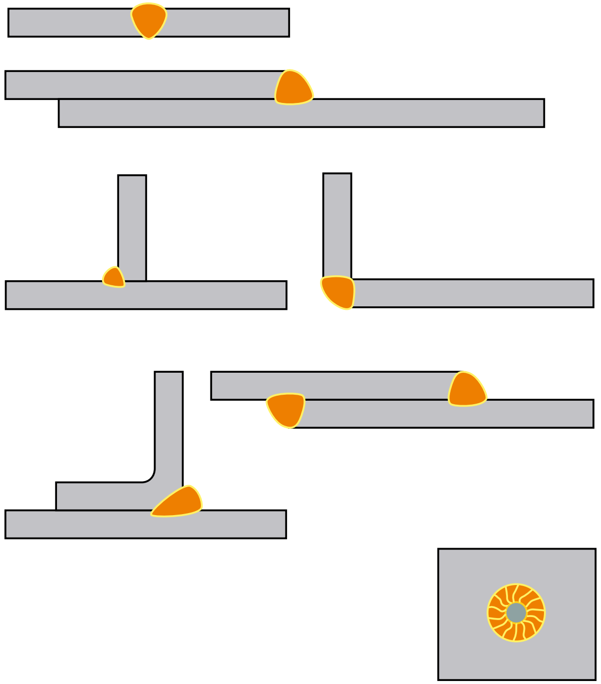
In **figure 4.1**, different joint types are shown for arc welded Docol AHSS/UHSS. The most common joint type for these are butt joints and single sided welded lap joints. For butt welding of thin sheets of Docol AHSS/UHSS, square butt joints without any special joint preparation, are normally used. Shearing, punching, milling or thermal cutting can be used for the preparation of the sheet edges. The requirements on the edges are not very strict for ordinary arc welding. Also for lap joints the demands on the edges are moderate.

Typical for arc welding in comparison with other welding methods (resistance spot welding, laser welding) is the high heat input. The heat input can be calculated according to **figure 4.2**. Due to the high heat input with arc welding, certain precautions are needed to reduce distortions of the sheets.

Despite the higher alloying content for Docol AHSS/UHSS, there is no increase in welding imperfections compared with mild steel arc welds.

Zinc coated steels are more difficult to weld than uncoated steels. Special measures must therefore be taken in order to obtain a good welding result.

Figure 4.1 Examples of different joint types for gas metal arc welding of Docol AHSS/UHSS.



4.2 Arc welding of uncoated steels

WELDING RECOMMENDATIONS FOR DOCOL AHSS/UHSS

For GMAW of thin sheets of uncoated Docol AHSS/UHSS a mixed shielding gas (M21) of argon (Ar) and carbon dioxide (CO_2) is normally used in combination with a solid welding wire.

The risk for material related weld defects is very low for Docol AHSS/UHSS. The main reason for that are the lean chemical compositions of these steels. In order to avoid corrosion damage, the sheet steel is normally coated with a thin oil film. However, this oil film is so thin that it does not give any porosity problems in conjunction with GMAW. The oil is gasified and quickly disappears during welding. However, if the sheet is stored in an environment where dirt may accumulate on the surface of the sheet, some precautions have to be taken. In order to avoid welding defects in this case, some form of cleaning of the sheet may then be necessary before welding.

Filler metals recommended for GMAW of some Docol AHSS/UHSS are shown in **table 4.1**. Only solid wires are mentioned in **table 4.1**, since the use of cored wires for welding of Docol AHSS/UHSS is still less common. However, cored wires can also be used.

In **table 4.1**, only matching welding wires are included. However, if the welds are placed in low stress areas, welding wires of lower tensile strength can also be used. Results from tensile testing of welded joints with different tensile strength of filler metals are shown in the section "Welding results for Docol AHSS/UHSS".

Welding of thin sheet steel places strict demands on the welding parameters used. To avoid burning-through and to minimize distortions of the sheet, it is important to use a low heat input. Another benefit with a low heat input is also a higher tensile strength of the welded joint. Preheating shall not be used for Docol AHSS/UHSS. The reason is that preheating will reduce the strength of the welded joints.

Forehand welding is normally used for GMAW of lap welds and fillet welds. Forehand welding provides a smoother transition between the weld metal and the parent metal. Side penetration is also somewhat larger, providing a greater tolerance range for positioning of the gun across the weld.

