SPOT WELDING EXPERIMENTS ON AUTOMOTIVE DUAL-PHASE STEEL SHEETS

László Prém
PhD student
University of Miskolc, Institute of Materials Science and Processes

1. INTRODUCTION

Besides conventional mild steels that have been determining for decades in automobile production, the application of advanced high-strength steels is coming into the limelight. Among the first generation AHSS steels Dual-Phase (DP) steels are of the utmost importance concerning their automotive use. DP steels possess prominently high strength and significantly lower deformation ability compared to the easily deformable, low strength mild steels which are excellent for spot welding (for example: DC 01).

In Hungary a lot of small and medium sized enterprises function as the suppliers of the big automakers settled in our country. Nowadays these enterprises, besides the welding of mild steel parts, often have the task of joining ferrite-martensite structured DP steels with spot welding. During the spot welding of DP steels, when using the technology familiar with mild steels, the risk of hardening, the unfavourable failure of the joint or even cracking during operation must be taken into account, therefore we must design the technology very carefully. Taking these factors into consideration the aim of my research was the examination of the spot welding technology of high-strength DP steels. In this paper I summarize the results of the spot welding experiments carried out on DP steels so far.

2. SPOT WELDING AND DP STEELS IN THE AUTOMOTIVE INDUSTRY

Due to the automotive innovations the application of adhesive bonding, soldering and various mechanical methods (clinching, riveting, etc.) became more common besides the conventional joining technologies used in the vehicle industry.

Table 1

Ratio of joining methods applied in the production of modern passenger cars

Method	Golf A4	Polo A04	Q7
Spot welding	81.54	68.83	74.54
Projection welding	1.78	4.57	0.62
Laser brazing	-	3.80	3.87
Laser welding	1.56	4.07	1.55
Stud welding	6.53	5.77	5.0
MIG brazing	1.32	11.86	0.95
MAG welding	7.27	1.1	11.06
Plasma brazing	-	-	2.41

However, from among the joining methods presented in Table 1, resistance spot welding still possesses the most engineering and economic advantages, therefore this process is still considered to be predominant in car production. This statement is confirmed by Table 1 [1].

As a result of the researches carried out in the UltraLight Steel Auto Body (ULSAB-AVC) programme it has been established that 85% of a passenger car's steel structure can be produced from AHSS steels, thereby achieving up to 25% of self-weight reduction compared to a common base model, without the significant increase in production costs. Figure 1 clearly shows that within the DP steel type the application of materials with 600 MPa, 800 MPa and 1000 MPa tensile strength has become general. The absolute predominance of the DP 600 material grade is notable [2]. DP steels with a tensile strength lower than 600 MPa and higher than 1000 MPa also exist.

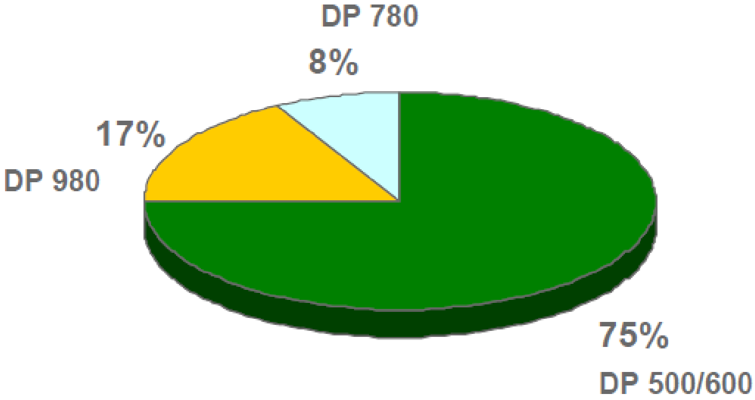

Figure 1
Application ratio of different DP steel types

Standard prEN 10338:2013 contains the the designations of automotive DP steel grades. However, the designation system used by this standard differs from the widespread DP (Dual-Phase) designations [3].

