FATIGUE BEHAVIOUR OF ARC WELDED ASSEMBLIES: PATHS OF IMPROVEMENT

Michel Duchet[a], Matthieu Amblard[b], Laurent Cretteur[b], Stéphanie Michaut[a], Jacques Goudemez[c], Bastien Weber[a], Olivier Brière[d], Vincent Desfontaine[d]

[a] ArcelorMittal Maizières-Lès-Metz, voie romaine, 57283 Maizières-Lès-Metz, France
[b] ArcelorMittal Montataire, 1 route de Saint Leu, 60760 Montataire, France
[c] ArcelorMittal Atlantique et Lorraine, 1 route de spycker, 59792 Grande Synthe, France
[d] Sonats S.A.S, 2 rue de la fonderie, Carquefou, France

Abstract. Regarding static strength, the weight reduction of automotive chassis and suspension parts is reachable by replacing current High Strength Low Alloyed or Ferrite-Bainite steel grades by thinner gauge ArcelorMittal Advanced High Strength Steels (around 800MPa). For a similar solicitation, the stresses around the weld will be higher on thinner sheets. As the fatigue resistance of Gas Metal Arc Welding (GMAW) lap joints does not increase with the grade, it may be necessary in some cases to be able to propose solutions in order to avoid durability troubles on components in service. Among the ways of improvement investigated on specimens, such as the welding processes, the thermal treatment (for stress relieving) and the post-treatments, three weld post-treatments were identified to achieve significant improvements in fatigue: the Tungsten Inert Gas (TIG) remelting, the shot-peening and the Ultrasonic Impact Treatment (UIT) by Sonats STRESSONIC® technology. A demonstrator has been designed and welded under industrial conditions by using robot. Both post-treatments (TIG remelting and UIT) have been also performed on demonstrators under industrial conditions. Finally the experimental validation confirms the improvement observed on lab specimens.

1 INTRODUCTION

Regarding static strength, internal studies of steels solutions led by ArcelorMittal for chassis and suspension parts have shown that weight reduction of the components is reachable by using our Advanced High Strength Steels (AHSS) with Ultimate Tensile Strength (UTS) around 800MPa in place of current High Strength Low Alloyed (HSLA) or Ferrite-Bainite (FB) steel grades (400MPa < UTS < 600MPa). The potential of mass saving is obtained by thickness reduction and assessed to more or less 25% [1]. Indeed if the use of AHSS allows saving weight by thickness reduction, it leads also to much higher stress loading for a same in-service usage. For a static loading, the stress increase is balanced by a higher Yield Stress (YS) and the thickness reduction will depend on the ratio between the yield stresses of both HSLA/FB and the AHSS substitution grades. For a dynamic loading (fatigue), if the fatigue strength increases with higher mechanical properties as in static case for the base material, the fatigue of assemblies joined by GMAW could become a problem because there is no difference between steel grades in term of fatigue strength of the weld. The stress concentration induced by the geometry of the weld (notch effect) explains this well-known behaviour. Therefore solutions to improve the fatigue strength of arc-welded assemblies have to be investigated in order to assist and support the introduction of AHSS grades, especially in automotive chassis part, i.e. to reach the mass saving target. For that, two main objectives have been defined:

1- test of solutions to improve the fatigue behaviour of GMAW lap specimens,
2- then, validation of the solutions on prototypes manufactured in industrial conditions.

2 STATE OF THE ART

The low fatigue resistance of fillet lap welds can be explained by the geometry of the weld. The angle and radius between the sheet and the weld at toe and root can be considered as notch which generates stress concentrations having a detrimental effect on the fatigue strength, as shown figure 1.

