PREDICTION OF POST WELD HARDNESS OF ADVANCED HIGH STRENGTH STEELS FOR AUTOMOTIVE APPLICATION USING A DEDICATED CARBON EQUIVALENT NUMBER







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ABSTRACT

Weldability of advanced high strength steels in automotive manufacturing is a key issue. There are two important aspects to weldability: producing the welds and the quality of the welds. Producing the welds concerns the process to be used, possible addition of filler materials, the electrodes to be used, et cetera. Weld quality concerns the performance of the welds in a construction (e.g. strength and crash). With advanced high strength steels issues arise with increasing strength levels concerning the weld-quality. Traditionally carbon equivalent numbers are used to predict weldability. These traditional carbon equivalent numbers are not sufficient to predict post weld hardness of advanced high strength steels. Sumitomo Metal Industries and Corus cooperate to research weldability of advanced high strength steels. This paper concentrates on the influence of the chemical composition on weldability, as a first step to assess weldability of advanced high strength steels. This is done in two steps. First the traditional use of carbon equivalent numbers to predict weldability is explored. Literature is reviewed and possible issues with welding of advanced high strength steels are identified. Next the application of carbon equivalent numbers to predict post weld hardness for various welding processes (e.g. laser beam welding and resistance spot welding) is discussed. A wide range of steels was evaluated experimentally to determine the relationship between chemical composition and post weld hardness. The influence of welding processes expressed in terms of the cooling rates. The results are combined into simple models to predict post weld hardness of advanced high strength steel joints.

IIW-Thesaurus Keywords: *Arc welding; Carbon equivalent; Composition; Gas shielded arc welding; Hardness; Laser welding; Mechanical properties; Photon beam welding; Plasma welding; Radiation welding; Reference lists; Resistance spot welding; Resistance welding; Weldability.*

1 INTRODUCTION

Weld failure modes of advanced high strength steels have been subject of research in various publications. It has been reported that these steels do sometimes fail in ways that affect the performance of these welds in automotive application, most notable the crash-performance. The increased carbon content of these steels (along with other elements) leading to increased post weld hardness in combination with high cooling rates is seen as the main cause of these undesired weld failure modes [1-2].

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Carbon equivalent numbers have been used now for several decades to compare the weldability of steels with different chemical compositions. Most famous of all is probably the Carbon Equivalent number commonly referred to as the IIW CE number.

$$CE(IIW) = C + Mn/6 + (Cr + Mo + V)/5 + (Ni+Cu)/15 \quad (1)$$

This carbon equivalent number was published in 1967 [3]. Over the years steels and their applications have changed considerably. As far as automotive applications are concerned, much higher strength levels are desired to enable manufacturers to reduce weight, whilst maintaining performance (fatigue and crash). The chemical composition and process routes of steels changed as applications posed new demands on the strength and formability of steels.

Carbon equivalent numbers relate the composition of a steel to its weldability, but they themselves are also dependent upon the chemical composition of the steel. The IIW CE number is usually used for steels with Carbon levels exceeding 0,18 wt % C, as it was found that other carbon equivalent numbers worked better for steels with lower carbon content. In 1968 Ito & Bessyo published a paper in which a more complete relation was derived to predict post weld hardness of steels containing carbon levels of less or equal to 0,12 wt % [4]. The chemical portion of this formula (Pcm) is commonly used as a carbon equivalent number for steels with [C] < 0,18 wt %.

$$CE(Pcm) = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B \quad (2)$$

Strictly speaking carbon equivalent numbers cannot to be used to compare the weldability of steels with different chemical composition, but the hardenability of steels. Weldability is often defined as the inverse of hardenability [5]. Post weld hardness is related to the strength of a weld. The hardness is increased by the accumulation of lattice defects caused by high cooling rates. These lattice defects can lead to cracks and ultimately weld failure. The hardness of a weld is not just determined by the hardness of its constituent phases, but also by microstructural characteristics such as occurrence of precipitates and grain size.

This paper is primarily concerned with the relation of chemical composition and post weld hardness as a measure of weldability. Other factors influencing weldability of steels, such as the occurrence of hot cracking and temper embrittlement are not discussed in this paper, although these do play their part.

2 BACKGROUND

2.1 Carbon equivalent numbers

As stated carbon equivalent numbers are used to compare steels of different chemical composition. The basis for these comparisons is the relation between post weld hardness and the weld strength. Post weld hardness is determined by a combination of three microstructural characteristics of the material:

– phases;
– chemical composition;
– occurrence of lattice defects.

Microstructural phases differ in hardness. Martensite is hard and brittle, whilst ferrite is soft and formable. Hard phases such as bainite and martensite form when material is quenched from elevated temperatures, where the material exists as austenite. The cooling rates needed to form martensite depend upon the chemical composition. The temperatures at which formation of martensite starts and ends are also dependent upon the chemical composition of the material. This is commonly expressed in CCT diagrams [6].

The chemical composition not only influences the post weld hardness through the formation of microstructural phases. The chemical composition can also lead to the occurrence of hard precipitates in the matrix. Another influence upon the resultant weld hardness can be found in the grain refinement and the inclusion of lattice defects. Gould [1] states that carbon is the main element affecting post weld hardness. Another element leading to increased post weld hardness is manganese. Some other elements are also well known to increase hardenability (i.e. the possibility to form martensite) of a material, most notably boron.

Lattice defects increase hardness through mechanisms in which the movement of dislocations in a material is hindered. The density of lattice defects in the matrix increases with increasing cooling rates, first of all because equilibrium density of lattice defects is higher at elevated temperatures. As the material is quenched this excess of defects is retained. Increased cooling rates also lead to increased formation of lattice defects due to undercooling, allowing more initiation sites for lattice defects to become active [7].

Seen from the perspective of the material the main characteristic of welding is the input of heat. The amount of heat in combination with time, are the catalysts which will determine the eventual post weld characteristics. During heating, the input of energy causes the weld material to melt, the material in the heat-affected zone (HAZ) to change and the surrounding material to heat up. Removing the heat will cause the material to cool. Critical for the effect this will have is the cooling rate. If the surrounding material is cold, and thermal conductivity is good, cooling rates will be high. If the surrounding material is pre-heated, or the work piece is thermally isolated, cooling rates will be reduced.

High cooling rates will lead to the formation of hard phases, with lots of lattice defects. Slow cooling will lead to the formation of soft phases and (auto) tempering. Cooling rates can be increased by forced cooling (i.e. water cooled electrodes in resistance spot welding) or reduced by thermal treatment (i.e. preheating a workpiece).