Table 2
Various designations of ferrite-martensite microstructured steels

Type of steel	according to prEN 10338
DP 600	HCT600X
DP 800 (DP 780)	HCT780X
DP 1000 (DP 980)	HCT980X

Nowadays several car parts are produced from DP steels, such as bumper reinforcements, crashboxes, door beams, waistline beams, A-, B-, C pillars, roof bows/roof rails, header front/rear, window members and seat tracks, seat frames [4]. Several of these parts serve passenger safety, since DP steels are of excellent energy absorbing ability. This favourable property is due to their high $R_{p0,2}$ / R_m ratio, that is their ductility reserve is very high. Figure 2 is to prove this statement.

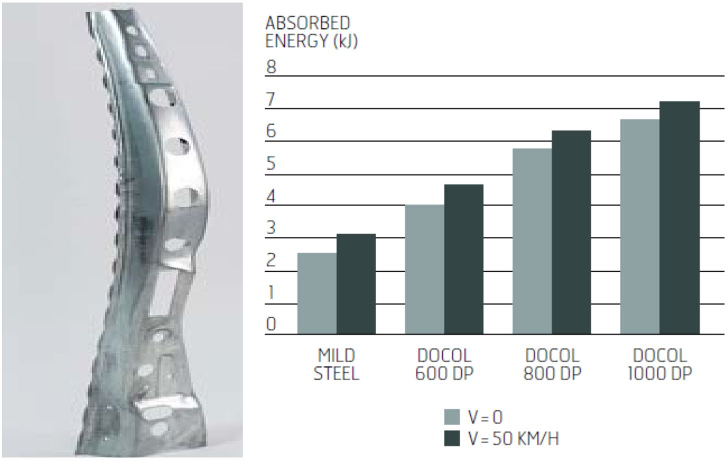

Figure 2
A B-pillar made of DP 1000; energy absorbing ability of DP steels compared to mild steels [4]

3. ABOUT AUTOMOTIVE DUAL-PHASE STEELS

The HSLA steels that have been decisive in car production for decades possess several excellent properties. Compared to their strength their plasticity is also remarkable, but in several cases it is not enough for the production of car parts which require extensive cold forming. That is why researchers focused on the development of a steel type which has a strength close to that of HSLA steels and its plasticity is similar to the plasticity of low-carbon unalloyed (C < 0,1%) steels. The developments started in the 1970s and by now practice has proven that the widely used DP steels meet the aforementioned objectives [5].

DP steels contain fine, dispersedly distributed, hard martensite islands embedded in a ferrite matrix. The soft ferrite ensures high deformability, whereas the hard martensite increases the strength of steel. By controlling the chemical composition, more precisely the carbon content and cooling rate, the ratio of martensite is variable between 20…70% [6].

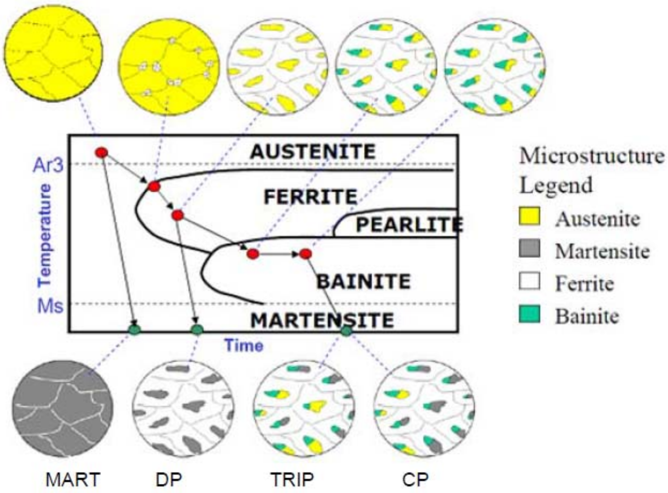

Figure 3
Schematic diagram of the production of DP steels [2]

This heterogeneous microstructure is usually achieved by continuous heat treatment (in a continuous annealing furnace or in a salt bath) or by controlled cooling after hot rolling [5]. The essence of these heat treatments is that the desired ferrite/austenite structure is formed within the $A_1 \ldots A_3$ temperature range, then the steel is cooled down at high rate from the intercritical temperature, this way martensite is produced from the austenite during the process. The greatest difference of the production of DP steels compared to the normal hardening of steels is that the austenitization is only partial, therefore the austenite crystallites are surrounded by ferrite [5].