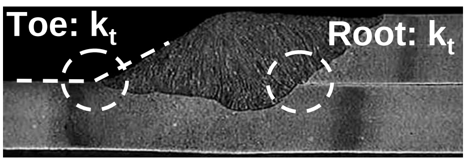
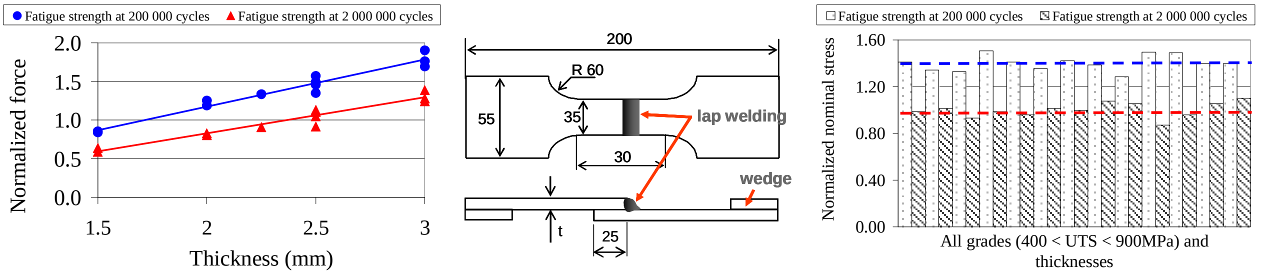


Figure 1. Location of stress concentrations in a fillet lap joint.

The severity of this "notch effect" can be quantified by stress concentration factors k_t, for which the values could be estimated either by FEA calculations or from graphs such as ones proposed by IS (French Welding Institute) [2]. Although the stress concentration factor k_t at root of weld is always higher than at toe, the fatigue failure could occur on the toe as well as the root [3-4]. We can explain this by the combined effect of irregularities in the geometry of the weld, variations of the gap between both assembled sheets, the presence of local defects, porosity, distribution of residual stresses and so on. All these defects induce scattering from an experimental point of view and could also explain that the fatigue strengths expressed in term of nominal stress are close one to the other regardless the tested grade as shown in figure 2.



Normalized Force = Force (N)/ Reference (N)

Normalized nominal stress = Normalized Force/(35 x t)

Figure 2. Evolution of the fatigue strength expressed in force vs. thickness or in nominal stress vs. the steel grades.

In fact, in homogeneous joints, a good relationship is obtained between the fatigue strength of the fillet lap weld expressed in term of force and the thickness of the steel sheet. It is true whatever the number of cycles considered (for example 2.10^5 cycles or 2.10^6 cycles). Less known is the influence of hardness profile along the Heat Affected Zone (HAZ) and the molten area. Effects of the hardness on the fatigue strength of the weld have been studied by using a simple approach.

3 INFLUENCE OF HARDNESS

Today some rules defined by the different carmakers concerning a hardness profile or a maximum hardness value acceptable in the welds can be found. The origins of these rules are not very clear, based on theoretical backgrounds or on OEM own experience. Among the most frequent rules, two of it can be mentioned: a hardness profile as flat as possible or hardness lower than HV 400/430. For evaluating the influence of hardness profile along the HAZ and the molten area, fatigue tests of welds made directly on a sheet were performed by using different metallurgy of steel grades.

3.1 Description of tests

The fatigue specimen sampled from a sheet and not a joint is the one used for the characterization of base material. The processes applied are either a Resistance Spot Welding (RSW) or a Gas Metal Arc Welding (GMAW), see fig. 3:

- **RSW** has been chosen because the fast cooling rate induces high hardness and there is no dilution with a consumable filler wire. A spot is “welded” in the middle of the specimen. It does not join two sheets but its role is just to do a metallurgic alteration (hardness profile) in the middle of the specimen. The aim is to obtain locally a new zone constituted of the nugget and the HAZ, surrounded by the parent material. This new zone has new microstructures and by consequences different hardness compared with those of the base material. The welded specimen does not show geometric notches, excepting the light local indentation of electrodes, in order to quantify only the influence of the micro-hardness on the fatigue resistance. The fatigue strengths will be compared to the base material.

- **GMAW** has been chosen because the cooling rate is lower than the RSW and an effect of dilution exists between the steel and the wire. The hardness of the molten zone and its chemical composition are the result of the dilution between wire and steel compositions and also the effect of the shielding gas. A bead is welded, with a current G3Si filler wire, across the width and in the central zone of the specimen. This configuration enables to study the combined influence of the geometry and the hardness effects on the fatigue resistance. After studying the fatigue on as welded assembly (bead on sheet), the bead is removed by grinding in order to test only the influence of the hardness (without geometric effect). This last configuration is very different from the spot weld because it crosses by a line the width of the specimen and the micro-hardness in the molten zone depends on the dilution rate.