Blondeau *et al.* derived equations that relate chemical compositions of steels and cooling rates after welding to post weld hardness [8]. Chaillet *et al.* elaborated on this work to determine statistical formulae to calculate the hardness after welding (in Vickers) for high strength steels [9]. Blondeau's equations:

$$\mathrm{HV(martensite)} = 97 + 949\mathrm{C} + 27\mathrm{Si} + 11\mathrm{Mn} + 8\mathrm{Ni} + 16\mathrm{Cr} + 20\log \mathrm{Vr} \quad (3)$$

$$\mathrm{HV(bainite)} = -348 + 158\mathrm{C} + 330\mathrm{Si} + 153\mathrm{Mn} + 66\mathrm{Ni} + 144\mathrm{Cr} + 191\mathrm{Mo} + \log \mathrm{Vr}\,(89 + 59\mathrm{C} - 55\mathrm{Si} - 22\mathrm{Mn} - 10\mathrm{Ni} - 20\mathrm{Cr} - 33\mathrm{Mo}) \quad (4)$$

$$\mathrm{HV(ferrite\text{-}pearlite)} = 42 + 223\mathrm{C} + 53\mathrm{Si} + 30\mathrm{Mn} + 13\mathrm{Ni} + 7\mathrm{Cr} + 19\mathrm{Mo} + \log \mathrm{Vr}\,(10 - 19\mathrm{Si} + 3\mathrm{Ni} + 8\mathrm{Cr} - 130\mathrm{V}) \quad (5)$$

where the concentration of elements is measured in [wt%], and Vr is the cooling rate of the material at 700 °C in °C/hr.

Chaillet *et al.* also give equations the effect of tempering on the resultant hardness of the welds using previous work done by Blondeau *et al.* [10].

Although these equations give good results, a lot of input is needed to calculate post weld hardness. This does not always make the equations suitable to estimate the post weld hardness in applications. First of all detailed knowledge of the exact chemical composition of welds is not always available. Also the effect of most elements on the resultant post weld hardness is limited compared to the effect of carbon. Most of all it is hard to measure cooling rates in a weld. Cooling rates in a weld can be estimated using simulation software (in this paper simulation results using SORPAS software are used to estimate cooling rates in resistance spot welding). However since the cooling rate is present in the equation as a logarithm of the cooling rate per hour, small deviations in the estimated cooling rate do not cause great errors in the eventual results.

These considerations have lead to the development of several dedicated carbon equivalent equations, each suited for a specific welding process (with approximately similar cooling rates). Taka and Yamauchi have proposed a carbon equivalent number to be used for resistance spot welding of high strength steels [11]:

$$\mathrm{CE} = \mathrm{C} + \mathrm{Si}/90 + (\mathrm{Mn} + \mathrm{Cr})/100 \quad (6)$$

Ono proposed a carbon equivalent number that can be used for laser beam welding of high strength steels [12]:

$$\mathrm{CE} = \mathrm{C} + \mathrm{Si}/50 + \mathrm{Mn}/25 + \mathrm{P}/2 + \mathrm{Cr}/25 \quad (7)$$

Yamamoto proposed another carbon equivalent number that can be used for laser beam welding of steels containing boron [13]:

$$\mathrm{CE} = \mathrm{C} + \mathrm{Mn}/22 + 14\mathrm{B} \quad (8)$$

For plasma arc welding the Ito-Bessyo PCM number Eq. (2) has been in general use.

2.2 Weldability for automotive applications

Weldability in automotive applications is more complicated than just the inverse of hardenability. There are two different aspects to the weldability of a material:
– the production of welds;
– the performance of welds.

In automotive manufacturing the production aspects (e.g. welding times, welding costs) are important factors, but these will not be discussed in this paper. The performance of welds is related to their qualities. Important aspects are the strength of the weld and performance in crash tests. For continuous welds, such as with laser and arc, formability is also an important aspect. In this paper post weld hardness is reviewed as the hardness of a weld is closely related to its strength.

Rule of thumb states that welds with a hardness exceeding 400 to 450 HV tend to show brittle failure [14]. This is detrimental for crash and fatigue performance as it reduces the amount of energy a weld can absorb. The hardness of welds can be reduced using post weld heat treatment to ensure acceptable hardness levels [15]. There are other influences that can decrease the weld quality, such as hot cracking susceptibility and tendency to temper embrittlement. These effects cannot be captured in carbon equivalent numbers and are therefore no subject of this paper. However carbon equivalent numbers can be used in models that will predict the performance of a weld. One such model has been developed by Nishi *et al*. [16] to relate the performance of resistance spot welds. In this model the carbon equivalent number proposed by them is related to a second parameter combining the influence of sulphur and phosphorous in a phosphorous equivalent number:

$$\mathrm{PE} = \mathrm{P} + 2\mathrm{S} \quad (9)$$

In which concentration of elements is given in wt%.

Both numbers can be combined in a graph, can be used to predict the failure mode of a resistance spot weld in a peel test, as can be seen in Figure 1 [16]. Another graph shown in Figure 2 has been used in Sumitomo Metal Industry. The carbon equivalent number by Taka and Yamauchi [11] and their original phos-

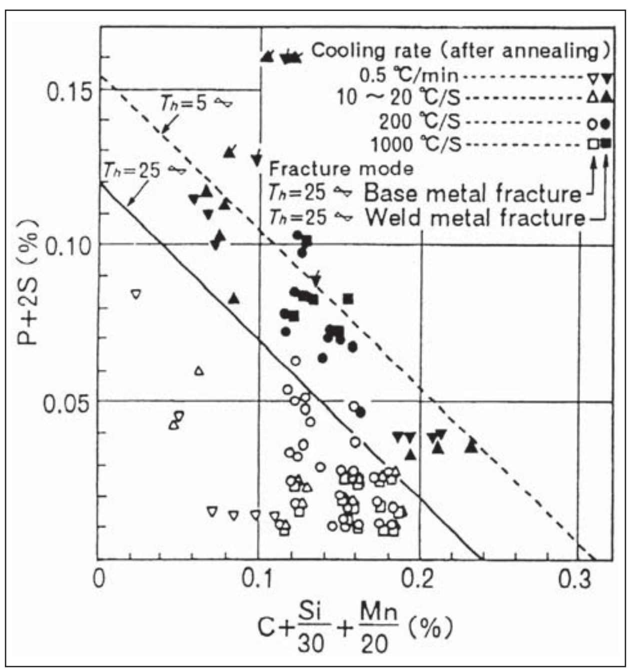


Figure 1 – Dependence of fracture mode in peel test on chemical composition of base metal [16]

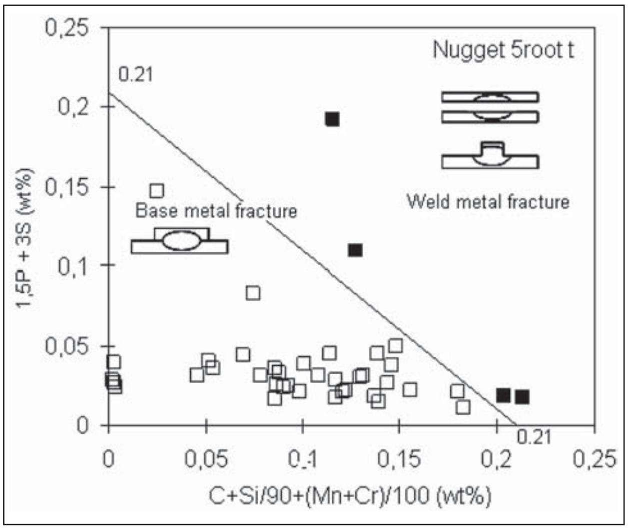


Figure 2 – Dependence of fracture mode in cross tensile test on chemical composition of base metal according to Sumitomo Metal Industry

phorus Equivalent number are used in the graph. The carbon equivalent number and phosphorus equivalent number in each graph are slightly different, however the concept of the graphs is the same.