WELDING RECOMMENDATIONS FOR DOCOL HR

All conventional fusion welding methods can be used for welding of Docol HR as for example:

- Gas metal arc welding (GMAW, MAG, MIG).
- Manual metal arc welding (MMA).
- Submerged arc welding (SAW).
- Plasma welding.
- Tungsten inert gas welding (TIG).
- Laser welding.

The most common welding method for Docol HR is GMAW. For GMAW of Docol HR, a mixed shielding gas (M21) of argon (Ar) and carbon dioxide (CO_2) is normally used in combination with either a solid wire or a cored wire. It is also possible to use pure

Figure 4.2 Formula for calculation of heat input. For gas metal arc welding k = 0.8.

$$Q = \frac{(k \cdot U \cdot I \cdot 60)}{(v \cdot 1000)}$$

Q = heat input (kJ/mm)
U = voltage (V)
I = current (A)
v = travel speed (mm/min)
k = arc efficiency

Table 4.1 Filler metals recommended for GMAW of Docol AHSS/UHSS.

Steel grade	Filler metal Solid wire
Docol 500 DP/500 DL	AWS A5.28 ER70S-X EN ISO 16834-B G59X
Docol 600 DP/600 DL	AWS A5.28 ER80S-X EN ISO 16834-B G59X
Docol 780 DP/800 DP/800 DL	AWS A5.28 ER100S-X EN ISO 16834-B G78X
Docol 980 DP/1000 DP/ 1000 LCE/ 1180 DP Docol 900 M/1100 M/1200 M/ 1300 M/1400 M/1500 M	AWS A5.28 ER110S-X AWS A5.28 ER120S-X EN ISO 16834-B G83X

CO_2 as shielding gas, but in this case the amount of spatter increases.

As joint preparation for thin sheets (thickness 2–3 mm) of Docol HR, ordinary shearing can be used. For thicker sheets both machining and thermal cutting can readily be used. When thermal cutting is employed, a thin oxide film is formed on the joint surface. It is recommended to remove this oxide film before welding.

Since Docol HR steels have a low content of alloying elements (low carbon equivalent values) and a very low amount of non-metallic inclusions, there is a low risk for weld defects depending on the material for example hot cracking or hydrogen cracking.

Filler metals (solid wires and cored wires) recommended for GMAW of Docol HR are shown in **Table 4.2**. These filler metals are all matching wires. However, if the welds are placed in low stress areas, welding wires of lower tensile strength can also be used. For Docol HR it is recommended to use filler metals, which provide a maximum hydrogen content of 10 ml/100 g weld metal.

To obtain high strength and good impact toughness of the welded joints for Docol HR it is recommended to use low heat input. With low heat input the mechanical properties are improved both in the weld metal and in the heat affected zone.

WELDING DISTORTIONS

Welding distortions is a very important issue when thin sheets of Docol AHSS/UHSS are gas metal arc welded. To minimize the distortions, it is important to use a welding plan and to use a certain welding sequence.

The recommendations for thin Docol AHSS/UHSS to minimize the distortions are as follows:

- Minimize the weld reinforcement and throat thickness by using a low heat input.
- Use a welding wire with small diameter (0.8 mm).
- If possible use a low strength filler metal.
- Use back step welding if possible.
- If the application allows, intermittent welding can be used.
- Weld near a bent area. This way, the area close to the weld will be stiffer and can better resist distortions.
- Use a short distance between the tack welds.

To minimize the distortions, it is important to use a low heat input to achieve a small reinforcement and throat thickness. The reason is that a small fused area will decrease the shrinkage forces.

The distortions will be lower if a low strength filler metal is used. Before choosing a filler metal with a lower strength, check that this is acceptable from the viewpoint of other demands on the component.

The method with back step welding is shown in **figure 4.3**.

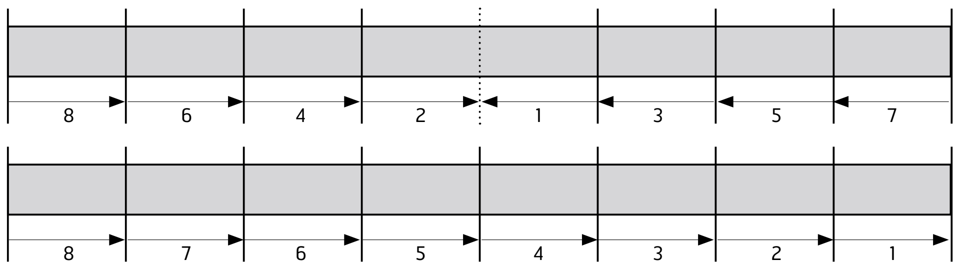
WELDING RESULTS FOR DOCOL AHSS/UHSS

The strength of the welds for Docol AHSS/UHSS increases with increasing base metal strength (**figure 4.6**). For Docol UHSS of very high strength (e.g. Docol 1000 DP and the Docol M steels), the strength of the welds is lower than the base metal strength. The reason is the soft zones in the heat affected zone (HAZ) due to the high heat input, which is typical for gas metal arc welding. The fracture position in the tensile testing is located to these soft zones. The amount of softening depends on the welding data used. With a low heat input the softening is less than for a high heat input.