3 steels grades of ArcelorMittal catalogue were selected, i.e. a Ferrite Bainite grade (reference, UTS = 589MPa), and 2 grades with much higher UTS (UTS ≥ 750MPa thanks to higher carbon and additive elements contents):

Grades	Thickness (mm)	YS (MPa)	UTS (MPa)
FB540	2.5	462	589
CP750	2.0	724	806
CP800	3.0	772	888

Table 1. Mechanical properties (transverse to rolling direction) of the 3 selected steel grades.

The specimens corresponding to the 3 different welding configurations are shown in figure 3. So, the drop in fatigue resistance between RSW and GMAW will be compared.

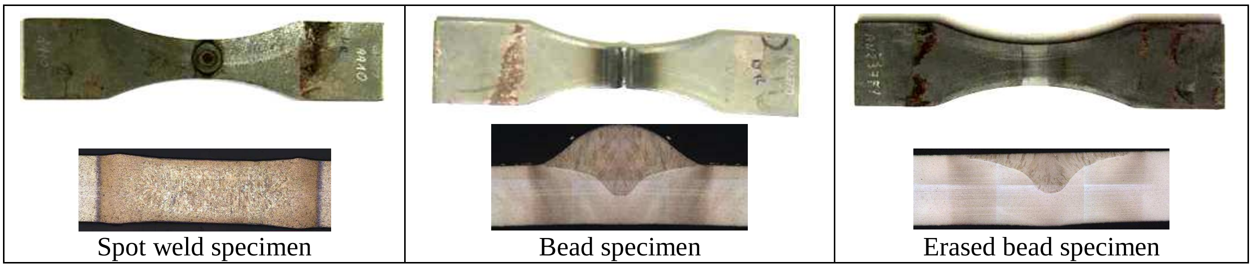


Figure 3. Presentation of specimens and micrographs corresponding to the 3 "welded" configurations.

3.2 Fatigue results

SN curves have been established from the fatigue tests carried out on the 3 grades, i.e. on base material, on spot weld, on bead erased or not (GMAW). The fatigue tests were performed on an axial servo-hydraulic machine with a loading ratio R=0.1 at a frequency of 30 Hz. The trend is almost the same whatever the grade: the SN curve of base material is above spot weld and erased bead (GMAW). The SN curves of spot weld and erased bead are close and above the not erased bead. For example, the SN curves obtained on CP800 grade are shown in figure 4. The drops of fatigue strength at 2 million cycles are respectively equal to -13% and -10% on spot weld and erased bead compared to the base material, while the bead is equal to -53%.

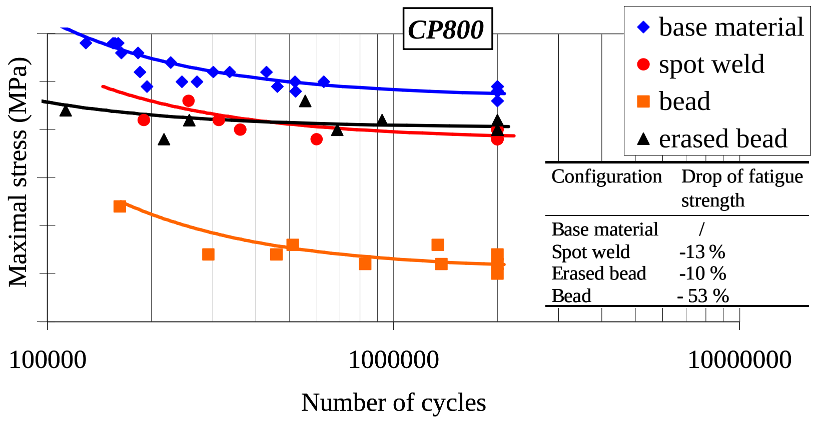


Figure 4. SN curves obtained on CP800 (base material, spot weld, bead erased or not).

The fatigue strengths at 2 million cycles estimated from SN curves as well as their drops are shown figure 5: on base material, on spot weld, bead erased or not for FB540, CP750 (no spot weld) and CP800 grades.

