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

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1 INTRODUCTION

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

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

This Carbon Equivalence number was published in 1967 [1]. 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 Equivalence numbers relate the type and composition of a steel to its weldability, but they themselves are also dependent upon the chemical composition of the steel. The IIW CE number was drawn up to be used for steels with Carbon levels exceeding 0,18 wt% C. Strictly speaking Carbon Equivalence numbers are not 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 [2]. Post weld hardness is related to the strength of a weld. Also excess hardness is a good indicator for microscopic weld defects in martensitic welds as the hardness of martensite increases with the accumulation of lattice defects. 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 inclusions, occurrence of precipitates and grain size.
In 1967 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 0,12wt% [3]. The chemical portion of this formula (Pcm) is commonly used as a Carbon Equivalence number for steels with [C] < 0,18 wt%.

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

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 Equivalence Numbers

As stated Carbon Equivalence 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 [4].

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. Some elements are well known to increase hardness, 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 [5].

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 warmed, 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, grain growth 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 e.a. derived equations that relate chemical compositions of steels and cooling rates after welding to post weld hardness. [6] Chaillet e.a. elaborated on this work to determine statistical formulae to calculate the hardness after welding (in Vickers) for high strength steels [7].

$$HV(martensite) = 97 + 949C + 27Si + 11Mn + 8Ni + 16Cr + 20\log Vr \qquad (Eq. 3)$$

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

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

Where the concentration of elements is in measured in [wt%] and Vr is the cooling rate of the material at 700°C in °C/hr.
Chaillet e.a. also give equations the effect of tempering on the resultant hardness of the welds using previous work done by Blondeau e. a. [8].
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 is 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 Equivalence equations, each suited for a specific welding process (with approximately similar cooling rates). Taka and Yamauchi have proposed a Carbon Equivalence number to be used for resistance spot welding of high strength steels [9]:

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

Ono proposed a Carbon Equivalence number that can be used for laser beam welding of high strength steels [10]:

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

Yamamoto proposed another Carbon Equivalence number that can be used for laser beam welding of steels containing Boron [11]:

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

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 and fatigue testing. For continuous welds, such as with laser and arc, formability is also an importance 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. 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 [12]

There are others influences that can decrease the weld quality, such as hot cracking susceptibility and tendency to temper embrittlement. These effects can not be captured in Carbon Equivalence numbers and are therefore no subject of this paper. However Carbon Equivalence numbers can be used in models that will predict the performance of a weld. One such model has been developed by Nishi et al. to relate the performance of resistance spot welds. In this model the Carbon Equivalence number proposed by them is related to a second parameter combining the influence of Sulphur and Phosphorous in a Phosphorous Equivalence number:

$$PE = P + 2S \qquad \text{(Eq. 9)}$$

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 [13]. Another graph shown in figure 2 has been used in Sumitomo Metal Industry. The Carbon Equivalence number by Taka and Yamauchi [9] and their original Phosphorus Equivalence number are used in the graph. The Carbon Equivalence number and Phosphorus equivalence number in each graph are slightly different, however the concept of the graphs is the same.

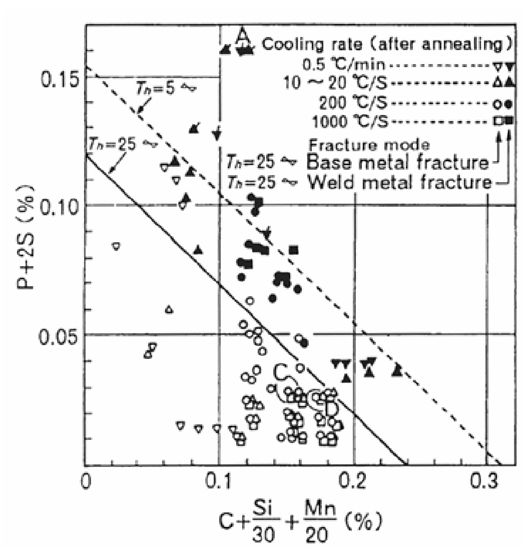

Figure 1: Dependence of fracture mode in peel test on chemical composition of base metal [13].

