Analysis of the mechanical performance of spot welding on PHS 22MnB5 steel

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Abstract

The hot pressing hardened steel known as “press hardened steel - PHS” is a steel of extreme importance for the automotive industry. The application of this type of steel in the structure of vehicles promotes the improvement of safety, mass reduction and lower fuel consumption. The increase in the use of this type of steel, culminated in the need to deepen knowledge about the joining processes, more specifically about the electrical resistance spot welding process - RSW, which is one of the most used processes in automotive structural construction. The aim of the present work was the evaluation of the autogenous spot weld of 22MnB5 steel hardened through heat treatment in laboratory scale, simulating the cooling rates used during the hot pressing, commonly used in the automotive industrial practice. Welds were made in two different conditions, with welding parameters in a single step (direct welding) and with parameters considering additional pre and post heating steps. Mechanically, the welds were evaluated through the standardized test called tension shear test. The results showed that, according to the American Welding Society - AWS standard, the performance of the welds meets the minimum requirements required for the group of materials in which 22MnB5 falls.

Keywords: PHS steel, 22MnB5, spot weld, tension shear test, automotive, RSW

Resumo

O aço endurecido por prensagem a quente conhecido como *press hardened steel* - PHS, é um aço de extrema importância para a indústria automotiva. A aplicação desse tipo de aço na estrutura de veículos promove o aprimoramento da segurança, redução de massa e menor consumo de combustível. O aumento do uso deste tipo de aço, culminou com a necessidade de se aprofundar os conhecimentos sobre os processos de união, mais especificamente sobre o processo de soldagem por resistência elétrica conhecido por solda a ponto, do inglês *resistance spot welding* - RSW, que é um dos processos mais usados na construção estrutural automotiva. O objetivo do presente trabalho foi a avaliação da solda a ponto autógena do aço 22MnB5 endurecido através de tratamento térmico em laboratório, simulando as taxas de resfriamento usadas processo de prensagem a quente comumente aplicado na prática industrial automotiva. Foram feitas soldas em duas condições distintas, com parâmetros de soldagem em etapa única (soldagem direta) e com parâmetros considerando etapas adicionais de pré e pós aquecimento. Mecanicamente as soldas foram avaliadas através do ensaio normalizado denominado “tension shear test”. Os resultados mostraram que de acordo com a norma da *American Welding Society* - AWS o desempenho das soldas atende os requisitos mínimos requeridos para o grupo de materiais em que se enquadra o PHS 22MnB5.

Palavras chave: aço PHS, 22MnB5, solda a ponto, ensaio por cisalhamento em tensão, automotivo, RSW

1. Introduction

Modi and Vadhavkar (2019) [1], noted that materials are the principal elements of any manufacturing industry. No matter how technological the final product is, the production always starts with basic raw materials. Over the last 100 years, the automotive industry has dominated the mass production of body in white made predominantly of steel with occasional use of aluminum, magnesium, plastics, polymer composites and even wood.

Neto at all (2020) [2], review the steels used to manufacture components for more demanding automotive applications, where the objective was to increase safety, reduce cost and weight with consequent reduction of pollutant emissions.

In one of the possible classifications Neto at all [2], subdivided the steels into 3 groups called advanced high strength steels of 1st, 2nd and 3rd generations, and the conclusion drawn from the review show that 1st generation steels currently have a wide use in the automobile industry and the technology used for the development of its multiphase microstructures are already well established; while the 2nd and 3rd generation, although they have reached high levels of performance, still need to be better studied in order to become viable from the point of view of technical and commercial application.

According to World Auto Steel (2021) [3], press hardening steels - PHS, are carbon, manganese and boron based steels. They are also commonly known as hot press forming steels - HPF (the most common term in Asia); boron steel, although this name can also be used for other steels in the automotive industry, the term boron steel is typically applied to PHS. Finally, they are also known as hot formed steels - HF (the term most commonly used in Europe).

Chatterjee (2017) [4], places HF steels in the group of first generation AHSS (advanced high strength steels). World Auto Steel (2021a) [5] also classifies PHS as AHSS and notes that AHSS includes all martensitic and multiphase steels with tensile strengths of at least 440 MPa.