The rest of this paper focuses on the development of suitable carbon equivalent numbers for modern high strength steels for use in automotive applications (i.e. thin sheet and high process speeds).

3 EXPERIMENTAL

Several series of experiments have been conducted. First a series of steels commercially available for automotive applications have been tested. The steels were produced on various production facilities and encompassed a range of high strength steels: High Strength Low Alloy (HSLA), Dual Phase (DP) and Transformation Induced Plasticity (TRIP) steels. All these steels were cold rolled. For each steel Table 1 lists the thickness in millimetres of the sheet material, the chemical composition for the main elements and the tensile strength (UTS) in MPa.

These steels were resistance spot welded using single pulse welding schemes. Resistance spot welding settings were chosen to ensure a 5√t weld diameter size (i.e. the weld nugget diameter equals 5 times the square root of the material thickness). Typically for welding a 1,2 mm thick GI-coated Advanced High Strength Steel (AHSS), this would require application of a welding current of 6,8 kA for 14 cycles (50 Hz AC), using Type G welding electrodes with a 6 mm radius (see Figure 3). After welding the post weld hardness in the weld nugget was measured for each sample. Hardness was measured using a 0,50 kg load on the cross section of the welds.

A second series of experiments concerns a batch of laboratory steels. These steels were especially casted to examine the influence of various chemical compositions on weldability. All steels were hot and cold rolled to a thickness of 1,4 mm. Tensile strength of all these steels was approximately 900 MPa. As the focus of the experiments was on the post weld hardness in the weld nugget; the steels did not undergo any further heat treatment (e.g. annealing) prior to welding.

Samples of the material were welded using different welding processes: resistance spot welding (RSW), laser beam welding (LBW) and plasma arc welding (PAW). Resistance spot welding was done using a 5 kA AC welding current, 2,94 kN electrode force and 18 cycles welding time (60 Hz). All samples were welded with a dome type electrode (dome diameter 16 mm, tip radius 40 mm and 6 mm diameter contact area). Each sample was welded with a 10 cycles (60 Hz) hold time after welding as well as with a 60 cycles (60 Hz) hold time

Table 1 – Thickness, chemical composition and tensile strength for several commercially available high strength steels

Steel [#]	Thickness [mm]	C [wt%]	Mn [wt%]	Si [wt%]	Cr [wt%]	P [wt%]	S [wt%]	UTS [Mpa]
A01	1,60	0,071	1,460	1,530		0,160	0,001	630
A02	1,50	0,077	0,515	0,005		0,008	0,007	350
A03	1,00	0,092	1,680	0,241		0,016	0,004	614
A04	1,05	0,105	1,680	0,240	0,530	0,001	0,001	800
A05	1,05	0,110	1,690	0,250	0,540	0,009	0,006	800
A06	1,50	0,149	1,830	0,207		0,013	0,002	869
A07	1,50	0,150	1,800	0,200	0,470	0,014	0,002	869
A08	1,50	0,150	1,520	0,000		0,007		1 000
A09	1,05	0,160	1,720	0,250	0,540	0,001	0,001	800
A10	1,25	0,185	1,610	0,352	0,020	0,089	0,003	743
A11	1,23	0,186	1,530	1,800		0,008	0,001	788
A12	1,00	0,205	1,520	0,380		0,077		800
A13	1,15	0,210	1,500	0,370		0,028		800
A14	1,00	0,210	1,500	0,400		0,020	0,006	1 000

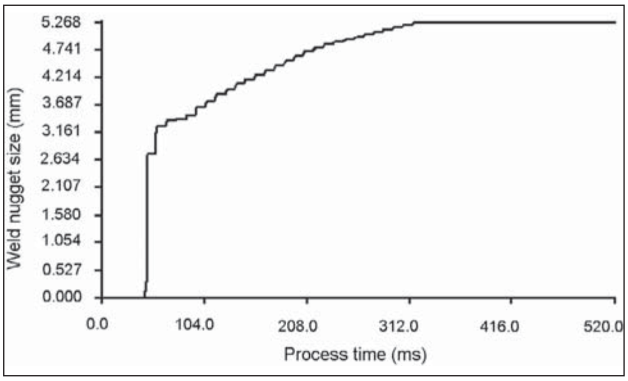


Figure 3 – Growth of weld nugget diameter in a 1,2 mm thick GI-coated AHSS welded with a welding current of 6,8 kA for 14 cycles (50 Hz AC) using Type G welding electrodes with 6 mm radius, as simulated using Sorpas software

after welding. After welding the post weld hardness for both sets of samples was measured. Hardness was measured using a 1,0 kg load on the cross section of the welds.

Laser beam welding was done using a 3 kW YAG laser (focus diameter: 0,6 mm). Process speed was 3 m/min and argon was used as shielding gas (15 l/min). After welding the post weld hardness was measured. Hardness was measured using a 1,0 kg load on the cross section of the welds.

Plasma arc welding was done using a 120 A welding current at a process speed of 1 m/min. The plasma gas used was argon + 10 % hydrogen, with a flow of 0,5 l/min. The shielding gas used was argon + 10 % hydrogen, with a flow of 10 l/min. After welding the post weld hardness was measured. Hardness was measured using a 1,0 kg load on the cross section of the welds.

The temperature in the weld metal during cooling was measured using R type electrodes (platinum-rhodium and platinum). In resistance spot welding the tip of the thermocouple was inserted in a hole where the weld nugget was projected to form. In laser beam welding the cooling rate was measured at the fusion boundary area on the back side of the work piece. In plasma arc welding the cooling rate was measured by inserting a thermocouple into the molten pool.

4 RESULTS

Figure 4 shows the post weld hardness after resistance spot welding of the steels listed in Table 1. The tensile strength (UTS) of the base material is also plotted in the diagram.

Figure 5 a) shows the post weld hardness of materials listed in Table 2 after resistance spot welding with a hold time of 60 cycles (1 second). Figure 5 b) shows the post weld hardness of materials listed in Table 2 after resistance spot welding with a hold time of 10 cycles (167 ms). Figure 5 c) shows the post weld hardness of materials listed in Table 2 after laser beam welding.

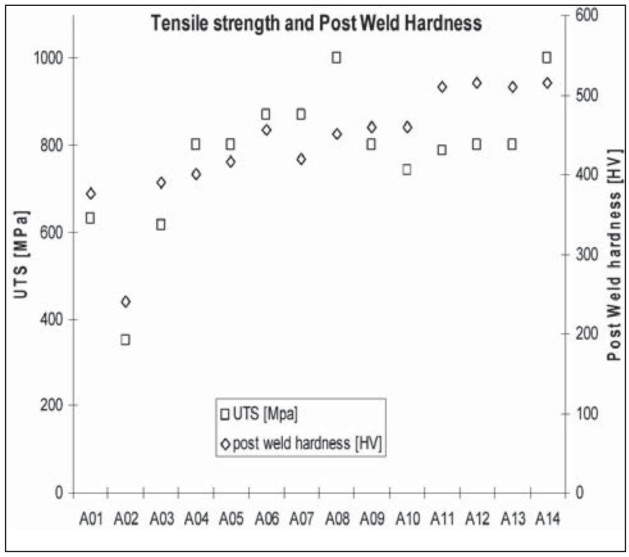


Figure 4 – Tensile strength and post weld hardness (RSW) of steels listed in Table 1

Figure 5 d) shows the post weld hardness of materials listed in Table 2 after plasma arc welding.