4. METALLOGRAPHIC EXAMINATION OF DP STEELS

DP steels possess very high tensile strength ($R_m = 500 \ldots 1400$ MPa) and reasonably high hardness (HV ≈ 200...350), but at the same time they have high tenacity and relatively high deformability ($A_{80} = 8 \ldots 30\%$).

Taking the domestic spread and primary automotive use of AHSS steels into consideration, I chose the cold rolled, continuously annealed, ferrite-martensite structured Docol DP 600, DP 800 and DP 1000 high-strength thin sheets of Swedish steel manufacturer SSAB as the base materials of my experiments.

Before carrying out the spot welding experiments on the base material I performed basic metallographic tests. In order to determine the mechanical properties I carried out standard tensile tests, as well as measurements of hardness. During the microscopic examination of the microstructure I determined the ferrite-martensite ratio of the different steel grades. Figure 4 shows the tensile-test diagram and the ferrite-martensitic microstructure of a DP 600 steel. The tensile-test diagram is continuous, the steel does not have a definite yield point. The ferrite-martensitic structure can be observed in the microstructural image.

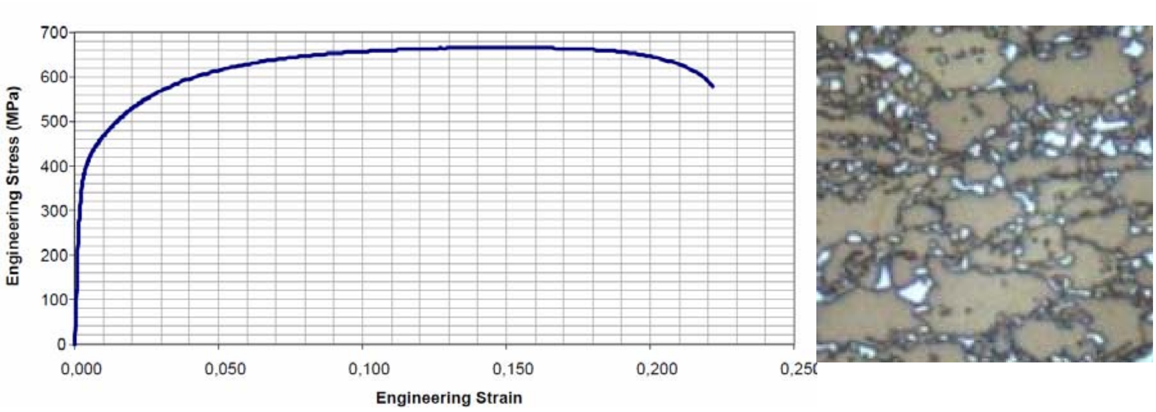

Figure 4
The tensile-test diagram and the micrograph of a DP 600 steel

Table 3 contains the results of the tensile tests and microscopic analyses of the available 1 mm thick DP steel sheets.

Table 3

Results of metallographic examination of DP steels

Type of steel	Mechanical properties				Microstructure
	R_m (MPa)	$R_{p0,2}$ (MPa)	A_{80} (%)	HV 0,2 (-)	Martensite (%)
DP 600	669	459	18.70	235	35 %
DP 800	874	668	13.67	265	45 %
DP 1000	1047	761	11.33	324	55 %

The chemical composition fundamentally influences the weldability of the base material to be joined by spot welding. Therefore we checked the alloy constituent of our experimental base materials with spectrometric measurements. The chemical composition of DP steels is characterised by a low carbon content ($C \leq 0,15$ %), the presence of microalloying elements (Nb, V, B) and extremely low impurity (S, P, O, N). Table 4 contains the results of our spectrometric measurements. During welding it has to be taken into consideration at any case that the base material contains so called ‘mild’ martensite with a low carbon content, and that the microalloying elements can facilitate the hardening of the austenitized material volumes.