According to World Auto Steel (2021) [3], the most common PHS class is PHS1500, often referred to as 22MnB5 (DIN 22MnB5) or 1.5528 (EN 1.5528).

Bian (2014) [6] noted that this steel was developed about 40 years ago, initially in the form of hot-rolled or forged in large thicknesses, having been considered suitable for hardening by pressing due to its moderate carbon content and good hardenability. For automotive application, this steel is normally cold rolled to thicknesses below 1.5 mm and subsequently coated with aluminum-silicon alloy or zinc alloy.

According to Bian (2014) [6], in addition to the high mechanical properties achieved in hot pressing, 22MnB5 has a high resistance increase capacity by bake hardening, above 100 MPa or more in the hot pressed condition; it also has good weldability (resistance spot welding) and ability to be coated, which are also very important criteria to consider for automotive applications.

This material is provided with a ferritic-pearlitic microstructure with a maximum tensile strength of up to 750 MPa. The total elongation must be above 12%, but depending on the type of coating and thickness it can exceed 18%. When heat treated, it reaches minimum yield strength of 950 MPa and maximum strength levels of resistance of the order of 1300 to 1650 MPa [3, 8].

The 22MnB5 steel is among the hardenable boron microalloyed steels. This grade is particularly characterized by its hot formability and high strength after heat treatment. The strength characteristics after heat treatment are achieved in particular by the presence of boron in addition to carbon and manganese (Salzgitter, 2019) [9].

In the hot rolled state, 22MnB5 typically exhibits a ferritic-pearlitic microstructure with a typical grain size of 9 according to ASTM (see Figure 1).

Figure 1. Typical microstructure of 22MnB5 steel in as-received state.

Source: SALZGITTER, 2019 [9].

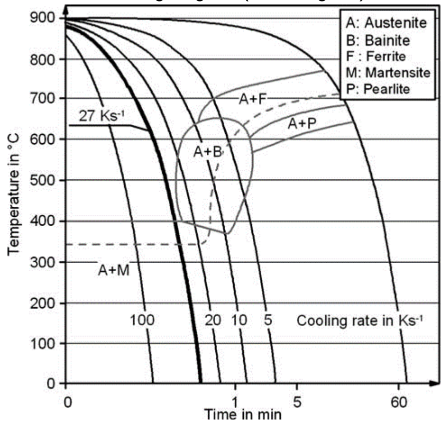
According to Karbasian (2010) [7], the investigations conducted by Naderi (2007) on ultra high strength steels showed that the boron steel grades 22MnB5, 27MnCrB5 and 37MnB4 are the only ones that result in a fully martensitic microstructure after hot stamping and cooling in the die tool itself.

After the hot stamping process, the component finally has a martensitic microstructure with a total strength of about 1500 MPa. In order to ensure the transformation of the microstructure, the blank has to be austenitized at 950 °C for at least 5 minutes (Karbasian, 2010) [7].

In the specific case of 22MnB5 steel, the cooling rate to obtain a fully martensitic microstructure (critical temperature) must be greater/equal to 27 °C(K).s^{-1} (Figure 2), with the start and end temperatures of the martensitic formation for PHS steels in general approximately 425 °C and 280 °C respectively [7, 10-12].

Modi and Vadhavkar (2019) [1] noted that resistance spot welding (RSW) is the most popular method for joining steel to steel in the automotive industry. The RSW Process is fast and cost-effective (about $ 0.03 per spot weld).

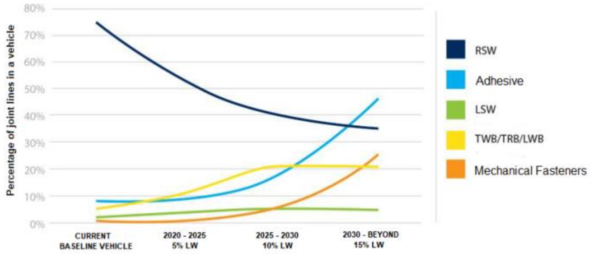
Figure 2: Continuous cooling diagram (CCT diagram) of 22MnB5 steel.



Source: Solbor 1500, 1998 [11].

In Figure 3, it is possible to observe that other joining methods tend to have a growth in the volume of use in detriment of the conventional resistance spot welding (RSW) process that is currently the most used, however, even so, the prediction is that the RSW be one of the most widely used processes in the future, with something around 35% of the total production volume. For this reason, it is important to continue studies and deepen knowledge in the union of new materials for this process.

