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Effect of resistance spot welding parameters on the residual stress of automotive ultra high strength steel

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ABSTRACT

Studies on residual stress effect in resistance spot welding (RSW) have not been widely explored for the new ultra-high strength steels (UHSS), such as, press-hardened steel (PHS) used for the automotive industry application. The number of PHS parts has been widely increasing in the vehicle structure, due to its ultra-high tensile strength achieved after the hot stamping process, which can reach 1500 MPa. This outstanding steel properties is function of steel grade and is a guaranty for lightweight and safety. Weldability is one of major issues to allow the large product application in the automotive industry however, the numbers of papers and works with focus on PHS weldability is still small. The residual stresses in spot welded joints play an important role in affecting the durability of the joint. It is well known that the residual stresses may reduce the mechanical properties of the welding joint and contribute to hydrogen embrittlement effect. This paper has undertaken an experimental survey of residual stress on 22MnB5 - PHS steel, using X-ray diffraction technique, before any heat treatment, i.e., without hot stamping, with variation of the main welding parameters. In general, it was found that the residual stress results showed a great influence of the resistance spot welding parameters. The residual stress measures showed levels up to 300 MPa in PHS material, which can impair the material usage.

Keywords: X-ray diffraction, residual stress, resistance spot-welding, PHS, 22MnB5.

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1. Introduction

In recent decades, the growing concern about the reduction of consumption of fossil fuels has led to the emergence of a pressure on the automotive industry to decrease the vehicular mass. Consequently, the issue of automotive safety is in a compromised position when one thinks of reducing the mass of components in a vehicle. Considering the relationship between vehicular mass / safety decrease, there was an expressive increase in the search and development of materials and processes that can meet these demands. One of the processes that came out of this quest is called press hardening, also known as hot stamping. The process is used to form automotive structural parts (body in white) such as A, B and C columns, side impact beams, bumper beam and etc. using such microalloyed steels [1].

The most commonly used microalloyed steel in press hardening processes is the 22MnB5, also commercially known as Usibor®. It contains in its chemical composition nominal carbon of 0.22% and nominal manganese of 1.25% (% mass). Boron is an interstitial element and has a very low solubility in α-solid solution (<0.003%) [2,3]. The primary function of boron additions to heat treatable steels is to increase their hardness [4]. Boron is also added to increase the hardenability [5]. The hot stamping process can increase yield and strength limits of 1000 MPa to 1500 MPa, respectively, showing high mechanical strength when compared to the more resistant steels that are cold stamped [7].

In the press hardening processes there is the combination of mechanical forming and heat treatment of sheet metal in a single process. A PHS steel sheet (22MnB5) is austenitized at 950 °C in a furnace, sequenced by a hot forming process of the sheet in a cooled die, requiring cooling rates in the order of 27 K/s for a complete martensitic transformation. This combination of hot forming and cooling allow the obtention of components with high mechanical strength and lightweight, with enormous potential of reduction of vehicular mass [8].

PHS plates are usually joined by a series of welding processes. A process widely used for joining such sheets is that of resistance spot welding. The welding occurs by combining the electrode pressure, the heat generated by the material resistance to the current flow and the process time. The process times vary according to the current flow in the joint, determined by the thickness and types of plates, cross-sectional area and their contact surface [7,8]. When there is cessation of the passage of electric current, the molten metal cools and solidifies on the pressure of electrodes cooled by the passage of water internally. After solidification the electrode pressures are removed and the welding point cools naturally, which generates residual stresses in the region due to heterogeneous thermal cycles and local phase transformations [9]. The welding schedules of mild steel with the same thickness follow the recommendations for high strength steels (HSS) [10].

- Increase the electrode force by 20% or more depending on yield strength.
- Increase weld time when appropriate.
- Try a multi-pulse welding schedule (several pulses or post heating).
- Larger tip diameter and/or change the type of electrode.
- Increase minimum weld size.