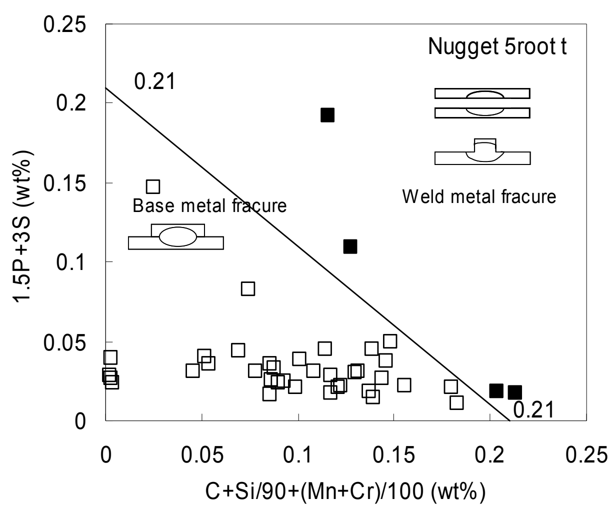

Figure 2: Dependence of fracture mode in cross tensile test on chemical composition of base metal according to Sumitomo Metal Industry.

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

3 MATERIALS AND EXPERIMENTAL DATA

Several series of experiments have been conducted. First a series of steels 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 steels table 1 lists the thickness in milimeters of the sheet material, the chemical composition for the main elements and the tensile strength (UTS) in MPa.
These steels have been 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 (see figure 4).

steel	**Thickness**	**C**	**Mn**	**Si**	**Cr**	**P**	**S**	**UTS**
[#]	**[mm]**	**[wt%]**	**[wt%]**	**[wt%]**	**[wt%]**	**[wt%]**	**[wt%]**	**[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*		*1000*
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*	*1000*

Table 1: thickness, chemical composition and tensile strength for several commercially available high strength steels.

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).

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						

Table 2: Chemical composition of set of lab cast steels.

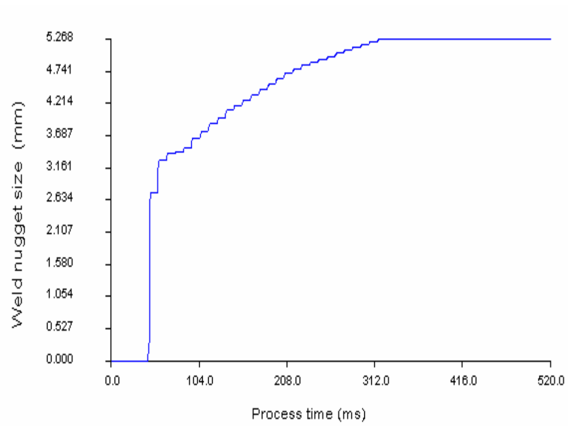

Figure 3: Growth of weld nugget diameter in a 1,2 mm thick GI-coated AHSS welded with a welding current of 6,8 kA for 14 cycles (50 Hz AC) using Type G welding electrodes with 6 mm radius, as simulated using Sorpas software.