Figure 3: Trends in merging processes.



Legend: RSW: resistance spot welding; LSW: laser spot welding; TWB: tailor welded blanks; TRB: tailor rolled blanks; LWB: laser welded blanks; LW: lightweighting as a percentage of curb weight. Note: Join point percentage does not add up to 100% due to overlapping applications, for example, adhesives and fasteners used simultaneously.

Source: Modi and Vadhavkar, 2019 [13] (adaptation).

Resistance spot welding was invented by Elihu Thomson. The development of the process dates back to 1890, when Thomson filed a patent for an electrical welding method. The idea was developed and in 1909 Thomson filed a patent on electric welding of sheet metal [13]. Since then the process has continually evolved and been widely used.

Hou (2016) [14] observes that due to the growing demand for the use of AHSS steels of the HF type, with requirements and properties tailored to hot stamped components, there are, on the other hand, limited studies on weldability and adaptation of solder specifically for 22MnB5 alloy; which, in turn, may limit its applicability. According to him, the optimization and analysis of resistance spot welding of 22MnB5 will allow a more efficient use of steel, and based on information obtained in the work of other researchers, lists a series of problems encountered in resistance welding of these materials.

One of the challenges with resistance spot welding of 22MnB5 is weldability. The operating window for RSW of the steel is generally narrower compared to conventional automotive steels, and this can be attributed in part to its surface coating that serves as a barrier to oxidation during hot stamping. In addition, alloying elements added for hardenability improvements contribute to accelerated resistive heat generation, resulting in greater chances of weld expulsion when welding 22MnB5 steels. Due to the high hardenability characteristics, resistance spot welds are prone to interfacial flaws due to notch sensitivity. The high hardenability results in microstructures with high hardness and low ductility in the heat affected zone (HAZ). A narrow softened or tempered zone subjected to subcritical temperatures is typically formed and surrounded by materials of high hardness, leading to brittle stress concentration points that promote crack propagation. An interfacial fracture mode is normally associated with low energy absorption. However, resistance spot welds on 22MnB5 steel typically fail interfacially, even when reaching high fracture strengths. Welds that fail interfacially still exhibit poor energy absorption properties. This is crucial in terms of welds subjected to impact loads and is essential for the crash resistance of vehicles (ibid).

2. Methodology

2.1. Material

In this work, the hot stamping steels known as press hardening steels - PHS were studied, in this case specifically the DIN 22MnB5 steel (material n° 1.5528), laminated with 1.4 mm thickness and Al-Si coated, manufactured by ArcelorMittal whose commercial reference is USIBOR 1500.

The chemical composition and typical properties of the material in the as-received condition according to ArcelorMittal data are shown in Tables 1 and 2, respectively.

Table 1: Chemical composition of the material used in the experiments. Source: Data provided by ArcelorMittal.

Chemical composition (mass %)						
Al	B	C	Cr	Mn	Si	Ti
0.037	0.003	0.238	0.199	1.190	0.239	0.029

Table 2: Mechanical properties of the material used in the experiments in the as-received condition. Source: Data provided by ArcelorMittal.

Tensile strength (MPa)	Yield strength (MPa)	Total elongation (%)
581	387	21

2.2. Heat treatment

The heat treatment was performed on specimens taken from sheets, this is a simplified laboratory simulation of the process normally applied to real components in the industry. A more realistic simulation would be very laborious and costly, given the need to use a press provided with a special tooling with a cooling control system.

Initially, heat treatment tests were carried out with samples being cooled in water, oil and air, in order to define the most appropriate means of cooling in the treatment of the specimens.

Based on the preliminary tests, the option was for oil cooling and the justifications are presented later in the topic that deals the results and discussions.

After the preliminary tests, the heat treatment of the specimens was carried out (Figure 4). The specimens were treated in a muffle furnace, where after the furnace reached a temperature of 950 °C, they were inserted inside, and, after a new stabilization of the furnace at mentioned temperature (since there is a drop in temperature when inserting of the sheets), they were left for 8 minutes for soaking and homogenization, after which they were removed from the furnace and immersed in oil for cooling.