Table 4.2 Filler metals recommended for gas metal arc welding of Docol AHSS.

Steel grade	Gas metal arc welding	
	Solid wire	Cored wire
Docol HR 460LA	AWS A5.18 ER 70S-X	AWS: A5.29 E81T-X
Docol HR 500LA	AWS A5.18 ER 80S-X EN ISO 16834-B G59X	
Docol HR 550LA	AWS A5.18 ER 100S-X	AWS: A5.29 E100T-X
Docol HR 600LA	EN ISO 16834-B G69X	
Docol HR 650LA	AWS A5.18 ER 100S-X	AWS: A5.29 E100T-X
Docol HR 700LA	AWS A5.18 ER 110S-X EN ISO 16834-B G78X	

Figure 4.3 Two examples of back step welding to reduce distortions of thin sheets.



Some examples of hardness profiles for Docol 1000 DP and Docol 1400 M are shown in **figures 4.4 – 4.5**.

In many applications, single-sided welded lap joints are often used. The strength of a lap joint is lower than the strength of a butt joint (**figure 4.6**). This is due to the unsymmetrical loading and the extra bending moment associated with this type of loading for the lap joint. The extra bending moment increases the stresses near the weld toe.

Also for lap joints a low heat input is beneficial for the strength of the weld. However, for lap joints, it is also sometimes important to have a high penetration in the base sheet. For example there are often requirements on the penetration in the base sheet. To reach a high penetration in the base sheet, it is not possible to use a very low heat input. In such cases, the heat input has to be chosen with regard to both strength and penetration.

Figure 4.4 Hardness profile across weld for a gas metal arc welded Docol 1000 DP (sheet thickness 1.2 mm, butt weld, heat input 0.09 kJ/mm, high strength filler AWS A5.28 ER 110S-G, mixed shielding gas of Ar and CO_2).

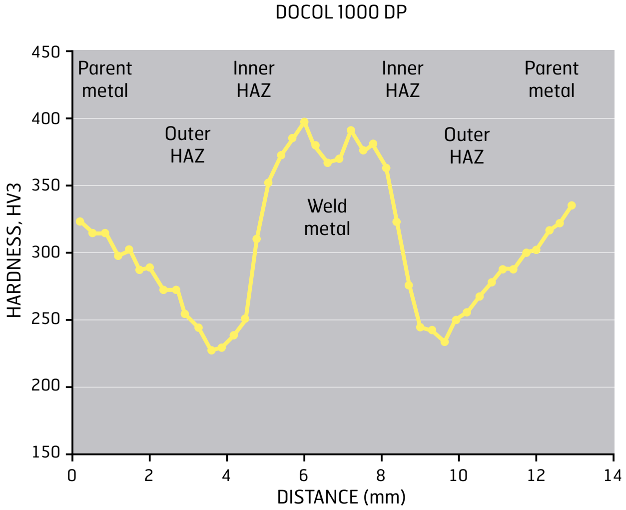
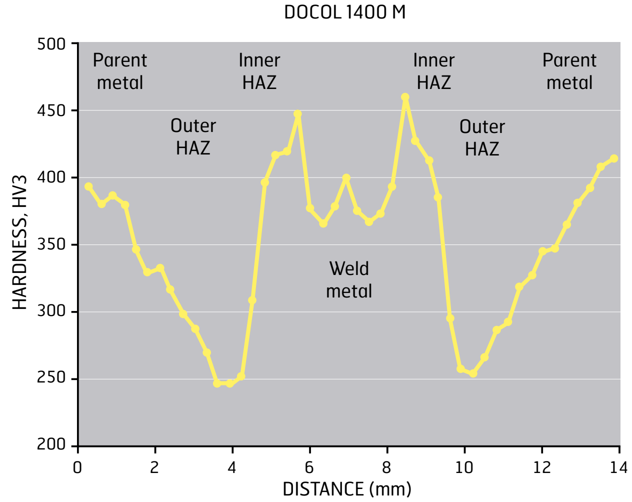


Figure 4.5 Hardness profile across weld for a gas metal arc welded Docol 1400 M (sheet thickness 1.0 mm, butt weld, heat input 0.09 kJ/mm, high strength filler AWS A5.28 ER 110S-G, mixed shielding gas of Ar and CO_2).