Cooling rates were very high for resistance spot welding. Between 1 073 K and 773 K the cooling rate was higher than 1 000 K/sec. Cooling rates for laser beam welding were lower. Between 1 073 K to 773 K cooling rates varied between 200-500 K/sec. For plasma arc welding cooling rates were even lower. Between 1 073 K to 773 K cooling rates between 50 and100 K/sec were measured.

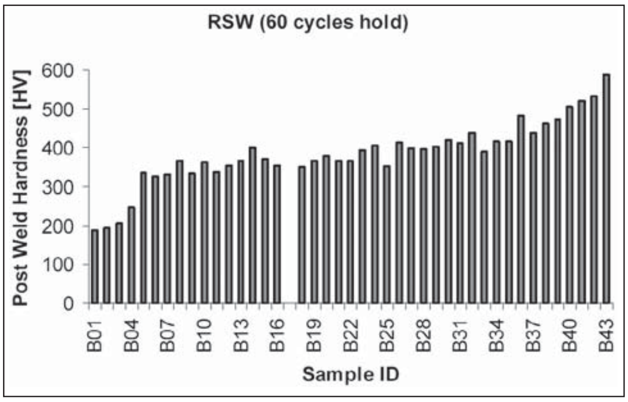
5 DISCUSSION

5.1 Carbon equivalent numbers

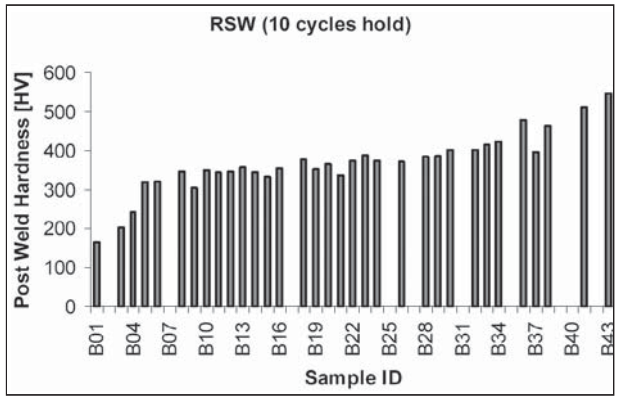
As stated there is a relation between hardness of a material and its strength. Figure 6 depicts the relation between the tensile strength of the materials listed in Table 1 and the post weld hardness. It can be seen that although there is a relation between the strength of a material and its post weld hardness, the relation is not precise enough to estimate weldability using only the tensile strength of a material as a criterion. For instance it can be seen in Figure 6 that material with a UTS of 800 MPa sometimes would need post weld heat treatment (i.e. post weld hardness exceeds 450 HV) and sometimes there is no need for post weld heat treatment.

The relative cooling rates decreasing from resistance spot welding to laser beam welding and plasma arc welding correspond well to the relation between cooling rates as predicted by calculations in literature. The cooling rates measured are sufficient to produce martensitic in the steels used in the experiments. The exception being the low carbon steel A02 [2].

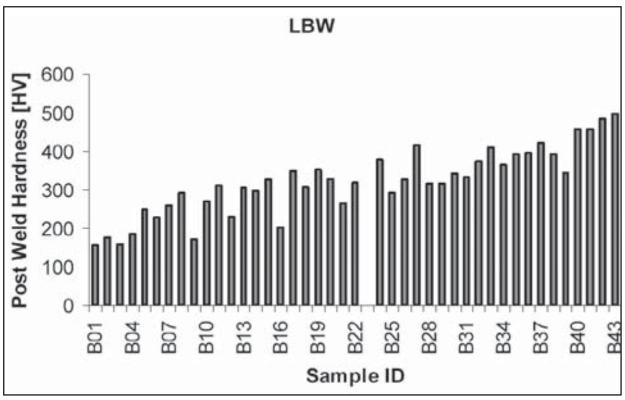
Figure 7 depicts the relationship between carbon content of commercially available high strength steel



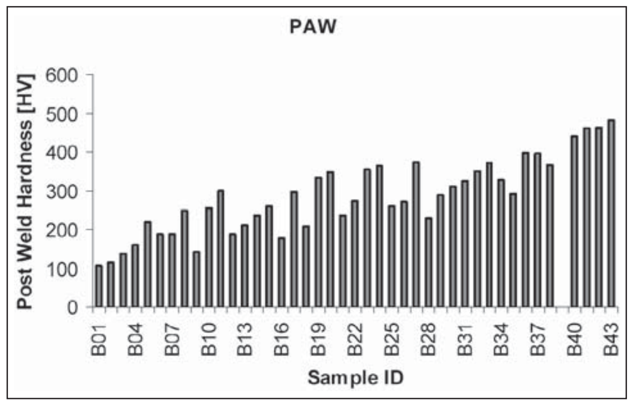
a) Using resistance spot welding with a hold time of 60 cycles (60 Hz)



b) Using resistance spot welding with a hold time of 10 cycles (60 Hz)



c) Using laser beam welding



d) Using plasma arc welding

Figure 5 – Post weld hardness for steels listed in Table 2

Table 2 – Chemical composition of set of lab cast steels

Steel [#]	C [wt%]	Si [wt%]	Mn [wt%]	Cr [wt%]	Mo [wt%]	Steel [#]	C [wt%]	Si [wt%]	Mn [wt%]	Cr [wt%]	Mo [wt%]
B01	0,001	0,04	1,44	0,00	0,00	B23	0,100	0,74	3,00	0,00	0,00
B02	0,001	0,04	1,46	0,00	0,00	B24	0,100	1,51	3,08	0,00	0,00
B03	0,001	0,68	1,53	0,00	0,00	B25	0,100	0,70	1,02	0,00	0,00
B04	0,004	1,88	1,51	0,00	0,00	B26	0,100	1,43	1,03	0,00	0,00
B05	0,050	0,69	1,53	0,00	0,00	B27	0,14	1,42	1,54	0,00	0,00
B06	0,050	0,07	1,39	0,00	0,00	B28	0,14	0,06	1,44	0,00	0,00
B07	0,050	0,06	1,47	0,00	0,00	B29	0,14	0,06	1,45	0,00	0,00
B08	0,094	0,70	1,50	0,00	0,00	B30	0,14	0,70	1,50	0,00	0,00
B09	0,094	0,01	0,02	0,00	0,00	B31	0,15	0,06	1,43	0,00	0,00
B10	0,095	0,05	1,02	1,00	0,00	B32	0,15	0,07	1,37	0,00	0,00
B11	0,095	0,06	1,00	0,00	0,99	B33	0,15	1,44	1,54	0,00	0,00
B12	0,097	0,06	1,00	0,00	0,00	B34	0,17	0,00	1,50	0,00	0,00
B13	0,098	0,05	1,47	0,00	0,00	B35	0,18	0,06	1,46	0,00	0,00
B14	0,098	0,10	1,44	0,00	0,00	B36	0,18	1,93	1,53	0,00	0,00
B15	0,098	0,20	1,43	0,00	0,00	B37	0,19	0,05	1,45	0,00	0,00
B16	0,098	0,71	0,01	0,00	0,00	B38	0,20	0,96	1,57	0,00	0,00
B17	0,098	1,94	1,58	0,00	0,00	B39	0,20	1,94	0,20	0,00	0,00
B18	0,099	0,05	1,49	0,00	0,00	B40	0,20	1,93	3,07	0,00	0,00
B19	0,099	0,06	1,00	1,96	0,00	B41	0,28	0,00	1,50	0,00	0,00
B20	0,099	0,06	1,02	0,00	2,04	B42	0,28	0,96	1,53	0,00	0,00
B21	0,100	0,02	1,56	0,00	0,00	B43	0,29	1,93	1,58	0,00	0,00
B22	0,100	1,48	1,57	0,00	0,00						

