STUDY OF THE RESIDUAL STRESSES BEHAVIOR DURING PLASTIC DEFORMATION OF DUAL-PHASE STEEL WELDING JOINTS

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Abstract. *Residual stresses are intrinsic to welding manufacturing process and are related with parameters used during the welding execution such as: joint geometry, number of passes, chemical composition of base metal, filler metal and other factors that are important to welding. The tensile residual stresses effects are known as harmful because they are added to the service stress, even in an elastic condition. These effects decrease the fatigue life of the material and increase the risk of stress corrosion cracking. Besides, compressive residual stresses have a good effect considering fatigue conditions and also inhibit the cracks nucleation and its propagation. For the present work, the residual stresses generated by the welding of Dual Phase steel and the shot peening treatment were analyzed. The behaviors of residual stresses under different deformation rates were also studied, and the results for the non-treated specimens compared with the ones that were treated by shot peening. Two GTAW conditions were used: autogenous and with filler metal, both of them under Argon protective atmosphere. Residual stresses were measured using X-rays diffraction $sin^2\Psi$ method, with $Cr\kappa\alpha$ radiation. The measurements were carried out in the welded metal, heat affected zone and in base metal. The results shown the compressive residual stresses generated by shot peening were more stable after plastic deformation at the welded metal and base metal, while they were relieved with low deformation rates at heat affected zone.*

Keywords*: Residual stresses, welding, dual phase steel, plastic deformation.*

1. INTRODUCTION

New steels have been developed in order to attend the demand to reduce vehicles weight and decrease fuel consumption in the automobile industry. The dual-phase steels (DP) are considered advanced high strength steels and have considerable interest in the automotive industry. These materials show an excellent combination of ductility and strength due to their high work-hardening rate during initial plastic deformation (Liedl *et al*., 2002; Tumuluru, 2006).

During the service life the components and structures are often subjected to loads that may cause plastic deformation and consequently change the distribution of residual stresses on the component surface.

The knowledge of the mechanical properties and behavior of welded structures in the case of severe plastic deformations is of special importance for the automotive industry. The development of residual stress is intrinsic to the welding process and it is a function of the welding parameters such as joint geometry, number of passes, the chemical composition of base and filler metal, and other relevant factors of the welding process (Nguyen and Wanab, 1996; Chang and Lee, 2007). These stresses are present in nearly all rigid metallic parts; these are products of the metallurgical and mechanical history of the component during the manufacturing process (Zhu and Chao, 2002).

It is well established that the presence of residual stresses may highly influence the mechanical properties of the material and particularly, its properties under fatigue. Therefore, residual stresses evaluation is an important quality control method in the manufacture of structures, pieces and components. Mechanical surface treatments such as shot peening process have been used to introduce compressive residual stress fields on the structures and components surface in order to increase the fatigue life (McGrath *et al*., 2000).

In this treatment usually steel spherical small shots are propelled by air jet against the surface. As a result of this process, overlapping ripples develop a uniform layer of metal in residual compressive stress produce the hardening of surface layers and increase the material yield stress, in addition to occasional changes in surface roughness of the part (Sanjurjo *et al*., 2010).

The aim of this paper is to develop an analysis of the residual stresses generated by plastic deformation in uniaxial joints welded by the Gas Tungsten Arc Welding process with and without filler metal a dual-phase steel used in the automotive industry with and without shot peening surface treatment.

2. MATERIALS AND METHODS

In the present work, a plate of DP steel manufactured by USIMINAS was used. This steel was produced by controlled lamination with 4.15mm thickness. The chemical composition and mechanical properties are shown in Tab. 1 and Tab. 2.

Table 1. Chemical composition of DP steel (weight %).

C	Si	Mn	P	S	Al	Cu	Nb	V	Ti	Cr	Ni
0.0522	0.98	1.19	0.014	0.001	0.040	0.01	0.004	0.002	0.002	0.02	0.0033

Table 2. Mechanical properties of DP steel.

σ_Y (MPa)	σ_U (MPa)	Elongation (%)
340-440	> 590	21

Welded plates were fabricated in horizontal position, from 4.0 mm thick plate using Gas Tungsten Arc Welding and keeping the direction of the transverse butt welds perpendicular to the rolled direction of the parent material, with and without filler metal, and Argon as shielding gas.