Much of the attention in research is usually devoted to the welding parameters and material aspects, but less care to such weld attributes as geometry and pattern of spot welds. But one of the important phenomena that have been the subject of not sufficient studies in the past is a shunting effect. This effect appears when two or more weld spots exist in a row. The main reason for this event is just shunting current; i.e. the current passing through the preceded spot [11,12]. Although the other areas of the sheets are touching each other and may let some electrical current to pass, but the oxide layer and the lack of electrode pressure have significantly reduced shunting in these sections.

Even more, it was shown that it was possible to realize sufficiently sized spot welds in short-pitch resistance spot welding by increasing input energy to compensate for heat loss caused by the short-circuiting of the welding current. In addition, an application study of short pitch spot welding showed that a reduced weld pitch of 15 mm in high stress regions reduced peak stress in the weld, making the use of thinner steel sheets possible [13-15]. However, the residual stress influences have not been considered on the fatigue or hydrogen embrittlement.

Residual stress can be defined as a stress that occurs in the materials, even though they are free from external loads [16]. Such tensions occur originally from non-uniform plastic formations, caused mechanically, by phase transformations or thermal cycles [17]. In a weld, the intense localized thermal energy causes a non-uniform and transient temperature field, which, followed by rapid expansion and thermal contraction, affects the material. The temperature gradients and the degrees of limitation of the weld joint impose thermal deformations that determine the final state of the stresses. In this way, the residual stress field must be combined with service loads in development calculations.

Thus, there is a deleterious effect, where residual stresses of high tensile values are known to promote brittle fractures and fatigue [18]. When comparing spot-welds with other types of welded joints, it is observable that very few methods of measuring residual stress for such situations have been sufficiently studied and this is due to the small size of the weld joint. One of the most used methods for such measurement is the X-ray diffraction. X-ray diffraction is based on the measurement of the distortions occurring in the interplanar spaces of the crystals of a polycrystalline material [9].

2. Experimental

For the present study, samples of 22MnB5 steel Al-Si coated in the as received condition (before the hot stamping process) were welded according the welding parameters described in Tab. 1.

Table 1. Resistance spot welding parameters used for the present work.

Welding parameters										
	Squeeze				Welding		Heat treatment		Hold	
Test	**Current (kA)**	**Time (ms)**	**Ramp up**	**Pulse**	**Current (kA)**	**Time (ms)**	**Current (kA)**	**Time (ms)**	**Time (ms)**	**Pressure (kN)**
P.1	5.0	60	50	NA	9.0	390	NA	NA	225	3.0
P.2	7.0	60	50	NA	9.0	390	NA	NA	225	3.0
P.3	5.0	100	50	NA	9.0	390	NA	NA	225	3.0
P.4	7.0	100	50	NA	9.0	390	NA	NA	225	3.0
P.5	7.0	100	50	NA	8.0	400	NA	NA	225	3.0
P.6	7.0	100	50	NA	8.5	400	NA	NA	225	3.0
P.7	7.0	100	50	NA	9.0	400	NA	NA	225	3.0
P.8	7.0	100	50	NA	9.5	400	NA	NA	225	3.0
P.9	7.0	100	50	2.0	8.5	200	NA	NA	225	3.0
P.10	7.0	100	50	2.0	9.0	200	NA	NA	225	3.0
P.11	7.0	100	50	2.0	9.5	200	NA	NA	225	3.0
P.12	5.0	100	50	2.0	9.3	200	6.0	100	225	3.0
P.13	7.0	100	50	2.0	9.3	200	6.0	100	225	3.0
P.14	5.0	100	50	2.0	9.3	200	8.0	120	225	3.0
P.15	7.0	100	50	2.0	9.3	200	8.0	120	225	3.0

The sheets were also sheared into 50 mm wide and 170 mm long coupons and welded in stacks of two identical coupons using a mid-frequency DC welding machine. On each stack, four spot welding equally spaced welds were produced from the coupon center to evaluate the welding parameters maintaining the welding diameter, weld current and weld time were, respectively, been varied from 8.0 kA to 9.5 kA and 200 milliseconds to 400 milliseconds. The pre-weld current and time, varied from 5 kA to 7 kA and 60 milliseconds to 100 milliseconds. The squeeze, weld force and hold time were respectively kept constant at 150 millisecond, 3.0 kN and 225 milliseconds.