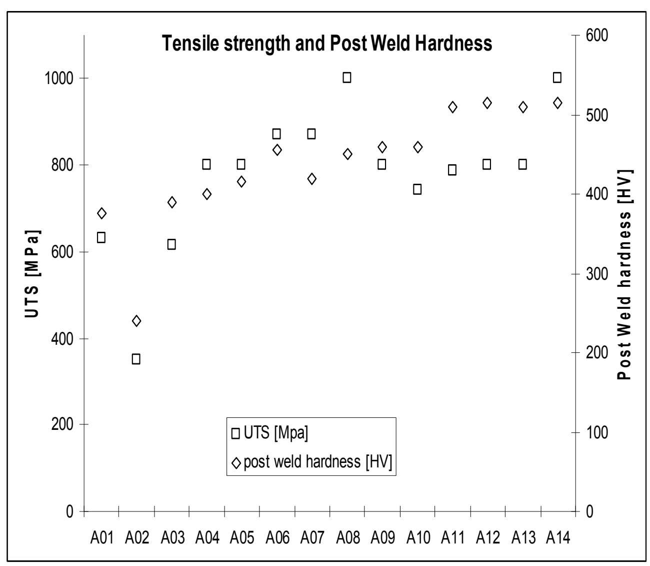

Figure 4: Tensile strength and post weld hardness (RSW) of steels listed in table 1.

Resistance spot welding was done using a 5kA 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 after welding as well as with a 60 cycles (60 Hz) hold after welding. After welding the post weld hardness for both sets of samples was measured (see figure 5 a & b).
Laser beam welding was done using a 3 kW YAG laser (focus diameter: 0,6 mm). Process speed was 3m/min and Argon was used as shielding gas (15 l/min). After welding the post weld hardness was measured (see figure 5 c).
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 (see figure 5 d).

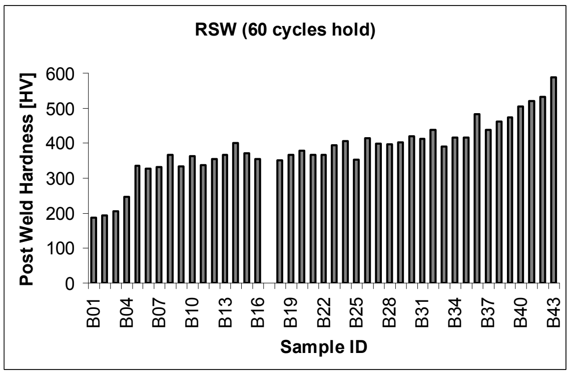

Figure 5a: Post weld hardness for steels listed in table 2 using resistance spot welding with a hold time of 60 cycles (60 Hz).

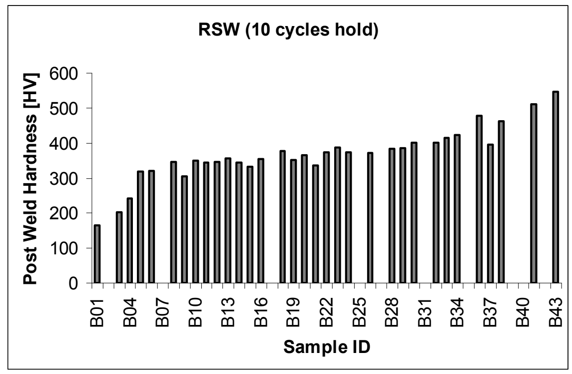

Figure 5b: Post weld hardness for steels listed in table 2 using resistance spot welding with a hold time of 10 cycles (60 Hz).

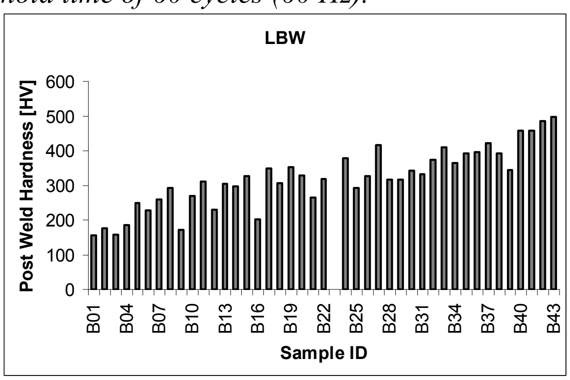

Figure 5c: Post weld hardness for steels listed in table 2 using laser beam welding