The welding parameters for the GTAW process with filler metal are shown in Tab. 3.

Table 3. GTAW with filler metal parameters.

Filler Metal			Current		Voltage (V)	Speed (mm/min)	Air Flow (l/min)
Rod	F-N°	Ø (mm)	Type and Polarity	(A)			
ER 80SD2	6	2.4	CC-	100-150	10	106.2	10

For the condition of welding with filler metal was used a V groove with an angle of 60 degrees, a root face between 3 to 5 mm, tungsten thorium electrodes with diameter of 2.4mm, point angle of 60 degree and arc length between 3 to 4 mm. Filler wire with similar chemical composition and mechanical properties of the base metal, were specified, as seen in Tab. 4 and Tab. 5.

Table 4. Chemical composition of filler metal (weight %).

C	Si	Mn	P	S	Ni	Mo	Cu
0.077	0.73	1.82	0.009	0.008	0.04	0.44	0.2

Table 5. Mechanical properties of filler metal.

σ_Y (MPa)	σ_U (MPa)	Elongation (%)
470	550	17

The autogenous welding was performed using an “I” groove with two passes, tungsten thorium electrodes with diameter of 3.2 mm, point angle of 30 degrees and arc length between 3 to 4 mm. The welding parameters are shown in Tab. 6.

Table 6. Autogenous GTAW parameters.

Side	Current		Voltage (V)	Speed (mm/min)	Air Flow (l/min)
	Type and Polarity	(A)			
1	CC-	163	12	140	10
2	CC-	163	12	139	10

From the two welded joints (one with filler metal and the other autogenous) were manufactured 6 tensile specimens for each welding condition, according to ASTM A370. Three specimens were just welded and the others three specimens were welded and treated with shot peening.

The shot peening treatment was performed at Almen intensity (A) using metallic shot with diameter of 0,38mm. The Almen intensity applied in the peening treatment was determined according with SAE J442 specification. Grade II, type “A” Almen strips were used firmly screwed to Almen blocks. The arcs generated in the strips were measured using an Almen gage provided by a magnetic support system with an uncertainty of 0.001mm.

Superficial residual stress measurements were taken in base metal, weld bead and at the heat affected zone after manufacturing and treating the specimens, for a non-deformed state, and for 5, 10 and 15% of uniaxial plastic deformation obtained after tensile test.

The measurement and analysis of superficial residual stresses in the welded joints were made at the Stress Analysis Laboratory (LAT/UFF), using X-rays stress analyzer "Stressrad", by $\sin^2\psi$ method, with CrKα radiation, diffracting {211} plane. The equipment can be seen in Fig. 1.

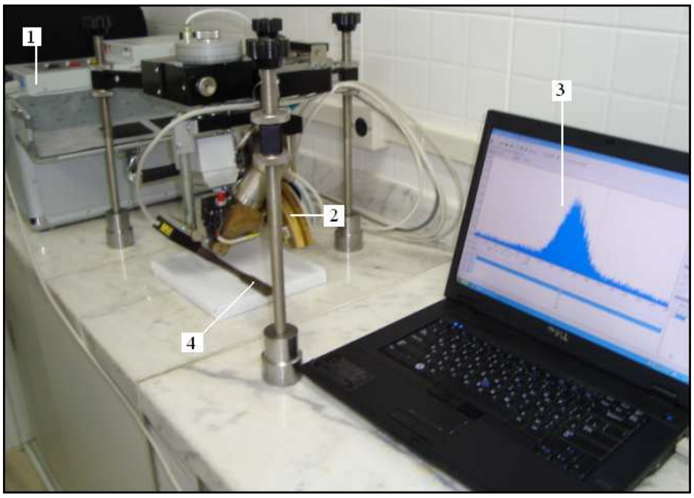

Figure 1. X-rays stress analyzer "Stressrad": 1 – control unit; 2 – Goniometer; 3 – data acquisition system; 4 – analyzed specimen.

3. RESULTS AND DISCUSSIONS

Measurements results in the base metal are shown in Tab. 7 and Tab. 8. As it can be observed, the residual stresses for non-deformed specimens reach compressive values for both welding conditions. The compressive values obtained for the specimens without shot peening treatment were related with machining process utilized to manufacture the specimens and presents homogeneous values, except for specimen 2B, that broke during the test. Considering that the main objective of this work is to evaluate the residual stress behavior due to different deformation rates, and to avoid eventual microstructure changing, heat relief stress treatment was not made in the specimens.