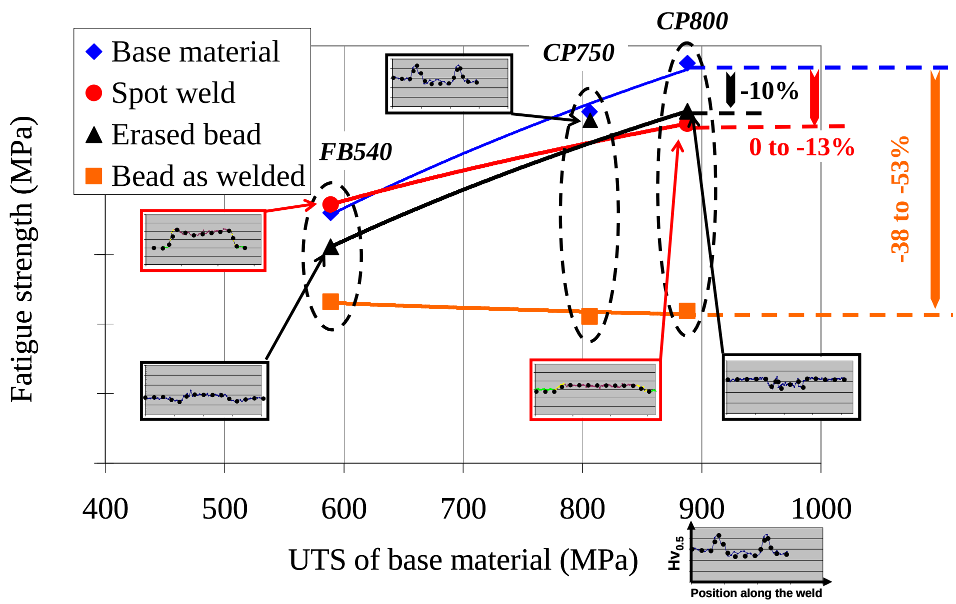


Figure 5. Fatigue strengths for the 3 configurations and the 3 grades with their respective hardness profiles.

Whatever the grade and because of the combined effects of geometry of the weld (k_t at toes) and hardness gradient, the fatigue limit of not erased bead specimens remains almost the same. The drop of fatigue strength due to the influence of hardness was estimated with the erased bead and spot weld specimens between 0 and -13%. However some questions remain about the effect of the indent on spot weld and the grinding quality to erase the bead, especially for the higher grades. It would have been better to grind all the specimens on both sides because the surface aspect could have also an effect for grades above 800MPa.

3.3 Conclusion on the effect of hardness

For the investigated grades, the fatigue strengths at 2 million cycles obtained on specimens with the not erased bead are aligned horizontally. On these grades, the drop in the fatigue strength certainly due to the sole influence of hardness varies roughly between 0% and 13%, whatever the value of hardness and its profile (flat, U, M, W), as shown in figure 5.

4 TEST OF SOLUTIONS TO IMPROVE THE FATIGUE BEHAVIOUR OF GMAW LAP SPECIMENS

For automotive chassis part, T and lap configurations are mainly used. In the framework of this study only lap joint configuration was investigated. The tested specimens to evaluate the solutions to improve the fatigue behaviour were extracted from a fillet weld according to the geometry shown in figure 2. All post-treatments or operations have been performed on the welded sheets before sampling the specimens. The fatigue tests were performed on a servo-hydraulic machine under axial loading for loading ratios R=0.1 or R=-1 at a frequency of 30 Hz. The study focuses on two steels grades of ArcelorMittal catalogue, i.e. a Ferrite Bainite grade (the reference, UTS = 589MPa) and a Complex Phase steel CP800 (ferrite, bainite and martensite, belonging to Advanced High Strength Steel with UTS = 888MPa).

4.1 Matrix of experiments

4 main axes were investigated to improve the fatigue strength of arc welded assemblies:

- Welding processes:
  - Standard GMAW with wire G3 Si (the influence of wire was not investigated)
  - GMAW pulsed current
  - Cold Metal Transfer (CMT)
  - Hybrid laser/GMAW

- Design of the specimen:
  - A single weld specimen (figure 2)
  - A double lap welded specimen, having its upper and lower sides welded
  - A single specimen with a gap between sheets (~ 10% of the thickness)

- Thermal treatments:
  - No thermal treatment
  - 480°C during 10 minutes with the objective to release the residual stresses

- Post-treatments:
  - Ultrasonic Impact Treatment STRESSONIC® technology supplied by Sonats
  - Shot-peening
  - TIG remelting
  - TIG remelting with a thermal treatment for residual stress relieving