Table 4

Chemical composition of cold rolled DP steels

Type of steel	C (%)	Si (%)	Mn (%)	Cr (%)	Ni (%)	Nb (%)	V (%)	B (%)
DP 600	0.098	0.20	0.81	0.03	0.04	0.014	0.01	0.0002
DP 800	0.129	0.20	1.52	0.03	0.03	0.015	0.02	0.0003
DP 1000	0.148	0.49	1.50	0.03	0.04	0.015	0.01	0.0004

5. DIFFERENT CONTROLLING METHODS FOR SPOT WELDING OF DP STEELS

DP steel sheets can be welded by the conventional AC and MFDC power sources alike. However, the use of AC power sources is yet more common among Hungarian firms. Depending on the control unit we can choose from different control methods during the programming of power sources: operation with percentage setting, constant-energy operation and constant-current operation. From among the listed control methods probably constant-current operation is the most benefitial from an engineering point of view. The greatest benefit is that we can set the desired welding current value directly. The control unit measures the root mean square (RMS) value of the welding current every half period during welding and maintaines the set current intensity based on a mathematical correction algorithm. This operation mode, besides making programming easier, makes it possible to achieve the desired welding current even if the following factors change: main voltage, impedance of the weld circuit, as well as the condition of electrodes and the surface condition of materials to be machined. In the course of my welding experiments I used an AC power source in constant-current operation in every case.

6. SPOT WELDING EXPERIMENTS OF DP STEELS

DP steels are characterised by higher specific resistance and higher strength at elevated temperatures compared to conventional mild steels. Due to the microalloying elements DP steels are also characterised by tempering resistance during a short-term thermal effect (eg. spot welding). According to the literature, when spot welding DP steels, because of these characteristics, the applied electrode force should be 20…50% higher and the welding time should be approx. 20% higher than in the case of mild steels. According to the recommendations of SSAB, the manufacturer of the experimental base materials, DP steels can be spot welded in appropriate quality with both continuous and impulsed energy input [7]. In the preliminary spot welding experiments of DP steels I took the technological parameters of the continuous energy input spot welding of the DC01 steel as a basis, taking the aforementioned considerations into account.

In short time programme I prepared spot welds on the DP 1000 grade material. During the hardness measurement of the prepared weld we found that the heat-affected zone (HAZ) and the weld nugget became hardened, their average hardness was between 450…500 HV (Figure 6). Next I prepared welds in long time programme, as it is appropriate to weld materials prone to harden in this working programme. In this case it was found that we managed to reduce the hardness of the HAZ to 350…400 HV, but the hardness of the weld nugget remained very high.

However, when welding in long time programme we must take a number of disadvantages into account. The biggest problem is the extended cycle time, which is unacceptable for manufacturers in the production of a car body that contains 4-5000 spot welds. Besides the growing of cycle time we must reckon with the coarse, brittle dendrite microstructure of the weld nugget, a greater electrode impression and wear, as well as the decrease in the load bearing capacity of the joint. We assume that the higher heat input characteristic of the long time programme causes part of the martensite to temper, which may cause a decrease in the tensile shear strength of the welds. Figure 5 proves this statement. The figure presents the tensile shear strength of the spot welded joints prepared in short and long time programme and the average hardness of the heat-affected zones, concerning materials DC01, DP 600, DP 800 and DP 1000, in relation to the tensile strength of the base materials.

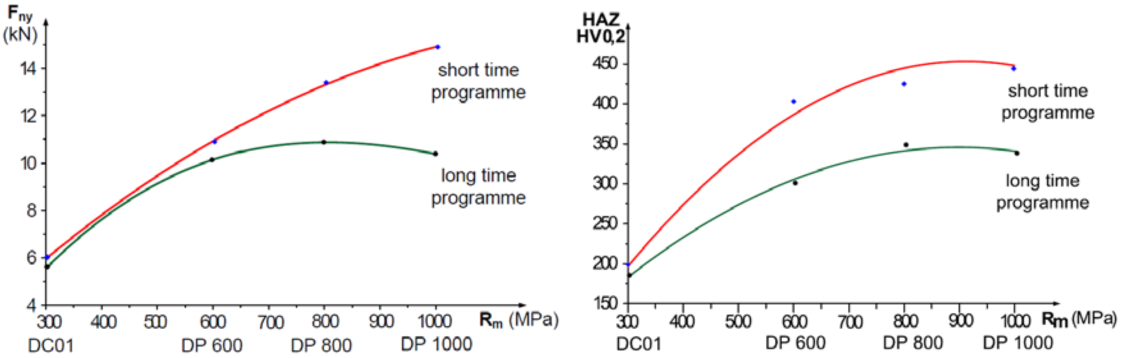

Figure 5

Tensile shear strength of spot welded joints

Hardness of heat-affected zones of spot welded joints

Knowing the thickness of the sheet and the diameter of the spot weld, we can determine the load bearing capacity of the joints prepared in short time programme with the equation *(1)*.

$$F_s = k_1 \cdot t \cdot d \cdot R_m \quad (1)$$

where:

- F_s is the tensile shear strength of the joint expressed in N,
- k_1 is a coefficient depending on the material grade,
- t is the sheet thickness expressed in millimeters,
- d is the diameter of the spot weld expressed in millimeters,
- R_m is the tensile strength of the base material expressed in MPa [7].