Figure 4: Detail of the sheets ready to be heat treated. Source: author files.

Source: author

2.3. Hardness

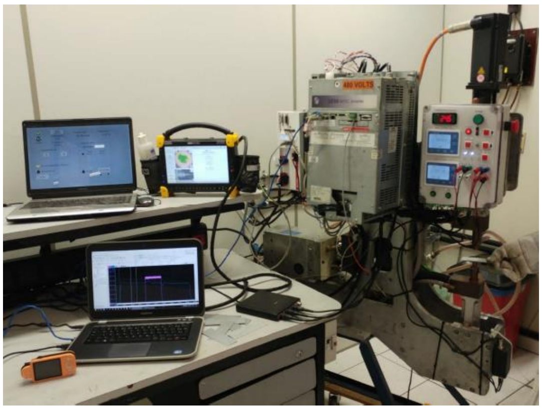
Samples of the heat treated material were subsequently subjected to hardness tests. Measurements were made on the HRC scale with a load of 150 kgf, and the equipment used was an Officine Galileu durometer belonging to the Max Gear Company.

2.4. Welding

After the heat treatment, the specimens were welded in a self-developed stationary spot welding equipment (Furlanetto, 2014) [15] belonging to the Welding Science company.

The Figure 5 shows an overview of the welding equipment with the data capture instruments attached. The image shows too the ultra sound equipment Telsonic-SWA-F1, used for dimensioning the size of each one spot weld.

Figure 5: General view of the welding equipment with attached instrumentation.



Source: Batista, 2020 [16].

Welds were made in two different conditions, the first with welding parameters in a single step (direct welding) and the second with parameters considering additional pre and post heating steps. Hemispherical electrodes (domed B) in Cu-Cr material and flat surface of 6.8 mm diameter with 5 kN load, were used in the welding. The welding parameters used are shown in Table 3.

The average diameters of the spot welds obtained in the welds were 4.62 mm in the specimens welded in a single step, and 5.15 mm in the specimens welded with additional steps of pre and post heating, which is in accordance with the minimum of 3.5√t established by the British Standard BS 1140:1993 [17], which is one among several other standards that address this same subject.

Table 3: Welding parameters used for the present work.

		Single step weld	Weld with additional steps of pre and post heating
Welding parameters	Squeeze	100 ms	100 ms
	Pre heating	-	3,5 kA - 200 ms
	Cooling	-	10 ms
	Weld	7 kA - 350 ms	7 kA - 450 ms
	Cooling	-	120 ms
	Pos heating	-	4,0 kA - 350 ms

Source: author.

2.5. Mechanical strength tests

After welding, the specimens were subjected to specific tests to evaluate the resistance of spot welds called tension shear tests according to AWS B4.0:2016 [18], and the results obtained in load values were also converted into stress values taking into account the effectively resistant areas based on the dimensions of each spot weld that were obtained in the ultrasound measurements. Figure 6 shows a specimen ready to be tested made according to AWS B4.0:2016 [18].

Figure 6: Detail of a specimen for tension shear tests, ready to be tested.

Source: author.

3. Results and discussion

3.1.Heat treatment and hardness

The Table 4 shows the results of hardness tests performed on samples from preliminary heat treatment tests. Preliminary test results led to the observation that the most suitable cooling system would be in oil. The cooling in water is very abrupt promoting the appearance of high residual stresses, accentuated deformation of the component and can even impair the good performance of the material when in operation. In air cooling, the hardness achieved is very low, thus offering no guarantee that a martensitic microstructure will form under the conditions required for PHS steels.

Table 4: Hardness values found in preliminary heat treatment samples.

	Water cooled	Oil cooled	Air cooled
Hardness values	53 HRC (550 HV)	46 HRC (458 HV)	8 HRC (188 HV)

Source: author

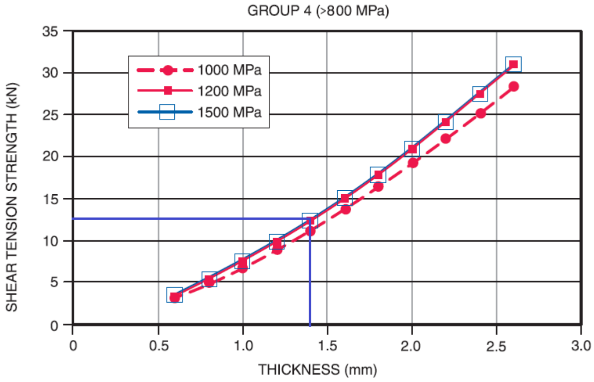
Bardelcik et al. (2010) [19], in their studies with 22MnB5, obtained values of 47.7 HRC in the cooling of specimens in oil, and assumed a resulting microstructure very close to 100% martensitic.