Finally, to evaluate the pulse weld a single pulse and double pulse were performed and the quenching condition was evaluated with post-heat treatment varied from 6 kA to 8 kA and 100 milliseconds to 120 milliseconds. The caps (6.0 mm face diameter) that were placed at the end of each water-cooled electrode were regularly measured to prevent cap wear from altering weld characteristics, in particular, dimensions. Each stack of two coupons provided four identical spot welds with 30±2 mm distance between spot weld according resistance spot recommendation to avoid shunt between welds as shown in Fig. 1.

The residual stresses of the spots were determined using an X-ray diffractometer and the method of the sen² Ψ was used throughout this work. More specifically, the software of the X-ray diffractometer calculates the internal residual stresses using the X-ray beam elongation constant and the elastic elongation of the crystal lattice, taking the values of deformation to obtain the internal stresses intensity. These elongations are calculated by means of the Bragg´s law from the X-rays diffracted of the crystal lattice at the analyzed area. For this, the equipment was configured with the parameters of the analyzed material and the operational system of the diffractometer was set up to realize the residual stress calculation of the crystal lattice variation inside the welding spots.

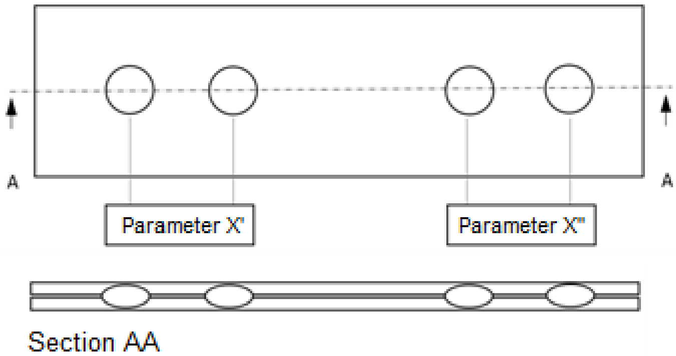

Figure 1. Tests samples and spot welding locations used for the present work for the 22MnB5 press hardening steel type.

For the X-ray diffraction measurements, the parameter utilized in the equipment operational system is shown Tab. 2.

Table 2. X-ray diffractometer configuration used for the present work.

Radiation	Cr Kα
Filter	V Kβ
Scanning plan	Fe α (211)
Poisson´s coefficient	0.29
Young modulus [MPa]	210000
2Θ angle range	149° a 161°
Ψ angle tilts	0.0; 16.8; 24.1; 30.0; 35.3; 40.2; 45.0
2Θ uniform steps	0.40

The residual stress value resulted from an analysis is the representation of the average deformations of the scanning area. These deformations can be measured at preferential directions, especially when there is a need to visualize the residual stresses that can positively or negatively impact certain project loads. For the stress analysis, each spot welds were measured in two different directions in relation to the longitudinal axis of the specimens: 0° and 90°, as shown in Fig. 2.

Figure 2. Sample directions of measurement used and X-ray diffractometer positioning.

The X-ray beam has 20 mm of width. In order to only measure the internal area of the spot weld and exclude the external areas, there was necessity to isolate the around areas with a Pb tape. This procedure is show in the Fig. 3.