The tensile shear strength values obtained from the preliminary experiments are in good agreement with the load bearing capacity calculated with the equation *(1)* (Figure 5). The load bearing capacity of the joints welded in short time programme meets the expectations. However, the failure mode of the welded joints was unfavourable in many cases during the tensile shear tests, which suggests the brittle state of the joints. This phenomenon primarily occured in the case of DP 800 and DP 1000 material grades. This may be caused by the brittle martensite with relatively high hardness found in the heat-affected zone, and the coarse dendrite branches of the weld nugget, which can lead to cracking or even to brittle fracture during operation. This should be avoided in any case. One of the solutions could be the reduction of the HAZ hardness and fining the microstructure of the weld nugget. This can be achieved by applying impulsed energy input from a technological point of view. Both the use of asymmetric double pulse and symmetric double pulse could be a solution as well. I have prepared a few welded joints with impulsed energy input. By applying the asymmetric double pulse the HAZ hardness can be significantly reduced, still the load capacity of the welds is more favourable than in the case of a long time welding. Disadvantages are the slightly extended cycle time and the fact that the structure of the weld nugget cannot really be fined. During the application of the symmetric double pulse we experienced that the HAZ hardness can also be reduced and the microstructure of the weld nugget, the size of the dendrite branches can be significantly fined, also the impression and the spot diameter will be smaller. Figure 6 shows an example for this.

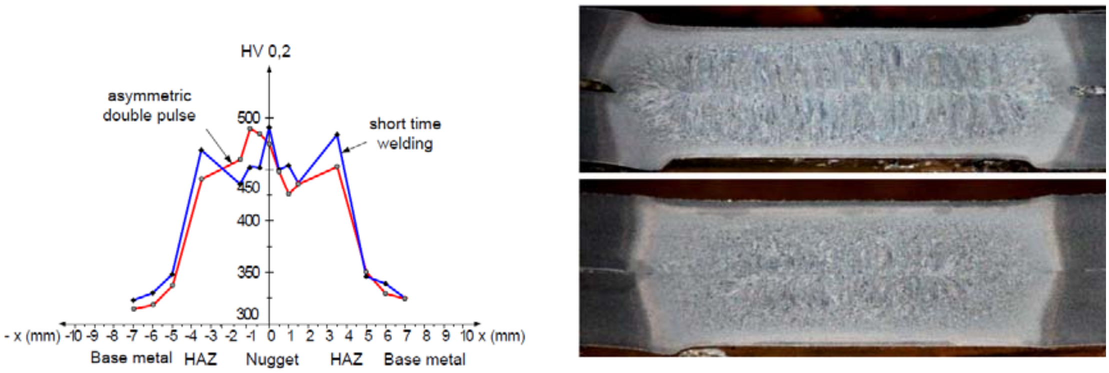

Figure 6

Hardness and macrostructure of spot welded joints in case of using continuous and impulsed energy input

7. SUMMARY

Our experiences during the experiments of the spot welding of DP steels can be summarized as follows:

1. The spot welding of DP steels in the production of modern passenger cars is of utmost importance. DP 600 is the dominant grade among DP steels.
2. The load capacity of the joints welded in short time programme usually complies with the regulations, however, some part of the weld and the heat-affected zone can be hardened, which under given stress can lead to cracking or brittle fracture during operation.
3. When applying a long time programme the tensile shear strength of the welded joints is reduced, presumably due to the tempering of martensite. The significantly extended cycle time and the faster wear of the electrode mean serious disadvantages.
4. By applying impulsed energy input we can reduce/avoid the risk of hardening while keeping the high load bearing capacity of the welded joints. A further advantage is the fining of the weld nugget's microstructure which can lead to the increase in the deformation capability of the weld before cracking.

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