All post-treatments listed above were applied on FB540 grade assemblies. On a second time, the most interesting post-treatments, considering the improvement of the fatigue behaviour and their industrial feasibility, have been applied on assemblies done with CP800. Initially, all fatigue tests were performed for a load ratio R=0.1. A convergence of all SN curves at low number of cycles (around 100 000 cycles) was observed on assemblies having undergone mechanical treatments such as shot-peening and UIT. This behaviour is well-known, for example after shot-peening, because a high loading (i.e. low number of cycles) induces plasticity due to the geometry of the weld (notch effect). As a consequence it removes the beneficial effect of introduced compressive residual stress in relaxing them. It was decided to investigate the behaviour between 100 000 cycles and 2 000 000 cycles for a loading ratio R = -1 expecting that the maximal loading during the cycles, being lower than for R=0.1, avoids the residual stresses relieving after mechanical post-treatments.

4.2 Fatigue results

The SN curves have been established for each configuration by a Stromeyer regression thanks to the ESOPE software to statistically proceed the data. For an easier reading, the improvements calculated on the fatigue strength at 2 million cycles in comparison with the reference state “as welded” are provided in the table 2 in percentage (based on the nominal stress defined in figure 2).

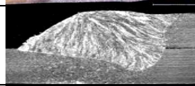
Axes	Configurations	Micrographs	Grades			
			FB540		CP800	
			R=0.1	R=-1	R=0.1	R=-1
Welding Process	CMT	-/-	0%			
	Pulsed current	-/-	-7%			
	Hybrid laser set 29 (5 settings)		+24%			
Design	Double weld		+16%			
	Gap		-21%	-6%	-34%	-60%
Thermal Treatment	Stress relieving		-9%		-11%	
Post-Treatment	TIG remelting		+40 %		+27 %	
	TIG remelting + stress relieving				+17 %	
	UIT STRESSONIC® Sonats 5 (6 settings)		+16 %	+31 %	+29 %	+29 %
	Shot peening 2 (3 settings)		+28 %	+67 %	+22 %	+29 %

Table 2. Evaluation of the tested solutions for the FB540 and CP800 grades (fatigue strength at 2.10^6 cycles).

4.3 Discussion

Whatever the “cold” welding process, pulsed current or CMT, the fatigue strength did not change even if we could expect lower distortions and residual stresses than those observed for standard GMAW. Considering that the residual stresses induced by joining are detrimental [5], the fatigue strength for standard process would lead to lower fatigue properties than ones obtained in “cold” process. This behaviour could certainly be explained by the fact that the residual stresses induced during joining are for a part relieved after sampling the specimen from the welded sheets. It is noticed that interesting improvement is achieved by optimizing hybrid laser welding procedure.

The fatigue improvement due to a double weld (complex feasibility in industrial conditions) is equal to +16% with only fatigue failures located at toe. This improvement could be mainly explained by a less severe stress distribution (both lap ends support the loading) and less bending effect as well as the non solicitation of the root.

The stress relieving thermal treatment (480°C / 10 minutes) induces a drop of the fatigue strength close to -10%. It is not very important in term of reduction, but it means that low and well distributed residual stresses for fatigue were relaxed (i.e. assumption of compressive residual stresses).

After a TIG remelting on the toe of the weld, the improvement of the fatigue strength reaches +40% on FB540 and +27% on CP800 grades. The increases of angle and radius at toe are not sufficient to explain this improvement since the geometry of the root remains unchanged. In fact, TIG remelting involves an increase of the weld width too. A FEA analysis has shown that the stresses decrease similarly at the root and the toe. If a thermal treatment of stress relieving (480°C/10min) is applied after TIG remelting, the fatigue limit decreases by -10% in comparison with TIG remelting alone. This could be interpreted also as a non modification of the residual stresses at root when TIG remelting is applied at toe.

As shown in table 2, the mechanical processes such as shot-peening and UIT need to go through optimization phases to obtain interesting improvements in fatigue (test of 3 and 6 settings respectively). Mechanical treatments may be beneficial or not for the fatigue life according to the setting parameters and the quality of the resulting treated surface. Indeed work hardening and compressive residual stresses have a clear beneficial effect on fatigue while the surface of the part can have a detrimental influence due to the introduction of defects such as a large roughness, marks… As already explained, a convergence of SN curves for a loading ratio R=0.1 is observed at low number of cycles. The plastic activity in the most loaded area leads to cyclic adaptation and consequently to relaxation of compressive residual stresses. At long life, i.e. low loading, the beneficial effect brought by the post-treatment remains.