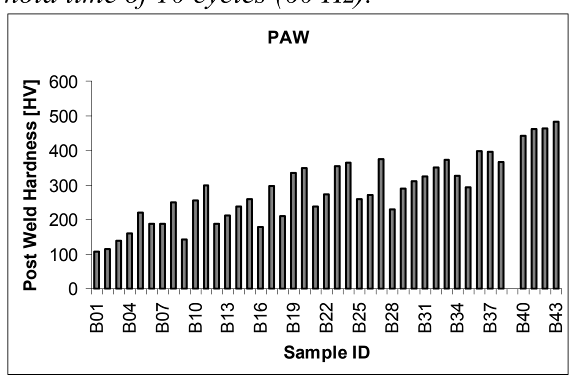

Figure 5d: Post weld hardness for steels listed in table 2 using plasma arc welding.

4 DISCUSSION

4.1 Carbon Equivalence 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 UTC 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.
Figure 7 depicts the relationship between Carbon content of commercially available high strength steel (listed in table 1) and the resultant post weld hardness after resistance sport 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 sport 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.

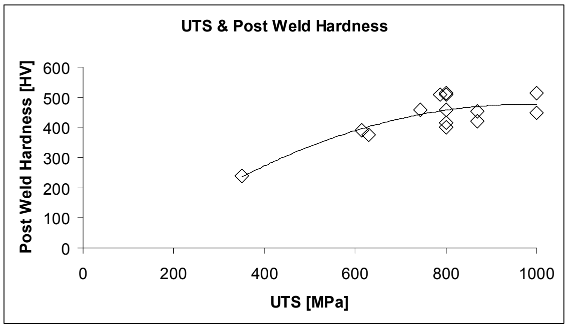

Figure 6: Relation between tensile strength of materials listed in table 1 and the post weld hardness (using resistance spot welding)

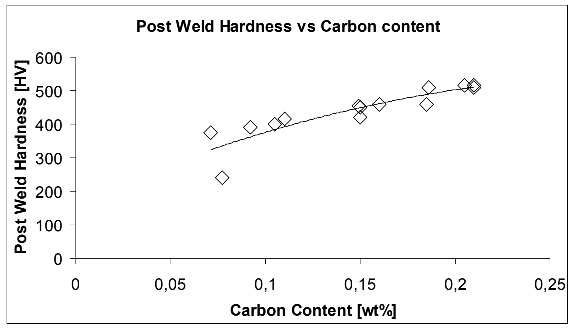

Figure 7: Relation between the Carbon content of commercially available high strength steels (table 1) and the post weld hardness after resistance spot welding.

Figures 8a, 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 the 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 a simulated 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 when the electrodes are released after 10 cycles (thus ending forced cooling through the water cooled electrodes) the temperature in the centre of the weld has not yet reached 700°C. Therefore the critical cooling rate as used by Blondeau and Chaillet is lower for the samples welded with a holding time of 10 cycles compared to that of sample welded with a holding time of 60 cycles. This should result in higher post weld hardness for materials welded with longer holding time, as can be seen in figure 10, although the differences are only small.

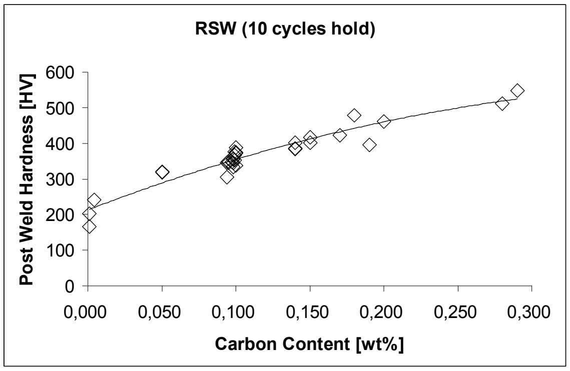

Figure 8a: Post weld hardness for materials listed in table 2 using resistance spot welding (with 10 cycles holding time after welding) vs. Carbon content.