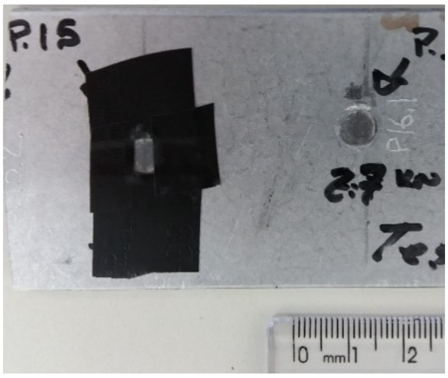

Figure 3. Sample preparation for residual stress analysis and limiting analysis area procedure.

3. Results and discussion

The X-ray diffraction results show the residual stress in two different directions (Ψ 0° and Ψ 90°) in a function welding parameters P and the distance between spots. The summary of the results for all evaluated spot welds is shown in the Tab. 3 and it also shows the difference between two performed spot welds (first and second spot weld).

Table 3. Residual stress results as measured using X-ray diffraction.

Parameter / spot First (f) Second (s)	Ψ 0°	Ψ 90°	Difference between Ψ 0° and Ψ 90°	Distance between spots (mm)	Difference between Ψ 0° (f) and Ψ 0° (s)	Difference between Ψ 90° (f) and Ψ 90° (s)
P.1 (f)	157	166	-9	30.9	-54	-66
P.1 (s)	211	232	-21			
P.2 (f)	183	130	53	28.0	64	18
P.2 (s)	119	112	6			
P.3 (f)	60	102	-42	29.3	-99	15
P.3 (s)	159	87	72			
P.4 (f)	139	157	-18	30.0	-22	56
P.4 (s)	161	101	60			
P.5 (f)	204	98	106	30.7	53	-97
P.5 (s)	151	195	-44			
P.6 (f)	31	54	-23	28.9	-82	-62
P.6 (s)	113	116	-3			
P.7 (f)	135	180	-45	32.2	-51	95
P.7 (s)	187	85	102			
P.8 (f)	143	70	73	29.0	80	-48
P.8 (s)	63	118	-55			
P.9 (f)	209	221	-12	31.3	7	73
P.9 (s)	202	148	54			
P.10 (f)	256	262	-6	29.3	-27	3
P.10 (s)	283	259	24			
P.11 (f)	247	214	33	27.3	-90	-3
P.11 (s)	337	217	120			
P.12 (f)	320	324	-4	29.1	28	123
P.12 (s)	292	201	91			
P.13 (f)	156	180	-24	30.1	2	60
P.13 (s)	154	120	34			
P.14 (f)	212	252	-30	30.2	-49	46
P.14 (s)	271	206	65			
P.15 (f)	269	158	111	32.2	69	18
P.15 (s)	200	140	60			

According to the Tabs. 1 and 3 the welding schedule without pulse conditions and with pulse conditions showed differences. The single pulse welding schedule showed the average residual stress measurements smaller than average of the welding schedule with double pulse.

The welding schedule with no pulse does not showed significant differences between the first spot and the second spot-weld on residual stress measurement. The pre-burn current do not showed major influence in residual stress but lower the pre-burn time higher the residual stress and can be explained because of the fast cooling rate during the spot welding execution.

The residual stress results do not showed differences between the measured in the two different directions in relation to the longitudinal axis of the specimens. The increase of the welding current do not showed an increase of the residual stress but the residual stress change from the first spot weld longitudinal axis to the second spot weld. It can be related with the current flow (shunt) even with recommended spot welding spacing.

The welding schedule with pulse indicates that the welding current increase the residual stress and it clear because the higher residual stress measurements were found out on welding parameters P.11 and P.12. Also the parameter P.11 showed the major difference between the two different directions in relation to the longitudinal axis of the specimens. The post weld treatments also showed higher values of residual stress but the higher welding current at the post weld treatment reduce the residual stress measurement. It can be because of a stress release due to a lower cooling rate.

For a simple visualization of the previous discussion the Fig. 4 was created. Each sample represents a spot weld and the sequence of welding. For example, the sample 1 is the first spot weld with the parameter P.1 and the sample 2 is the second spot with the same welding parameter. The result of the residual stress measurement at each direction was plotted for all the samples. The residual stress for the parameters without pulse (samples 1st to 16th) showed lower residual stress than the parameters with pulse simples (17th to 30th).