4.4 Highlight on Ultrasonic Impact Treatment STRESSONIC® performed by Sonats

The UIT was applied on welded sheets with a gun by using two different types of needle having two different tip shapes. The first procedure consists in a grid of tips allowing hammering a surface. The second procedure consists of three aligned tips allowing hammering locally and linearly a narrow area (figure 6). The combination of the first and second procedures was used to test 6 configurations having more or less a realistic feasibility from an industrial point of view.

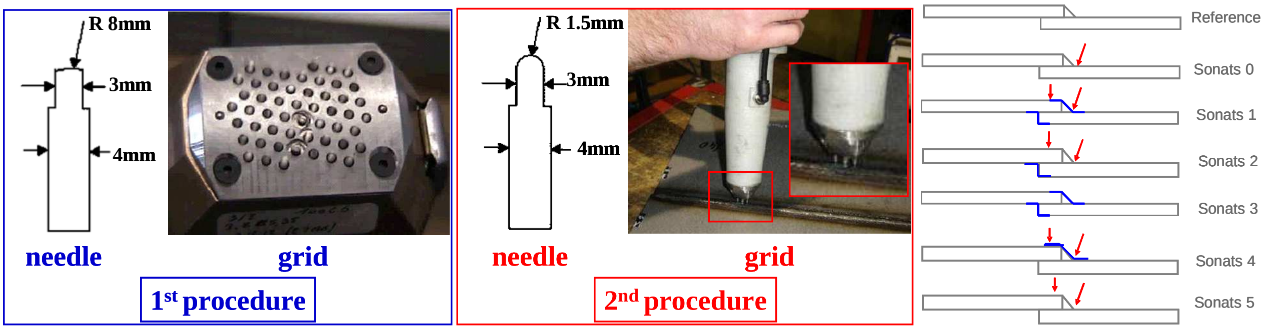


Figure 6. Both STRESSONIC® procedures allowing to hammer surfaces or linear narrow zones and all investigated configurations.

The configuration "Sonats 2" provides the best fatigue improvement but it has no industrial application possibility because it requires treating both sides of the weld. On the other hand, if the configuration "Sonats 0" is easy to apply, it provides unsatisfactory results for R=0.1. Finally the configuration "Sonats 5" is the strongest setting even if it does not provide the highest improvement but this configuration is industrially feasible.

4.5 Conclusion on the retained paths for fatigue improvement

The most interesting paths for improving the fatigue strength of welded lap joints are:

- The TIG remelting on the toe of the weld because this process increases the weld width and by consequence the stress levels at toe and root for a same loading are reduced. This solution can be applied under industrial conditions by using a robot.
- The shot-peening allows also achieving interesting levels of improvement after optimization of the process parameters. However be careful that the component is not subjected to quite high loads that may relax the residual stresses rapidly.
- The UIT has the same advantages and drawbacks than the shot-peening, nevertheless this process can be used directly in industrial conditions by using a robot for a local treatment.
- Both last mechanical post treatments need a specific equipment to avoid working people exposure to high noise levels.

5 VALIDATION OF PATHS OF FATIGUE IMPROVEMENT ON PROTOTYPES

As illustrated in figure 7, a demonstrator has been designed to validate the best retained solutions for fatigue strength improvement being the result of the study done on specimens.

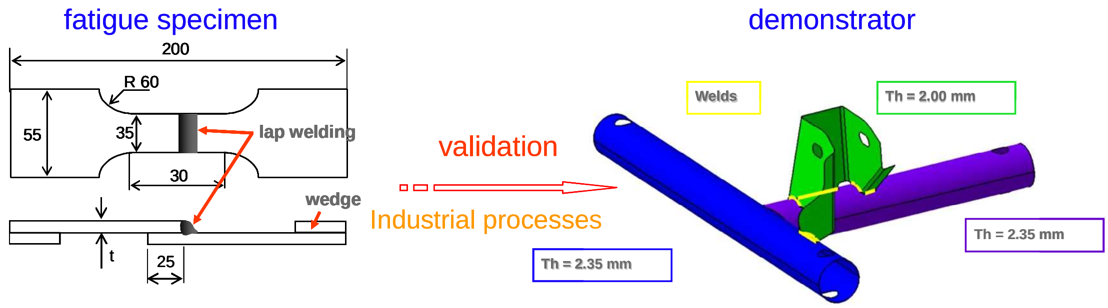


Figure 7. Approach to valid on prototype the best solutions of improvement investigated on specimens.