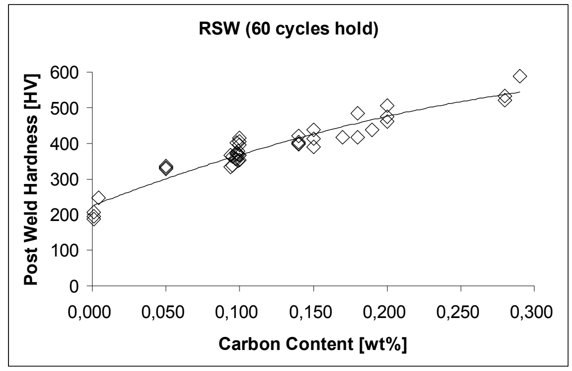

Figure 8b: Post weld hardness for materials listed in table 2 using resistance spot welding (with 60 cycles holding time after welding) vs. Carbon content.

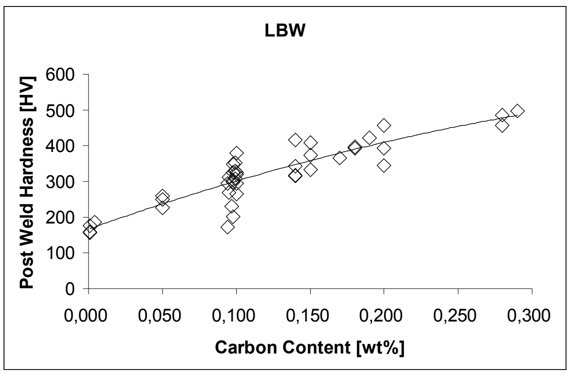

Figure 8c: Post weld hardness for materials listed in table 2 using laser beam welding vs. Carbon content.

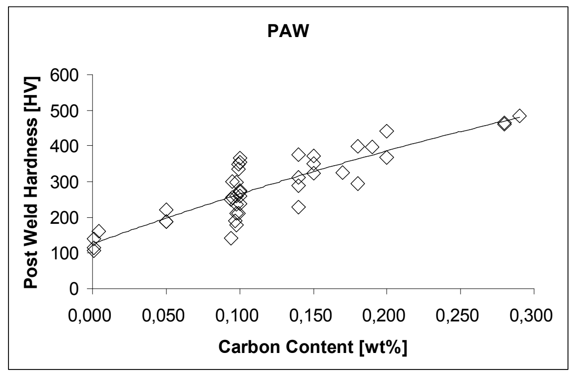

Figure 8d: Post weld hardness for materials listed in table 2 using plasma arc welding vs. Carbon content.

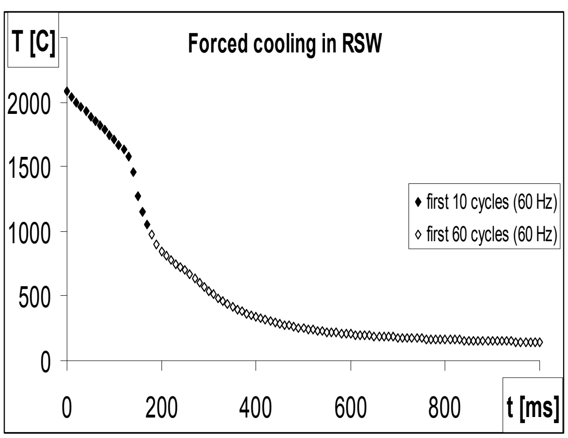

Figure 9: temperature vs. time in the centre of the weld during the first 60 cycles (60 Hz) of forced cooling after welding, as simulated using Sorpas software. The first 10 cycles are depicted with closed diamonds; the following 50 are depicted by open diamonds.