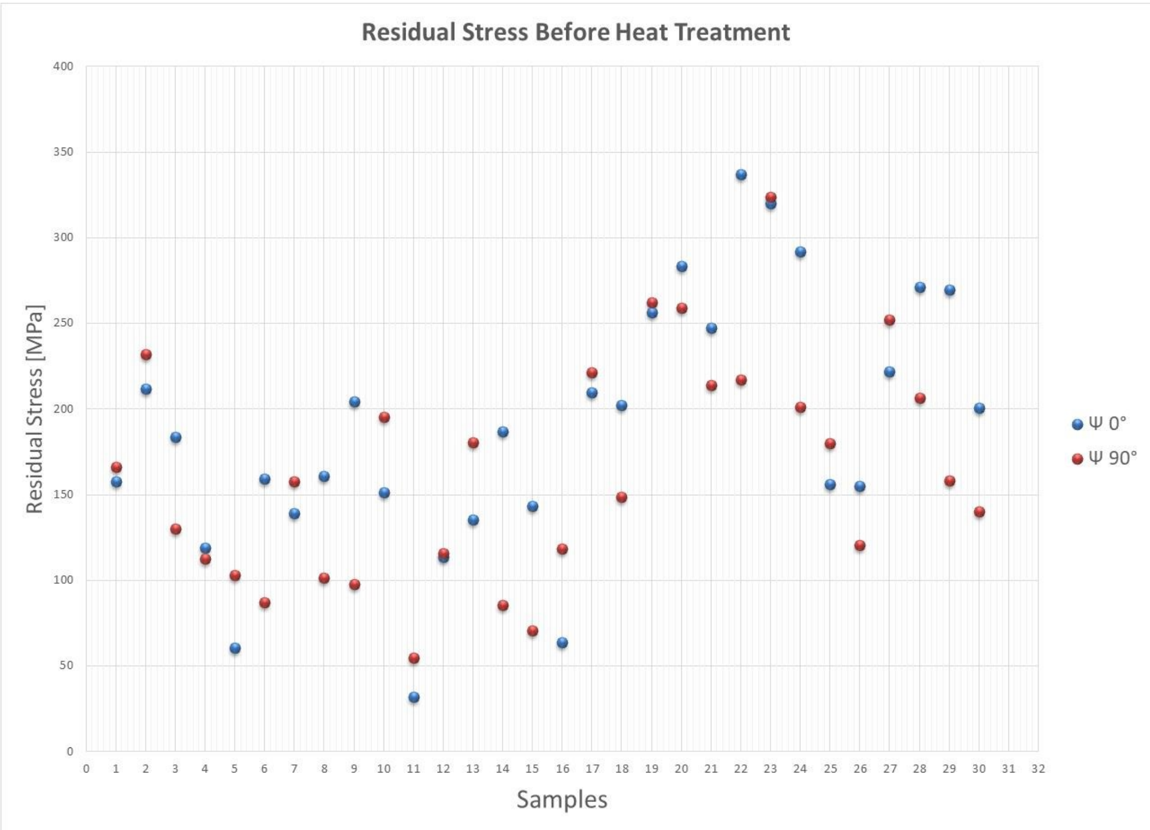

Figure 4. Graphic of the residual stress measured values versus the X-ray measurement directions.

3. Conclusion

The residual stress on PHS steel before hot stamping showed values up to 336 MPa after resistance spot welding.

The double pulse at welding schedule suggested to improve the welding properties in UHSS should be used with caution in PHS steel because the higher levels of residual stress measure on the present experiments.

The double pulse welding current increase results in higher residual stress.

The post weld heat treatment can reduce the residual stress with stress release.

The welding parameters showed influences on residual stress in spot welding following the recommended spacing to avoid shunting.

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