In **figure 4.7**, the influence of filler metal strength for single sided gas metal arc welded lap joints is shown for some Docol AHSS/UHSS steels of different strength levels. These results mainly show that an increased strength of the filler metal increases the strength of the lap weld for the Docol UHSS of very high strength. For the steels of lower strength the difference between low strength filler and high strength filler is very small.

Arc welds are normally used in local areas of the vehicle where the loads are high. The length of the arc welds is also often quite short. The reduction in strength for the Docol UHSS welds can be compensated by increasing the length of the weld.

WELDING RESULTS FOR DOCOL HR

In **Table 4.3** some examples of obtained mechanical properties are shown for gas metal arc welded (butt welds) Docol HR LA steels. Matching filler metals have been used in these welding tests. For the thicker plates (t=6 mm) impact toughness results are also included.

The results show that the minimum tensile strength requirement of the base metal can also be fulfilled for the butt welded joints. Good impact toughness is also obtained both in weld metal and heat affected zone. Docol HR LA hot-rolled cold forming steels have very good weldability.

Figure 4.6 Strength of welds for Docol AHSS/UHSS. (GMAW, high tensile strength filler metal AWS A5.28 ER 110S-G, mixed shielding gas of Ar and CO_2). A steel of lower strength is included as reference.

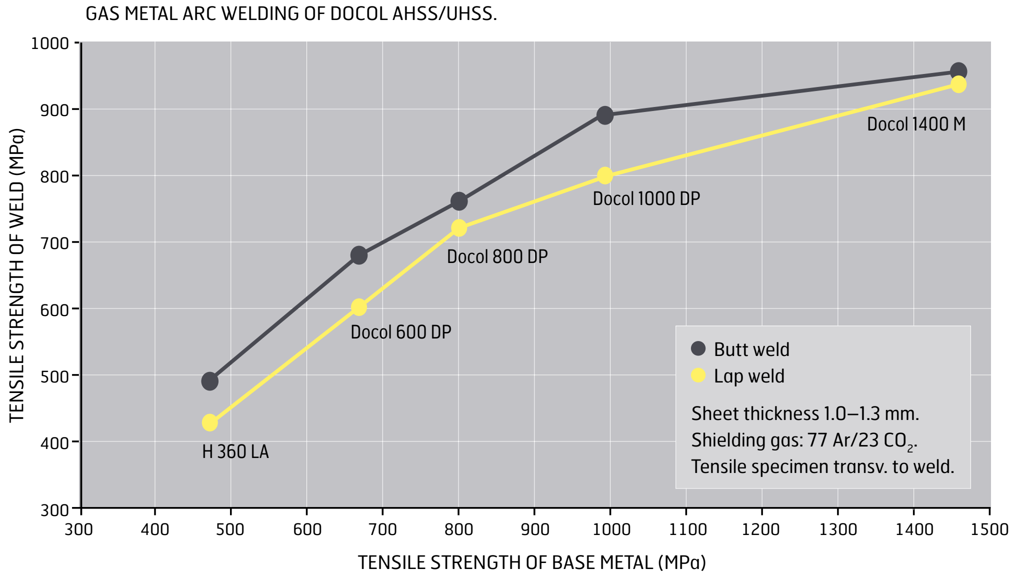


Figure 4.7 Influence of filler metal strength for single sided GMA welded lap joints of Docol AHSS/UHSS. Tensile strength is 560 MPa for the low strength filler and 890 MPa for the high strength filler. Tensile strength of weld equals peak load divided by cross-sectional area of specimen.