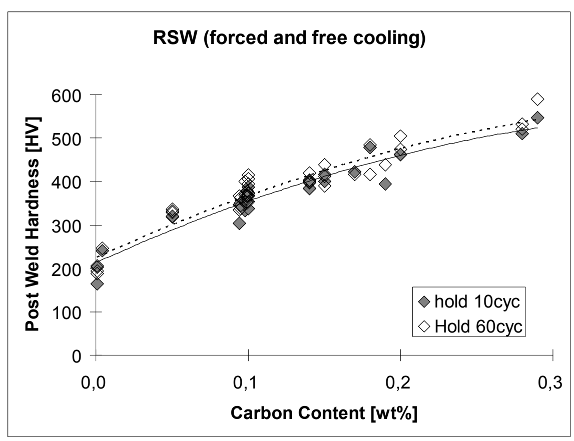

Figure 10: Post weld hardness for materials listed in table 2 using resistance spot welding vs. Carbon content. Samples welded with a holding time of 60 cycles are depicted using open diamonds with a dashed trendline. Samples welded with a holding time of 10 cycles are depicted using closed diamonds with a continuous trendline.

If cooling rates are slower, the influence of additional alloying elements upon the post weld hardness increases. This can be expressed, using the Carbon Equivalence number proposed by Taka and Yamauchi (see figure 11 a & b). Although the differences are very small it can be seen that the use of the Carbon Equivalence 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 compare to a holding time of 60 cycles.

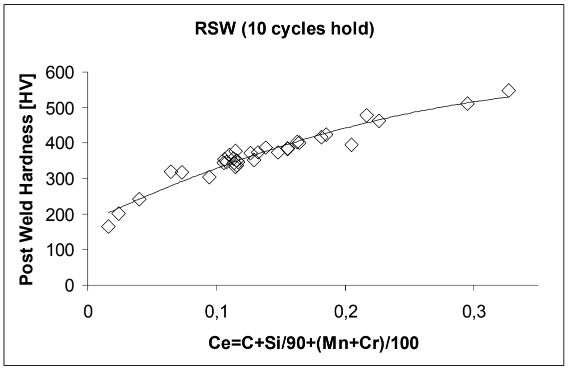

Figure 11 a: Post weld hardness for materials listed in table 2 using resistance spot welding (with 10 cycles holding time after welding) against the Carbon Equivalence number proposed by Taka and Yamauchi.

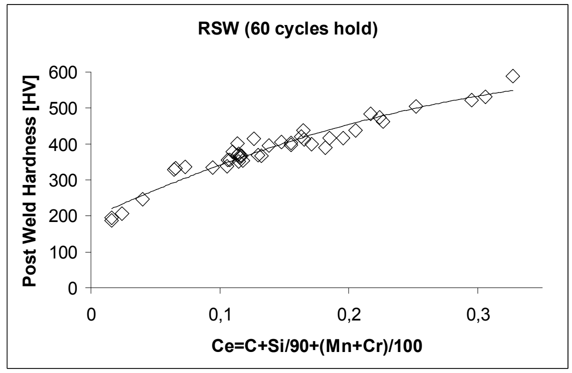

Figure 11 b: Post weld hardness for materials listed in table 2 using resistance spot welding (with 60 cycles holding time after welding) against the Carbon Equivalence number proposed by Taka and Yamauchi.

Although the difference in predictability of weldability using plain Carbon content and dedicated Carbon Equivalence numbers may be small with respect to resistance spot welding. The accuracy gained using dedicated Carbon Equivalence numbers increased when cooling rates decrease. Figure 12 a gives the relation between post weld hardness and the Carbon Equivalence number proposed by Ono. Figure 12 b gives the relation between post weld hardness and the Carbon Equivalence number proposed Yamamoto. The accuracy is much better in both cases compared to figure 7 c. The addition of extra elements in the Carbon Equivalence number by Ono does give better results, but the single addition of the influence of Manganese in the Carbon Equivalence number proposed by Yamamoto already increases accuracy significantly.