5.1 Definition and manufacturing of demonstrators

The geometry of prototypes is the result of the simplification of an actual automotive rear sub-frame part, analysed in the framework of a previous internal project [6]. The demonstrator must meet the following requirements:

- Take into account a welds realized in industrial conditions.
- Be representative of a real automotive component including clamping stresses.
- Have a global acceptable cost.
- And use a representative material.

The demonstrator consists in two 2.3mm tubes perpendicularly welded on which a 2mm bracket is welded. The steel grade quality used for the tubes and the bracket is a CP800. The demonstrators have been manufactured under industrial conditions by using a welding robot (figure 8). Both main critical welds have been identified by FEA calculations and post-treated by using TIG remelting or UIT under industrial conditions too:

- The TIG remelting was performed at 500mm/min on a full automatic equipments at the French Welding Institute (IS Yutz)
- The STRESSONIC® UIT was performed at 300mm/min on a robot by Sonats (Carquefou) with the “Sonats 5” setting.

Figure 8. Welding of demonstrators under industrial conditions.

5.2 Fatigue tests on prototypes

6 demonstrators by configuration were carried out on a fatigue bench using a sine signal with a loading ratio R=0.1. Only one load level was tested at 12kN (maximal force) at a frequency of 25Hz (figure 9).

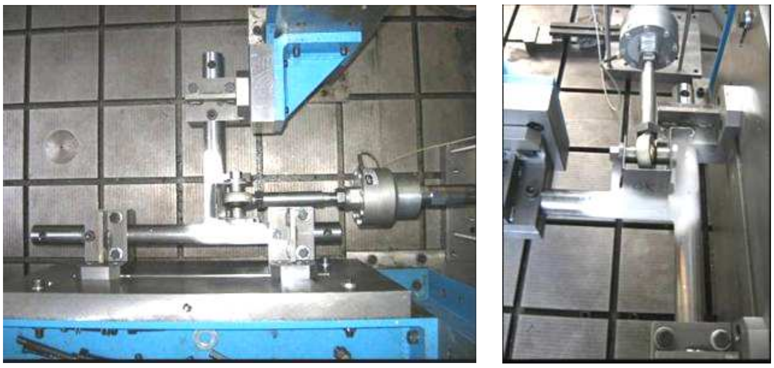


Figure 9. A demonstrator under fatigue loading.

The damage criterion used was the number of cycles for a visible fatigue crack (few millimetres), knowing that the propagation phase was very short in comparison to initiation phase. In all cases, a first crack appeared on the tip of weld 7 without further propagation (local re-distribution of loading) while a second crack appeared on weld 6, see figure 10.

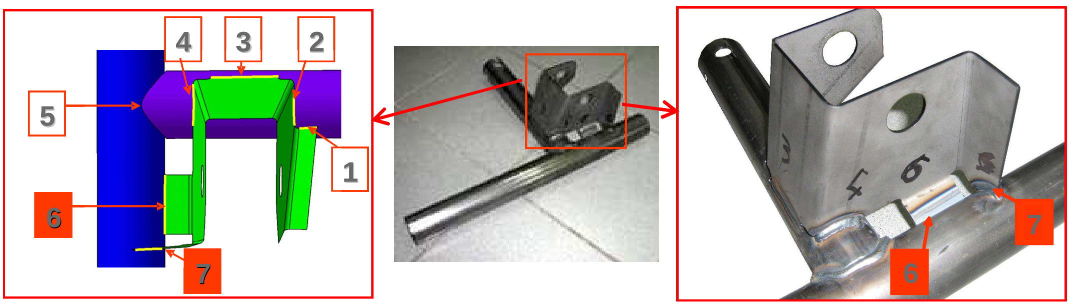


Figure 10**.** Location of the welds on the demonstrator.

The main fatigue results in terms of average number of cycles are provided in table 3.