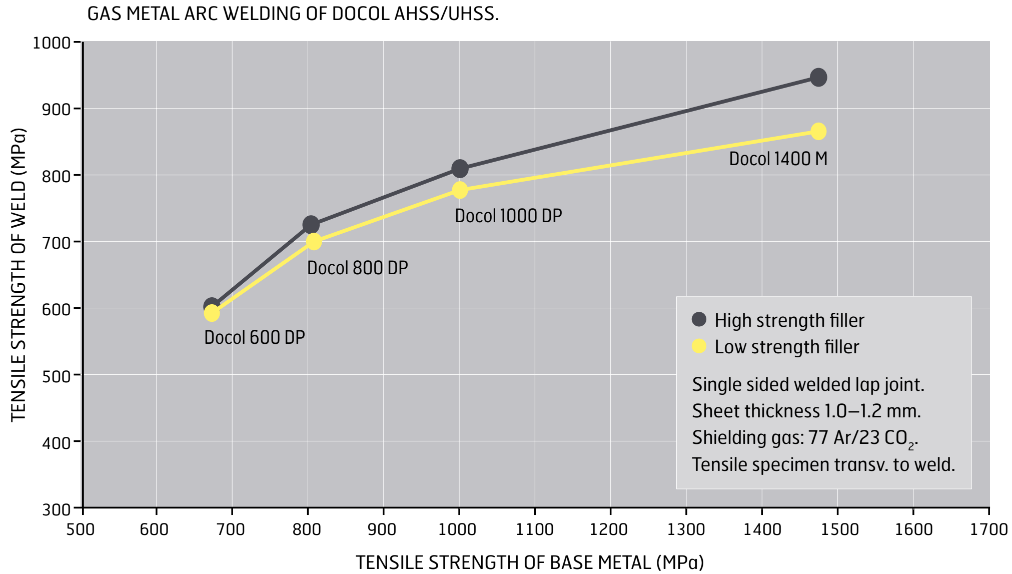


Table 4.3 Tensile strength and Charpy V impact toughness of welded joints in a number of Docol HR LA steel grades. Gas metal arc welded butt welds with reinforcement removed before testing.

Steel grade (thickness, mm)	Wire (AWS)	Pass	Heat input (kJ/mm)	Tensile test		Impact test (Charpy V)			
				Rm (MPa)	Fracture location 1)	Test direction 2)	Position 3)	Impact energy (J/cm²)	
								-20°C	-40°C
Docol HR 460LA (3)	A5.18 ER70S-X	1	0.60	595	BM				
Docol HR 460LA (6)	A5.18 ER70S-X	1 2 3	0.58 0.61 0.62	605	BM	L	WM HAZ	147	129 264
Docol HR 500LA (6)	A5.18 ER70S-X	1	1.2	595	BM	L	WM HAZ	168 256	174 244
Docol HR 600LA (4)	A5.18 ER100S-X	1	0.79	706	HAZ				
Docol HR 650LA (6)	A5.18 ER120S-X	1 2	0.73 0.81	810	HAZ	T	VM HAZ		207 107
Docol HR 700LA (3)	A5.18 ER100S-X	1	0.39	846	HAZ				
Docol HR 700LA (6)	A5.18 ER100S-X	1 2 3	0.61 0.41 0.42	825	BM	L	WM HAZ	130 154	112 145

1) WM = weld metal, BM = base metal, HAZ =heat affected zone.
2) L = longitudinal, T = transversal.
3) WM = weld metal, HAZ =heat affected zone (1 mm from fusion line).

4.3 Arc welding of zinc coated Docol AHSS/UHSS

It is more difficult to perform arc welding of zinc coated Docol AHSS/UHSS in comparison with uncoated Docol AHSS/UHSS. The arc welding method normally used for the zinc coated steels is gas metal arc welding. The other arc welding methods (TIG, SAW) cause too many problems and are therefore not normally used.

GAS METAL ARC WELDING OF ZINC COATED DOCOL AHSS/UHSS

It is more difficult to carry out gas metal arc welding of zinc coated Docol AHSS/UHSS in comparison with uncoated Docol AHSS/UHSS. The factors that make it more difficult for these joint types are:

- Difficulty achieving a stable arc.
- Increased porosity in the weld metal.
- Increased amount of spatter.
- Impaired penetration.

The reason for these problems is that zinc quickly gasifies during welding. The gasification temperature of zinc is 907 °C, which is much lower than the melting temperature of steel, which is about 1500 °C. This affects the arc and it may sometimes be difficult to weld in the normal way. In addition, spatter and porosity in the weld may occur.

WELDING RECOMMENDATIONS

The best solution from a welding point of view for zinc coated Docol AHSS/UHSS is to grind away the zinc coat locally. In order to retain good corrosion resistance after welding, some form of anti-corrosion treatment is needed such as painting with a zinc-rich paint.