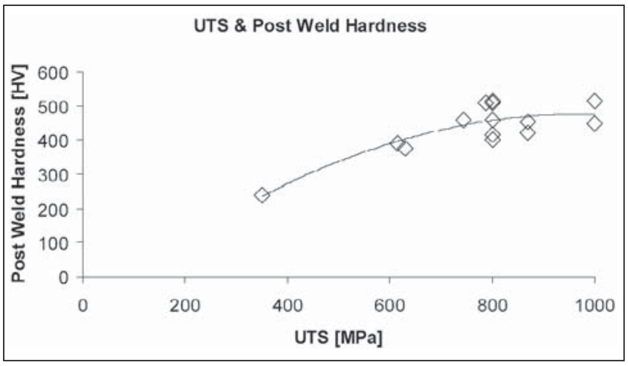


Figure 6 – Relation between tensile strength of materials listed in Table 1 and the post weld hardness (using resistance spot welding)

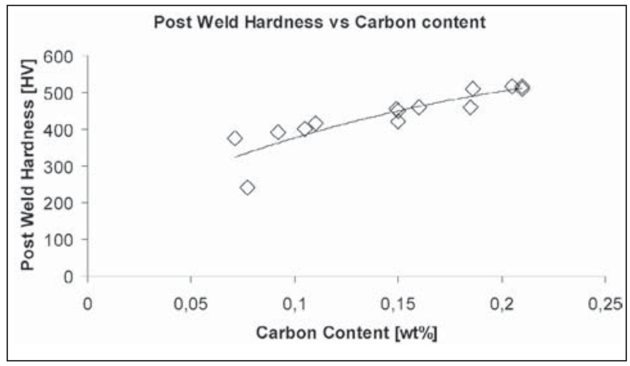
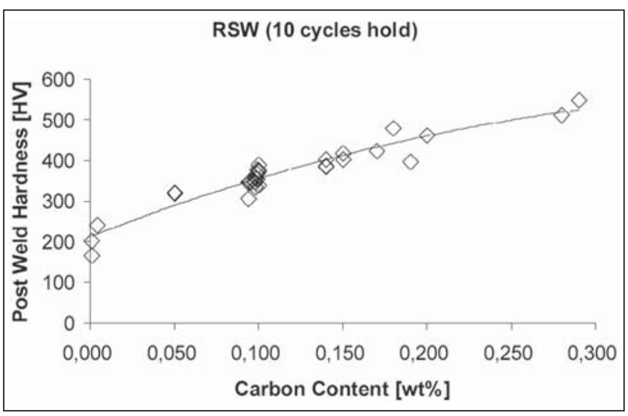


Figure 7 – Relation between the carbon content of commercially available high strength steels (Table 1) and the post weld hardness after resistance spot welding

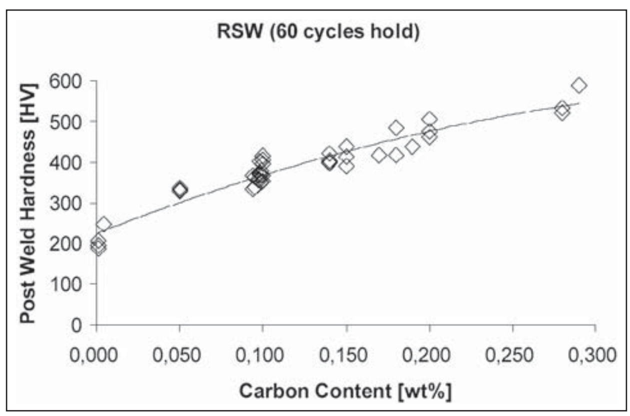
(listed in Table 1) and the resultant post weld hardness after resistance spot welding. It can be seen that there is a quite clear relationship between the carbon content of a material and its post weld hardness (after resistance spot welding). The only exception being steel A02 with 0,077 wt % C and comparably small amounts of other elements. From this it can be concluded that when high strength steels are resistance spot welded, the carbon content can be used to estimate relative post weld hardness, provided steels are similarly alloyed as far as other elements (i.e. not carbon) are concerned.

Figures 8 a), b), c) & d) give the post weld hardness of the materials listed in Table 2 depicted against their carbon content. From these figures it can be seen that when cooling rates decrease (such as in the case of laser beam welding, but even more significantly) elements other than carbon increasingly influence post weld hardness.

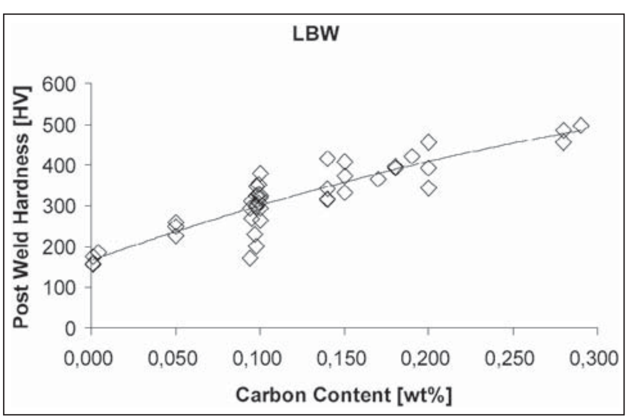
In Figure 9 the measured cooling curve is given for the centre of the weld during resistance spot welding, using the welding conditions used during the experiments. In this figure it can be seen that the cooling rate is similar above 773 K. Therefore the hardness



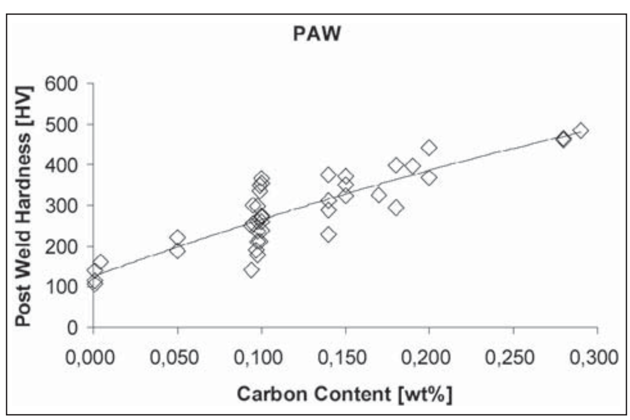
a) Using resistance spot welding (with 10 cycles hold time after welding)



b) Using resistance spot welding (with 60 cycles hold time after welding)