Table 7. Residual stresses in the base metal – specimen 1.

Specimen \ Strain rate (%)		Residual Stress (MPa) (1) without shot peening				Residual Stress (MPa) (1) with shot peening			
		0	5	10	15	0	5	10	15
1	A	-70	220	100	150	-540	-170	160	90
	B	-60	150	120	130	-460	-390	190	100
	C	-60	160	110	100	-500	-310	170	100
	Average	**-63**	**177**	**110**	**127**	**-500**	**-290**	**173**	**97**

(1): The sign "-" means compressive residual stress.

Table 8. Residual stresses in the base metal – specimen 2.

Specimen \ Strain rate (%)		Residual Stress (MPa) (1) without shot peening				Residual Stress (MPa) (1) with shot peening			
		0	5	10	15	0	5	10	15
2	A	-390	-40	-30	110	-420	-400	-410	150
	B	-90	200	-	-	-480	-370	-400	130
	C	-270	170	90	110	-550	-480	-510	80
	Average	**-250**	**122**	**30**	**110**	**-483**	**-417**	**-440**	**120**

(1): The sign "-" means compressive residual stress.

Figure 2 shows the average variation of the residual stresses of the specimens in the base metal region during plastic deformation by uniaxial tensile test up to 15% above the not deformed material yield strength. It is possible to observe for both welding conditions a residual stress tendency for the specimens that were not treated by shot peening. The reversal from a compressive stress condition to a tensile stress condition occurred really fast because with only 5% of plastic deformation the residual stress reached values higher than 150MPa, unless for the specimen 2A (-40MPa). However, this tendency is not observed for the specimens treated with shot peening. For condition 2 (autogenous welding) the residual stresses are more stable, keeping compressive values until a deformation level of 10% and presenting changes only when the deformation reaches 15%, while in condition 1 this inversion occurs between 5 and 10%. The analysis of the curves of Fig. 2 presents a material fact regarding the behavior of residual stresses that at the end of the tests have values very similar in all specimens and conditions (around 120MPa).

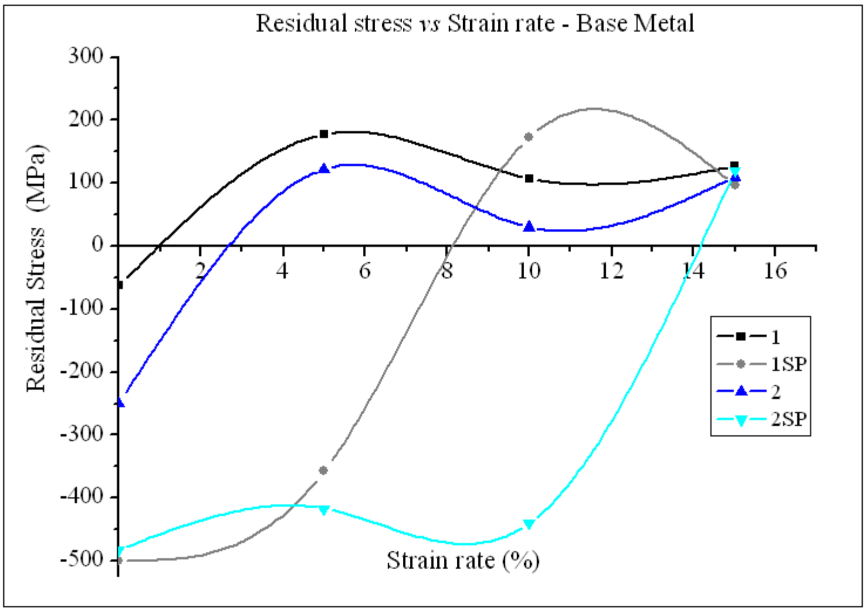

Figure 2. Residual stress average *vs* strain rate – base metal.

In the Table 9 and Table 10 are represented the residual stress values for the region of HAZ (heat affected zone). Unlike what happened in the base metal, all specimens showed the same pattern in the variation of residual stresses after the application of plastic deformation, becoming tensile after application of 5% strain, getting stabilized around 130MPa and matching values around 110MPa at the end of the tests (Fig. 3).

Table 9. Residual stresses in HAZ – specimen 1.