If the zinc coat cannot be ground away, one or several of the following measures are recommended:

- Use as thin of a zinc coating as possible. The amount of patter and porosity increases with increasing coat thickness.
- Lower the travel speed. This way, the amount of porosity can be reduced.
- Use a shielding gas with a high proportion of CO_2. Due to the higher amount of CO_2 the heat supply increases and this decreases the porosity.
- If possible for lap welds, use a small gap (0.1 – 0.2 mm) between the sheets. This will make it easier for the zinc fumes to escape and the risk of porosity will decrease.
- Use a flux cored wire that has been specifically developed for gas metal arc welding of zinc coated steels. Ordinary gas mixture (about 80 % Ar, 20 % CO_2) can be used as shielding gas. During welding, the wire should be connected to the negative pole. The wire has an increased content of aluminum. The wire causes less spatter and porosity and produces a more uniform weld.

4.4 MIG brazing of zinc coated Docol AHSS/UHSS

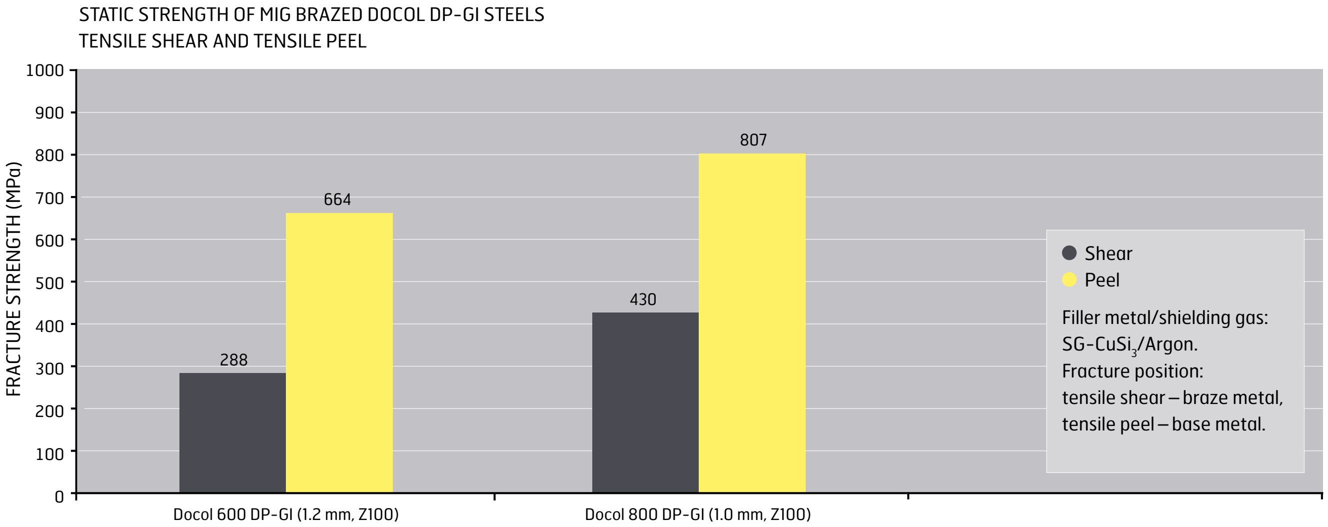
Problems that sometimes arise in gas metal arc welding of zinc coated Docol AHSS/UHSS can be avoided by using MIG-brazing. During MIG-brazing, the same equipment as for gas metal arc welding can be used. As filler metal a copper based wire with a low melting temperature is used together with an inert shielding gas (Ar). The most common filler metal for MIG brazing of Zn-coated steels is SG-CuSi$_3$ due mainly to the wide melting range (965°C–1035°C) which reduce the risk for defects during brazing.

Some advantages of MIG brazing in comparison with conventional gas metal arc welding are:

- Lower heat inputs.
- Less deformation of sheets.
- Less spatter, less porosity and better visible appearance.

One disadvantage of MIG brazing in some cases is the low strength of the filler metal. Results from tensile shear testing and peel testing of Docol 600 DP GI (GI50/50, t = 1.2 mm) and Docol 800 DP GI (GI50/50, t = 1.0 mm) are shown in **figure 4.8**. The strength of the flange welds (peel tests) is very good and the fracture position is located to the base metal. The strength of the lap joints (tensile shear tests) is lower than the strength of the base metal due to the low strength of the filler metal and in this case the fracture position is located on the braze metal.

Figure 4.8 Tensile shear (fillet weld on lap joint) and tensile peel tests (flange weld) of MIG brazed Docol 600 DP-GI (GI50/50, 1.2 mm) and Docol 800 DP-GI (GI50/50, 1.0 mm).



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