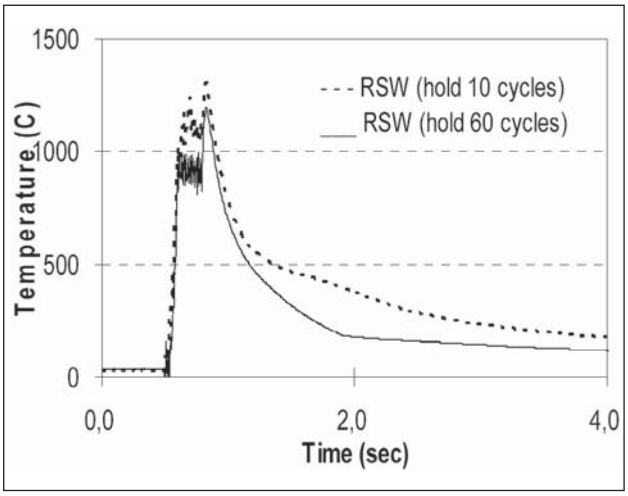


c) Using laser beam welding



d) Using plasma arc welding

Figure 8 – Post weld hardness for materials listed in Table 2 vs. carbon content

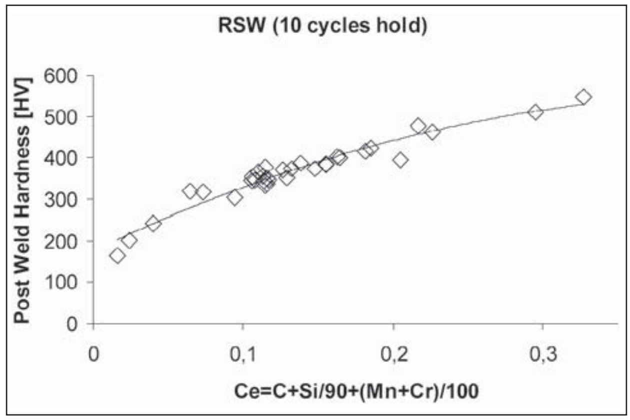


The continuous line represents forced cooling.
The dotted line represents free cooling.

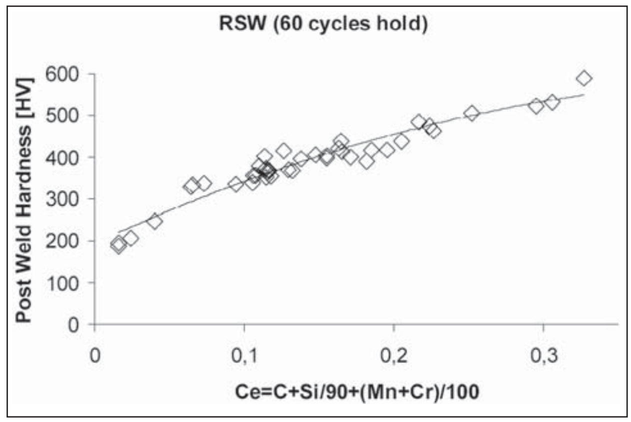
Figure 9 – Temperature vs. time measured in the centre of the weld

of the weld made with 60 cycles hold time and the welds made with 10 cycles hold time does not vary enormously. Cooling is slower at lower temperatures for the free cooling welds, accounting for some softening of the weld through auto-tempering. This slight effect can be seen in Figure 10.

If cooling rates are slower, the influence of additional alloying elements upon the post weld hardness increases. This can be expressed, using the carbon equivalent number proposed by Taka and Yamauchi [see Figures 11 a) & b)]. Although the differences are very small it can be seen that the use of the carbon equivalent number gives slightly better results in predicting the relation between the chemical composition of steels welded using resistance spot welding with a hold time of 10 cycles compared to a hold time of 60 cycles.

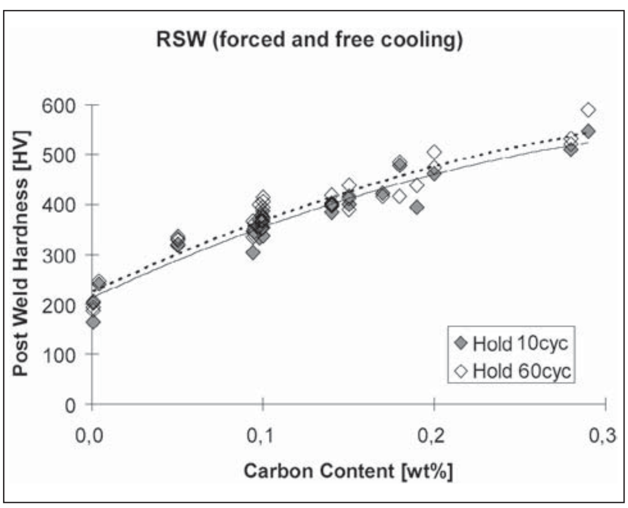


a) With 10 cycles hold time after welding



b) With 60 cycles hold time after welding

Figure 11 – Post weld hardness for materials listed in Table 2 using resistance spot welding against the carbon equivalent number proposed by Taka and Yamauchi

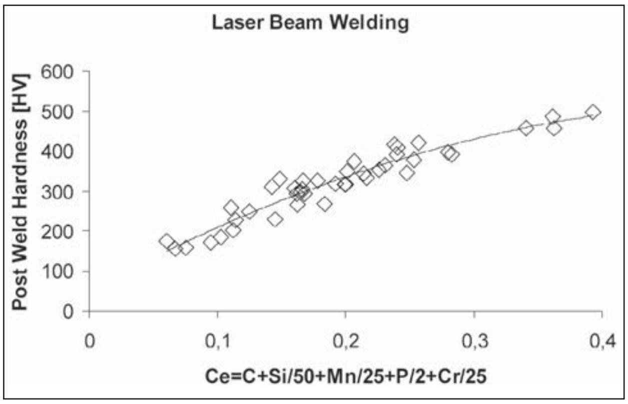


Samples welded with a hold time of 60 cycles are depicted using open diamonds with a dashed trendline.

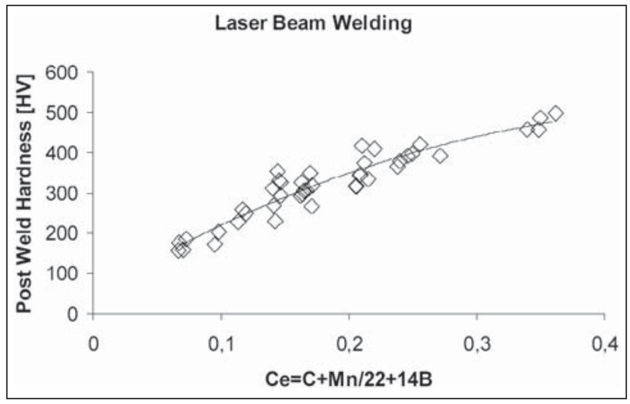
Samples welded with a hold time of 10 cycles are depicted using closed diamonds with a continuous trendline.