Although a microstructural analysis has not yet been carried out on samples of the materials treated in the present work, based on the hardness values found, it is also expected in this case a resulting microstructure 100% martensitic or something very close to that in the materials treated and cooled in oil, since the hardness found was very close to that found by Bardelcik at all (2010).

3.2. Shear strength

It should be noted that for the purpose of analyzing the performance in the tension shear tests, the AWS D8.1M:2013 [20] standard subdivides the materials into several groups according to their respective resistance ranges, among which are the group 4, which are those with strength higher than 800 MPa (see Figure 7).

Figure 7: Representative minimum values of shear tension strength for group 4 steels.

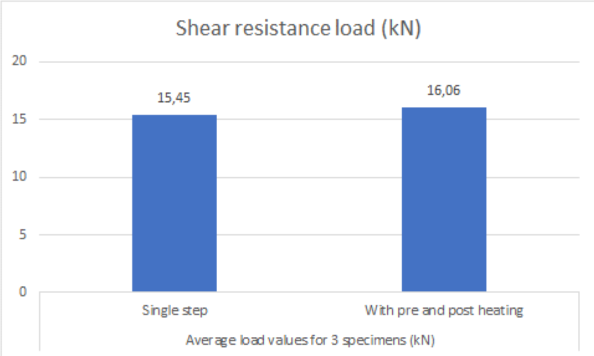


Source: AWS D8.1M:2013 (adapted) [20].

Group 4 materials according to the standard are generally called advanced high strength steels (AHSS), therefore, they can be considered equivalent to the material used in the present work in terms of characteristics and mechanical properties.

The load values obtained in the tension shear tests in the present work are shown in Figure 8.

Figure 8: Shear strength values obtained in the tension shear tests.



Source: author.

From the point of view of the shear strength load, if we look at the graph of figure 7, we will see that the minimum load value required for a thickness of 1.4 mm and stress 1500 MPa is just over 12.50 kN, and, when we compare this value with those obtained in the tests of the present work 15.45 kN (1576 kgf) and 16.06 kN (1638 kgf), it can be seen that both values obtained are above the minimum required by AWS D8.1M:2013. Therefore, by AWS these welds are considered acceptable.

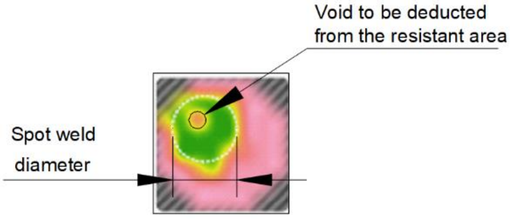
It is interesting to observe that the application of pre and post heating in the welds of the heat-treated steels did not exert a significant influence on the load values obtained in the shear tests, when compared to the values of the single-step welding.

Hou (2016) [14], in welding works with PHS 22MnB5 with and without heat treatment, observed that, contrary to the behavior observed in welds between untreated sheets, in welds between treated sheets there was no improvement in joint performance with the addition of tempering operations (pre and/or post heating) in the shear tests; however, there is also no significant decrease in performance, suggesting that tempering for welds of hot stamped steels does not affect joint shear performance,

Proceeding with an analysis from another point of view, from the load values obtained in the shear tests and the dimensions of the spot welds, it is possible to determine a relative resistance value, based on the load-resistant area. Thus, the value of the acting stress is calculated, which can be compared directly with literature values and with the base metal too.

Thus, it is possible to consider the individual sizes of each spot weld that were measured by ultrasound, even discounting from the area calculation any voids that have been revealed in the ultrasound images, resulting in stress values based on the effectively resistant areas to the loads. The Figure 9 shows an ultrasound image illustrating a situation where it is possible to identify the diameter of the spot weld and an empty area that must be discounted in the stress calculation.