Specimen \ Strain rate (%)		Residual Stress (MPa) (1) without shot peening				Residual Stress (MPa) (1) with shot peening			
		0	5	10	15	0	5	10	15
1	A	-200	220	180	110	-490	250	100	110
	B	-100	200	100	70	-550	150	90	160
	C	-170	230	140	90	-530	230	90	120
	Average	**-157**	**216**	**140**	**90**	**-523**	**177**	**97**	**130**

(1) The sign "-" means compressive residual stress.

Table 10. Residual stresses in HAZ – specimen 2.

Specimen \ Specimen rate (%)		Residual Stress (MPa) [(1)] without shot peening				Residual Stress (MPa) [(1)] with shot peening			
		0	5	10	15	0	5	10	15
2	A	-280	150	260	80	-360	90	120	70
	B	-210	140	-	-	-400	165	210	110
	C	-105	80	95	150	-470	120	80	140
	Average	**-198**	**123**	**153**	**115**	**-410**	**125**	**137**	**107**

(1) The sign "-" means compressive residual stress.

For the specimens welded with filler metal (condition 1), the maximum residual stresses values are higher than values obtained for the specimens welded using condition 2, autogenous, reaching values of 200MPa and 120MPa, respectively. Analyzing the results obtained (Fig. 3) it is evident that the region of HAZ residual stresses arising from mechanical peening did not had stability during plastic deformation, suffering abrupt relaxation to become high tensile magnitude with only 5 % of plastic deformation. This behavior was similar in specimens not blasted. Regarding the behavior of residual stresses in HAZ in all conditions studied, as occurred in the base metal, at the end of the tests were obtained average values of about 110MPa.

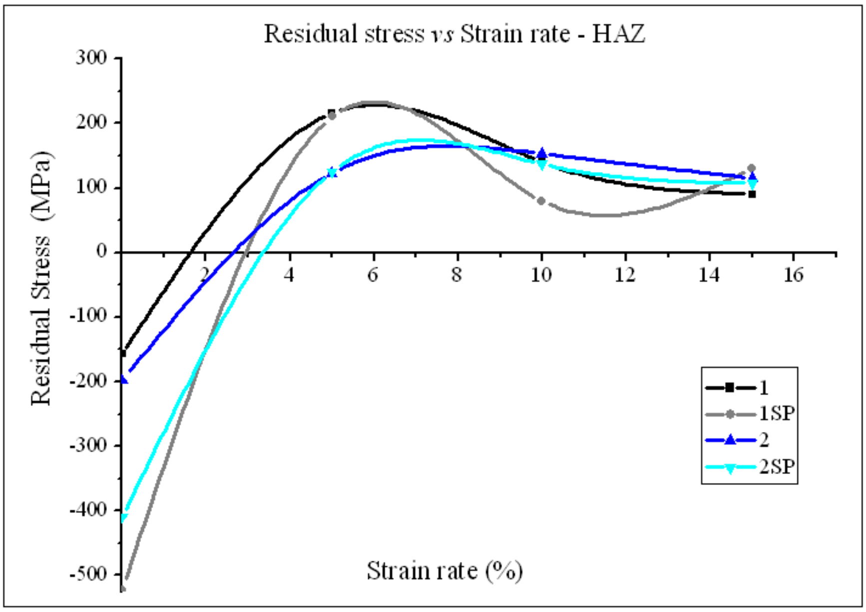

Figure 3. Residual stress average *vs* strain rate – HAZ.

The values of residual stresses for the welded metal area can be verified in Tab. 11 and Tab. 12. For the specimens that were not treated with shot peening, the behavior of the residual stresses were closer to other regions, metal base and HAZ, can be observed a quick reversal in the magnitude of residual stress to tensile, being that the highest values were verified for the specimens welded in condition 1 (Fig. 4). However, for these specimens (condition 1) the residual stresses values obtained after shot peening treatment had a singularity in the behavior of residual stresses, because after strain they were always compressive, ranging from -460 to -230MPa. In these specimens there was a marked plastic deformation in the base metal region showing a well-defined necking in this area, differently from the other specimens which were hard to identify a section with strong reduction of area. Therefore, it can be concluded that it was not a significant decrease of residual stresses in the welded metal regarding low plastic deformation in this region. Probably a higher mechanical strength of the weld metal used explains this behavior.