Figure 10 – Post weld hardness for materials listed in Table 2 using resistance spot welding vs. carbon content

Although the difference in predictability of weldability using plain carbon content and dedicated carbon equivalent numbers may be small with respect to resistance spot welding, the influence of additional elements increases with decreasing cooling rates. The accuracy gained using dedicated carbon equivalent numbers increased when cooling rates decrease. Figure 12 a) gives the relation between post weld hardness after laser welding and the carbon equivalent number proposed by Ono. Figure 12 b) gives the relation between post weld hardness and the carbon equivalent number proposed by Yamamoto. The accuracy is much better in both cases compared to Figure 8 c). The addition of extra elements in the carbon equivalent number by Ono does give better results, but the addition of the influence of manganese in the carbon equivalent number proposed by Yamamoto already increases accuracy significantly (Yamamoto also includes boron, but this was not added to the materials used here).



a) Carbon equivalent number proposed by Ono



b) Carbon equivalent number proposed by Yamamoto

Figure 12 – Relation between post weld hardness after laser beam welding and the carbon equivalent number

Plasma arc welding results in even lower cooling rates than laser beam welding. Figure 13 gives the relationship between the carbon equivalent number derived from the work by Ito-Bessyo (Pcm). Again the accuracy is much better than the results of Figure 8 d). It can be concluded that it is necessary to take more elements into account to relate chemical composition to post weld hardness as cooling rates decrease after welding.

From these results it can be concluded that:
– The carbon content can be used to estimate weldability of high strength steels as far as post weld hardness is concerned for resistance spot welding.
– The carbon equivalent number proposed by Taka and Yamauchi can be used to discriminate further between weldability of high strength steels if no forced cooling is applied after resistance spot welding (i.e. reduced hold times).
– It is necessary to take more elements apart from carbon into account to estimate weldability of high strength steels for laser beam welding and plasma arc welding.
– Both the carbon equivalent numbers proposed by Ono and Yamamoto can be used to estimate weldability of high strength steels as far as post weld hardness is concerned for laser beam welding.
– The carbon equivalent number proposed by Ono gives slightly better results to estimate weldability of high strength steels as far as post weld hardness is concerned for laser beam welding.
– The carbon equivalent number derived from the work by Ito and Bessyo can be used to estimate weldability of high strength steels as far as post weld hardness is concerned for plasma arc welding.

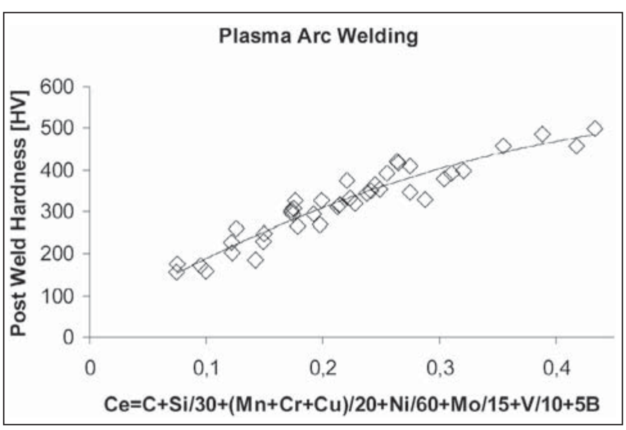


Figure 13 – Relation between post weld hardness and the carbon equivalent number derived from the work of Ito-Bessyo (Pcm)

5.2 Post weld hardness prediction

It has been reported that unstable failure modes (partial plug and interfacial failure mode) can occur in welds with hardness exceeding 400 – 450 HV. Interfacial failures have been found in welds with hardness exceeding 450 HV [14]. Gould reports that harder microstructures allow microstructural defects to propagate into cracks, allowing for undesirable failure modes [1]. It is important to realise however that there is no universal relationship between post weld hardness and failure mode. No maximum weld hardness can be specified to define the limit of suitable weldability, as other factors (e.g. material thickness and material type) can also have an effect [17].

The unstable failure modes are detrimental for crash performance. It is desirable to be able to predict post weld hardness from the chemical composition of the parent material. Therefore straightforward statistical linear regression was used to determine the relation between the chemical composition and the post weld hardness of the materials listed in Table 2. This relation was derived for 4 different welding processes used for automotive applications:
– resistance spot welding with forced cooling;
– resistance spot welding without forced cooling;
– laser beam welding;
– plasma arc welding.

The post weld hardness is determined by the chemical composition of the base material in combination with the cooling rate after welding. Therefore it is important that the results used to derive the equations have been based on 1,4 mm thick material. If the material thickness differs significantly the cooling rates may differ sufficiently to influence post weld hardness.

For resistance spot welding with forced cooling the following relation was determined:

$$HV = 229 + 1\,088*(C + Si/88 + Mn/102 + Cr/91 + Mo/99) \quad (10)$$

For resistance spot welding without forced cooling the following relation was determined:

$$HV = 217 + 1\,080*(C + Si/70 + Mn/113 + Cr/93 + Mo/71) \quad (11)$$

For laser beam welding the following relation was determined:

$$HV = 108 + 1\,063*(C + Si/77 + Mn/21 + Cr/28 + Mo/30) \quad (12)$$

For plasma arc welding the following relation was determined:

$$HV = 52 + 1\,161*(C + Si/44 + Mn/24 + Cr/20 + Mo/17) \quad (13)$$

with hardness in Vickers and element concentration in wt%.

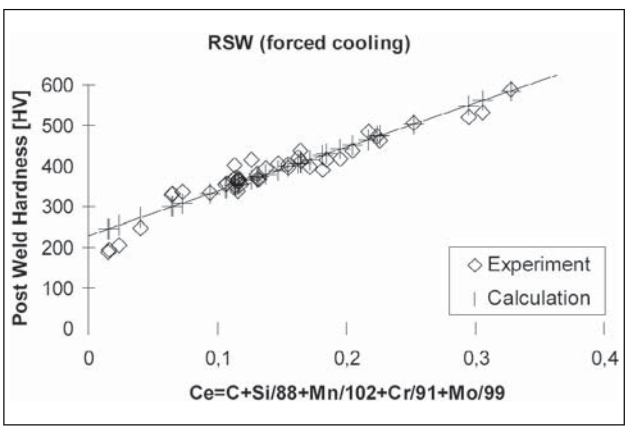
Figures 14 a), b), c) and d) show the determined relations with the experimental results.

Regression analysis was done using Microsoft Excel. Table 3 shows some statistical data for the regression analysis. The coefficient of determination, R^2, is over 0,9 for all welding processes. The adjusted R^2 value also exceeds 0,9 for all welding processes. It is considered that the equations have quite high significance for predicting post weld hardness in AHSS.