Figure 9: Illustrative image of ultrasonic spot weld measurement.



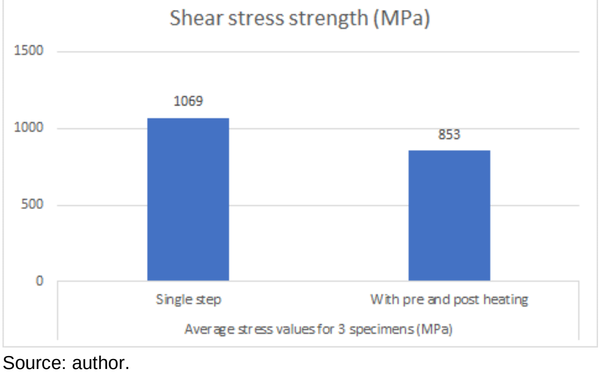
Source: author.

Carrying out the calculations according to Equation 1, considering too the respective discounts of the void areas in the applicable cases, it was obtained the shear stress values shown in Figure 10.

$$\delta st = \frac{F}{Aer} = \frac{F}{(\pi \cdot r^2) - \text{void area}} \qquad (1)$$

Where: δst = shear stress strength ($kgf.mm^{-2}$)
F = load value obtained in the test (kgf)
Aer = area effectively resistant to applied load (mm^2)
r = spot weld radius (mm)
void area = void that may exist in the spot weld (mm^2)

Figure 10: Shear stress strength values obtained from the data of the tension shear tests.



Source: author.

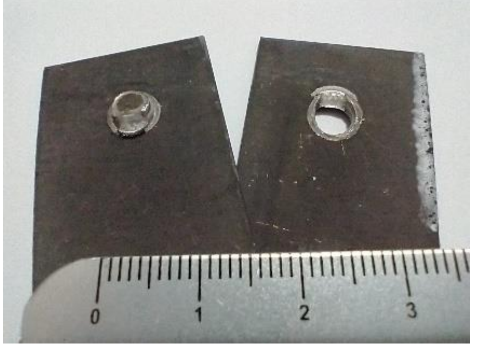
Based on the data presented in Figure 10, it is possible to establish, for example, a correlation (even if not so refined) between the performances of resistance spot welds in comparison with the strength characteristics of the base metal itself. Therefore, if we consider that, from a practical point of view, the shear stress represents about 75% of the maximum tensile strength of the material (Cozaciuc et al., 2000) [21], and we extrapolate the values shown in Figure 10 to 100 %, it will have that the estimated tensile strengths of the welds in this case would be approximately 1425 MPa and 1137 MPa minimum, since the rupture of the specimens did not occur in the resistant area of the spot welds, but in their surroundings.

These, therefore, are values very close to the maximum resistance value of the base metal itself. PHS 22MnB5 can reach after hot pressing operation at least 1500 MPa.

It should also be noted that the characteristic failure mode in the shear tests it was of the total "pullout" type (see Figure 11), therefore, the ruptures did not occur in the effectively resistant areas of the spot weld, but in the surroundings of its diameter, that is, in the so-called heated affected zone (HAZ).

Bacic (2016) [22] concluded in his study of the weldability of PHS 22MnB5, that the decrease in mechanical strength in the region of the HAZ, close to the base metal, would be related to the resulting final microstructure due to the non-uniformity of cooling of the weld process on the HAZ region.

Figure 11: Type of failure characteristic of the specimens shear tested in the present work.



Source: author.

4. Conclusion

The results of the tests carried out on the welds, showed that the parameters used in the welding of the specimens were, in principle, adequate for the conditions in which they were applied. The load values obtained in the shear tests, in this case, met the minimum values established for group 4 materials according to AWS D8.1M:2013.

The application of additional pre- and post-heating steps has no significant influence on the mechanical properties of the weld when compared to the results achieved with single-step welding.

The evaluation of the data obtained in the shear tests from the point of view of stress values associated with the effectively resistant areas, seems to be an interesting technique, allowing a more significant analysis of the results, allowing comparison with data from the literature and with the characteristics of the base metal.
The hardness values achieved in the material treated and cooled in oil suggest that the resulting microstructure in the specimens treated in the present work is fully martensitic, according to data from studies developed by other researchers.

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