Table 11. Residual stresses in weld metal - specimen 1.

Specimen	Strain rate (%)	Residual Stress (MPa) (1) without shot peening				Residual Stress (MPa) (1) with shot peening			
		0	5	10	15	0	5	10	15
1	A	-120	100	230	150	-350	-190	-290	-270
	B	-60	160	230	160	-490	-300	-370	-270
	C	-100	60	250	170	-550	-270	-290	-150
	Average	**-94**	**107**	**237**	**160**	**-463**	**-254**	**-317**	**-230**

(1): The sign "-" means compressive residual stress.

Table 12. Residual stresses in weld metal - specimen 2.

Specimen	Strain rate (%)	Residual Stress (MPa) (1) without shot peening				Residual Stress (MPa) (1) with shot peening			
		0	5	10	15	0	5	10	15
2	A	-250	200	180	175	-450	-100	-80	80
	B	-40	50	-	-	-510	140	20	90
	C	-100	190	90	180	-350	170	200	150
	Average	**-130**	**147**	**135**	**178**	**-436**	**70**	**47**	**107**

(1): The sign "-" means compressive residual stress.

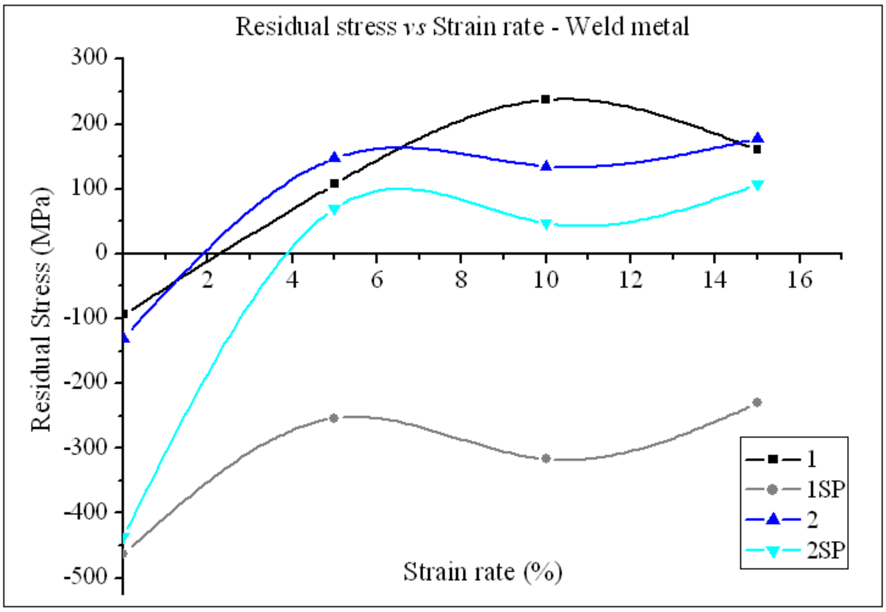

Figure 4. Residual stress average *vs* strain rate – weld metal.

4. CONCLUSIONS

The results of this work have shown that:

1. For the base metal, there was a pattern in the behavior of residual stresses in the specimens that were not treated by shot peening, both in terms of welding, because the inversion of the compressive nature to tensile residual stresses was relatively rapid, occurring with only 5% of plastic deformation in tension and reaching values above 150MPa.

2. In the specimens produced by autogenous welding and subjected to shot peening treatment the residual stresses in the base metal were more stable, holding its state until the compression level of 10% strain and suffering only change when the strain reached 15%, while provided with weld metal this reversal occurred between 5

and 10%. However, after 15% strain at the end of the trials, all conditions were very similar in all specimens (~ 120MPa).

3. Unlike what happened in the base metal, the HAZ in all the specimens showed the same pattern in the variation of residual stresses after the application of plastic deformation, which has become tensile after application of 5% strain and stabilized at about 130MPa. At the end of testing all conditions analyzed showed very close mean values (110MPa).

4. In the specimens welded with filler metal was found the highest average residual stress both in the base metal and HAZ.

5. The residual stress analysis in weld metal, the welded specimens with filler metal and treated by shot peening, showed a different behavior that was characterized by high magnitudes of compression, which did not had its nature changed with the plastic strain up to 15% of strain rate.

5. ACKNOWLEDGEMENTS

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