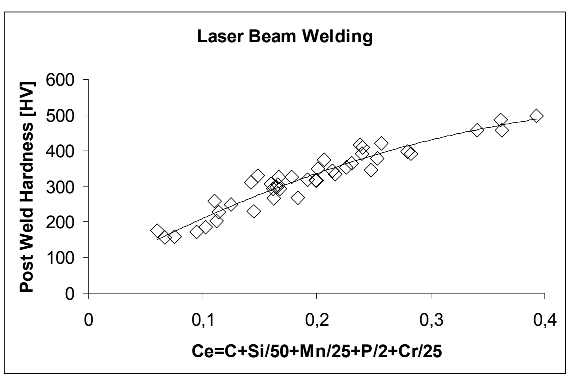

Figure 12 a: Relation between post weld hardness after laser beam welding and the Carbon Equivalence number proposed by Ono

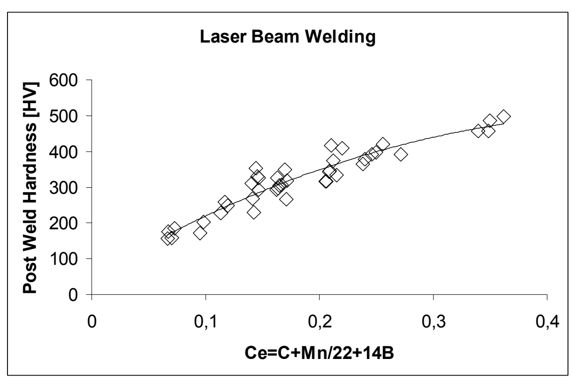

Figure 12 b: Relation between post weld hardness after laser beam welding and the Carbon Equivalence number proposed Yamamoto

Plasma arc welding results in even lower cooling rates than laser beam welding. Figure 13 gives the relationship between the Carbon Equivalence number derived from the work by Ito-Bessyo (Pcm). Again the accuracy is much better than the results of figure 7 b. 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.

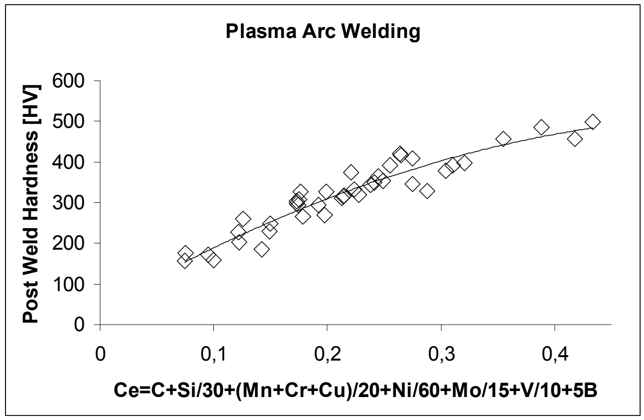

Figure 13: Relation between post weld hardness and the Carbon Equivalence number derived form the work of Ito-Bessyo (Pcm).

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 Equivalence 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 holding 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 Equivalence 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 Equivalence 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 Equivalence 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.

4.2 Post Weld Hardness Prediction

As mentioned a rule of thumb states that welds with a hardness exceeding 400 to 450 HV tend to show brittle failure. As this is detrimental for crash and fatigue 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 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.

As 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:

$$HV = 229 + 1088*(C + Si/88 + Mn/102 + Cr/91 + Mo/99) \qquad \text{(Eq. 10)}$$

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

$$HV = 217 + 1080*(C + Si/70 + Mn/113 + Cr/93 + Mo/71) \qquad \text{(Eq. 11)}$$

For laser beam welding the following relation was determined:

$$HV = 108 + 1063*(C + Si/77 + Mn/21 + Cr/28 + Mo/30) \qquad \text{(Eq. 12)}$$

For plasma arc welding the following relation was determined:

$$HV = 52 + 1161*(C + Si/44 + Mn/24 + Cr/20 + Mo/17) \qquad \text{(Eq. 13)}$$

With hardness in Vickers and element concentration in wt%.
Figures 14 a, b, c & d show the determined relations with the experimental results.