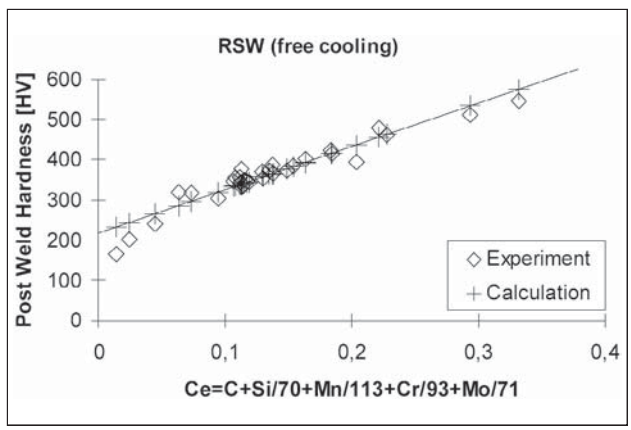
Table 3 – Statistical data for regression analysis

	RSW (forced cooling)	RSW (free cooling)	LBW	PAW
R^2	0,91	0,91	0,91	0,94
adjusted R^2	0,90	0,90	0,90	0,93
observations	42	33	42	42

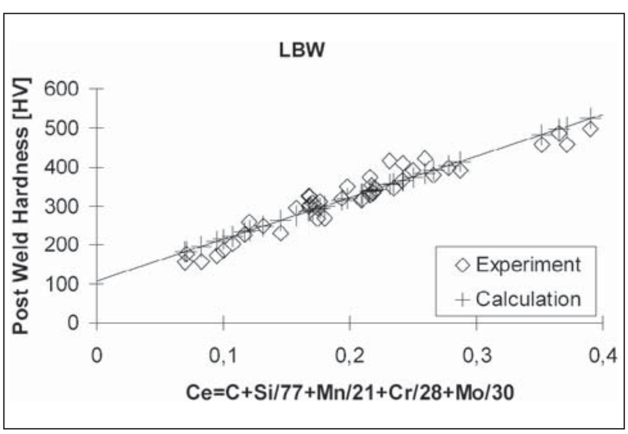
Table 4 gives the P-value (probability) for the coefficients for the various elements in all four equations, as well as the off-set value (intercept). The P-value is very low for carbon in all four cases. The P-value for the other elements varies between the different welding processes. The probability for the Mn, Cr & Mo coefficients is quite high for the resistance spot weld equations. But with decreasing cooling rates, the P value for the Si, Mn, Cr and Mo coefficients decreases to very low levels.



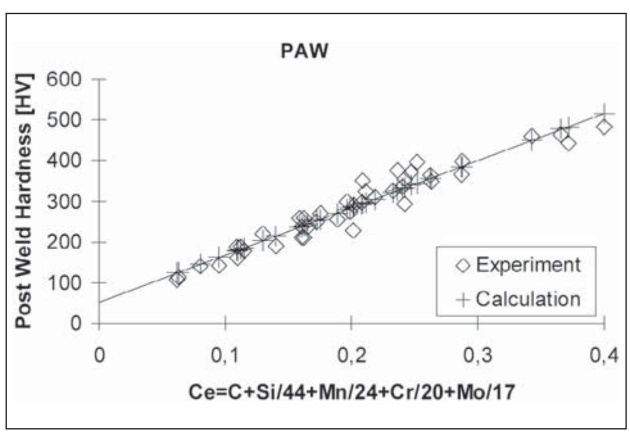
a) Eq. (10) for RSW with forced cooling and experimental results



b) Eq. (11) for RSW without forced cooling and experimental results



c) Eq. (12) for LBW and experimental results



d) Eq. (13) for PAW and experimental results

Figure 14

Table 4 – Coefficients and probability of the coefficients as derived by regression analysis

	RSW (forced cooling)		RSW (free cooling)		LBW		PAW	
	coeff.	P-value	coeff.	P-value	coeff.	P-value	coeff.	P-value
Intercept	229,10	1,96E-19	217,24	8,04E-15	108,19	3,24E-09	51,66	4,35E-04
C	1 088,02	1,85E-19	1 079,61	2,23E-15	1063,46	1,49E-18	1 160,52	3,22E-20
Si	12,36	6,18E-02	15,34	3,76E-02	13,85	3,77E-02	26,58	2,82E-04
Mn	10,62	1,44E-01	9,56	2,46E-01	49,97	5,58E-07	48,53	5,15E-07
Cr	11,97	3,43E-01	11,51	3,35E-01	37,60	6,65E-03	56,63	6,68E-05
Mo	11,02	3,67E-01	15,21	1,91E-01	35,10	8,72E-03	69,05	1,91E-06

It can be concluded that the main element determining post weld hardness is carbon for fast cooling rates. As cooling rates decrease other elements start to play their part. Compared to resistance spot welding the influence of manganese, chromium and molybdenum on post weld hardness increases for laser beam welding. The influence of silicon increases as the cooling rate decreases from laser beam welding to plasma arc welding. It can also be seen that with decreasing cooling rates the offset hardness decreases. This should happen as the offset hardness captures the influence of cooling rate (high cooling rates lead to the formation of hard phases, increase occurrence of lattice defects and it constricts auto-tempering).

6 CONCLUSIONS

The relation between chemical composition and post weld hardness was investigated for high strength steels for automotive applications. The post weld hardness is an important factor concerning the weldability of steels and the performance of the welds for automotive applications. Other factors influencing weldability of steels, such as the occurrence of hot cracking and temper embrittlement are not discussed in this paper, although these do play their part. From the work discussed in this paper several conclusions can be drawn.

– The carbon content can be used to estimate weldability of high strength steels as far as post weld hardness is concerned for resistance spot welding.

– The carbon equivalent number proposed by Taka and Yamauchi can be used to discriminate further between weldability of high strength steels if no forced cooling is applied after resistance spot welding (i.e. reduced hold times).

– It is necessary to take more elements apart from carbon into account to estimate weldability of high strength steels for laser beam welding and plasma arc welding.

– Both the carbon equivalent numbers proposed by Ono and Yamamoto can be used to estimate weldability of high strength steels as far as post weld hardness is concerned for laser beam welding.

– The carbon equivalent number proposed by Ono gives slightly better results to estimate weldability of high strength steels as far as post weld hardness is concerned for laser beam welding.

– The carbon equivalent number derived from the work by Ito and Bessyo can be used to estimate weldability of high strength steels as far as post weld hardness is concerned for plasma arc welding.

– For resistance spot welding with forced cooling the following relation was determined to relate chemical composition to post weld hardness:

$$HV = 229 + 1\,088*(C + Si/88 + Mn/102 + Cr/91 + Mo/99)$$

– For resistance spot welding without forced cooling the following relation was determined to relate chemical composition to post weld hardness:

$$HV = 217 + 1\,080*(C + Si/70 + Mn/113 + Cr/93 + Mo/71)$$

– For laser beam welding the following relation was determined to relate chemical composition to post weld hardness:

$$HV = 108 + 1\,063*(C + Si/77 + Mn/21 + Cr/28 + Mo/30)$$

– For plasma arc welding the following relation was determined to relate chemical composition to post weld hardness:

$$HV = 52 + 1\,161*(C + Si/44 + Mn/24 + Cr/20 + Mo/17)$$

– The influence of additional elements (Si, Mn, Cr & Mo) on post weld hardness increases with decreasing cooling rates.

– The offset hardness in equations to predict post weld hardness decreases with decreasing cooling rates.

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