Position	**Reference**	**TIG remelting**		**STRESSONIC® UIT by Sonats**	
	Fatigue life	**Fatigue life**	**Improvement (%)**	**Fatigue life**	**Improvement (%)**
Weld 7	157 000	260 000	**66**	272 000	**73**
Weld 6	261 000	357 000	**37**	486 000	**86**

Table 3. Fatigue lives obtained on demonstrators (average number of cycles).

In table 3, the fatigue improvements are provided in percent of number of cycles compared with the reference (and not in terms of stress such as on specimens). The fatigue life of demonstrators after either TIG remelting or UIT was improved in comparison to the reference. The increase after STRESSONIC® UIT is always higher than the TIG remelting. However the criterion of damage to define the fatigue life could be refined by using a more reliable indicator such as a loss of stiffness (measured by strain gauges for instance). Similarly, the results would lead to a better confidence by increasing the number of tested demonstrators.

5.3 Conclusion on the validation on demonstrator

The fatigue results on prototypes have confirmed the efficiency of best post-treatments defined on specimens. On demonstrators, the improvement has been investigated for a low numbers of cycles as it is often tested by carmakers to reduce the cost of the testing in saving time (about 150 000 cycles for the reference). Considering the trends of SN curves observed on specimens, we can assume that the improvement would be at least equal or higher for a high number of cycles, especially for Sonats UIT post-treatment.

6 CONCLUSION AND PERSPECTIVES

The influence of a hardness gradient (induced by welding) on the fatigue strength of steel grades ranging up to 800MPa has been studied. The decrease of the fatigue strength certainly due to the influence of hardness varies roughly between 0 and -13% (considered small), whatever the hardness value and the hardness profile (flat, U, M or W shapes).

Many ways of improvement (more than 40 SN curves) have been proved during the study, following 4 axes: the welding process, the design of specimens, the thermal treatment and the post-treatments. The best improvements were obtained by using TIG remelting, shot-peening and Sonats STRESSONIC® UIT. However it is clear that each process requests to go through an optimization phase of the process parameters to get the most benefits of these treatments, at least on specimens.

The interest to perform post-treatments on welds has been validated on representative of automotive chassis application, manufactured under industrial conditions by using automatic and repetitive process thanks to robots. The TIG remelting and Sonats STRESSONIC® UIT post-treatments have also been applied under industrial conditions following the same precautions.

In the objective to complete this study, it would be interesting to go further with:

- The effect of hardness: continue the study on grades upper than 800MPa and grind completely both sides of specimens in order to avoid any influence of small defects and indentation
- The welding conditions: investigate the influence of a Low Transformation Temperature wire for instance
- The fine evaluation of the improvement on prototypes: increase the number of prototypes to test, perform fatigue test on the initial configuration with the initial steel grade before mass saving by introduction of the AHSS and refine the criterion to stop the test.
- The introduction of the structural stress concept in order to match the fatigue results from specimen to prototype by using FEA, as well as the introduction of tests on T joint specimens.

Acknowledgements

The authors would like to thanks Christian Bellini from ArcelorMittal Tubular Products Vitry-Le-François for his great support in the manufacturing of prototypes under industrial conditions.

7 REFERENCES

1- M.Amblard, Presentation M.A.R.S (Mass saving Approach on a Rear Subframe) – A weight reduction study of chassis parts based on the elasto-kinematic behaviour and using Advanced High Strength steels, Vehicle Dynamics Expo 2007, 8-10 May 2007, Messe Stuttgart, Germany.
2- M.Bramat, Module de perfectionnement “Conception et calcul des constructions soudées” – Manuel d’accompagnement “Calcul en fatigue, nocivité des défauts”, Institut de Soudure
3- H.P. Lieurade, I. Huther and D.Lebaillif, Evaluation de la qualité des soudures vis à vis de la résistance à la fatigue. Mécanique & Industries 6, 133-143 (2005).
4- A. Galtier, M.Duchet Fatigue behaviour of high strength steel thin sheet assemblies, Welding in the World, March/April 2007, volume 51, N34 – 2007.
5- G.Çam, O.Özdemir and M.Koçak, Progress in Low Transformation Temperature (LTT) filler wires: Review, 63rd Annual Assembly & International Conference of the IIW, 11-17 July 2010, Istambul, Turkey.
6- M.Amblard, A.Tchorbadjiysky High strength steels for light and affordable chassis parts, 2nd International Munich Chassis Symposium 2011, June 7th.