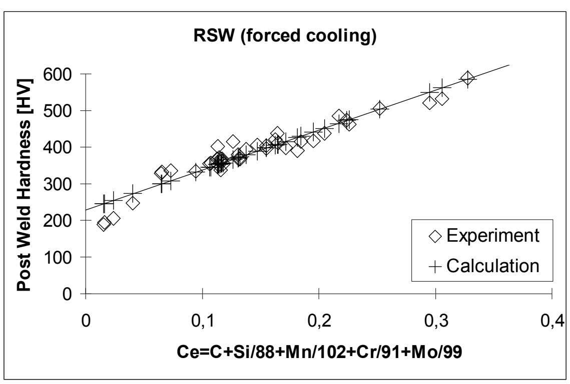

Figure 14 a: Equation 10 for RSW with forced cooling and experimental results

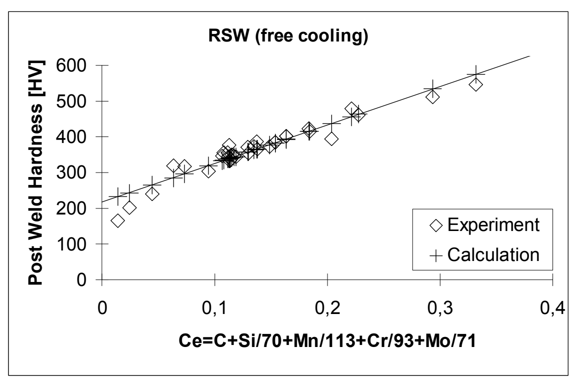

Figure 14 b: Equation 11 for RSW without forced cooling and experimental results

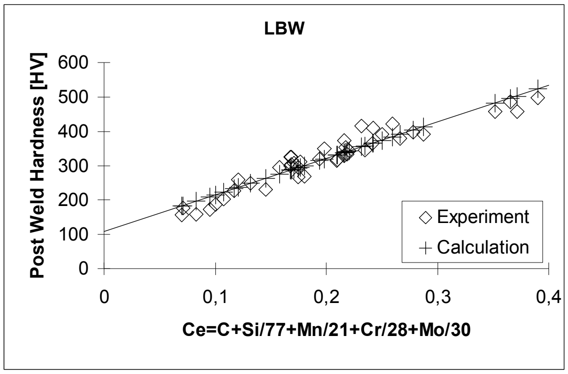

Figure 14 c: Equation 12 for LBW and experimental results

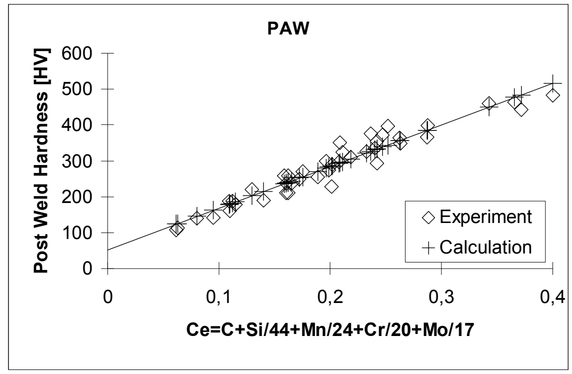

Figure 14 d: Equation 13 for PAW and experimental results

5 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 conclusion 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 Equivalence 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 holding 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 Equivalence 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 Equivalence 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 Equivalence 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:
  $$HV = 229 + 1088*(C + Si/88 + Mn/102 + Cr/91 + Mo/99)$$
- For resistance spot welding without forced cooling the following relation was determined to relate chemical composition to post weld hardness:
  $$HV = 217 + 1080*(C + Si/70 + Mn/113 + Cr/93 + Mo/71)$$
- For laser beam welding the following relation was determined to relate chemical composition to post weld hardness:
  $$HV = 108 + 1063*(C + Si/77 + Mn/21 + Cr/28 + Mo/30)$$

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

$$HV = 52 + 1161*(C + Si/44 + Mn/24 + Cr/20 + Mo/17)$$

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