ANALYSIS OF SPOT WELD JOINTS BY ULTRASONIC INSPECTION, FEM AND RESIDUAL STRESS MEASUREMENTS.

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Abstract: The present work seeks to determine the parameters for approval, through ultrasonic techniques, of spot welded joints of low carbon steel sheets. For such experience the mechanical behavior of a spotwelded joint was characterized under fatigue, in load cycles ranging from zero to 14 kN, on sheets of 1.5 mm thickness, joined by three spot welds of 7.5 mm of medium diameter, being the distance among spot weld centers 15 mm. The welding parameters were modified to generate indentations of up to 40% of the nominal thickness of the joints, measured by ultrasonic techniques. It was verified that fatigue cracks were nucleated in the areas of maximum equivalent von Mises stress, calculated by Finite Element Method (FEM) analysis, and their propagation occurred in the direction of the maximum main stress also calculated by FEM, together to the action of residual stresses, which were confirmed by X-Ray diffraction. The fatigue tests demonstrated that samples with indentation among 20 and 40% of the nominal thickness showed life equivalent to 77% of the life found in the joints where the indentation didn't overcome 20% of the nominal thickness. Besides, the fatigue life standard deviation of samples with indentation among 20 and 40% of the nominal thickness is equal to 35% of the medium value, while in the samples where the indentation did not overcome 20% of the nominal thickness, this deviation was not superior to 9%. The results proved the efficiency of FEM in the determination of stress acting in the joints, and validated the criterion of acceptance of the spot welds through the medium thickness measure of these joints through ultrasonic techniques.

Introduction: The material flaw as a result of cyclic loading was first mentioned by ALBERT, in 1838[1]; however, the definition of fatigue as flaw of material under alternate loads appears in PONCELET's (1839) [1] work, and the study of this flaw cause was performed by WÖHLER, in 1860[1], where the alternate stress were generated using rotative bending loads.

WÖHLER's work defines the S-N curves, Stress amplitudes applied in function of number of cycles for failure, where the medium stress applied in each cycle is null (in other words, the minimum stress is compressive and, in module, is equal to the maximum applied tension stress) [1].

However, it is necessary here the discussion of the mechanism of flaw formation for fatigue in metals [1,2], that begins with the formation of persistent slip bands, caused by dislocation movement in the crystalline structure over small distances, taking the formation of intrusions, extrusions and protrusions at the surface, or places for cracks nucleation, because of great plastic strain accumulation. These cracks grow from each stress cycle until the instability determinated by fracture mechanics. Being fatigue a process of highly located plastic strain, local stress concentration can rise the applied stress, releasing sessile dislocations, facilitating their movement and the crack nucleation and propagation.

Sheets used in automotive bodies can be joined through spot welds, obtained from heat generated by electric current passed through the sheets by electrodes under a certain pressure. The heat causes a local melt of the sheets, causing the spot weld formation.

One of the defects that can happen in spot welds is the deep penetration of the electrode, resulting in indentations in the sheet surfaces [3]; such indentations reduce the thickness of the welded joint locally and they can introduce stress concentration in these joints, and this could reduce the fatigue life of these joints.

One way of verifying the geometric stress concentrations due to these indentations is the finite elements method (FEM). The FEM technique employed for spot weld joints simulation can be as simple as possible since the focus of the simulation is on the load transfer from one plate to another. In the present paper, metal sheets were simulated using Reissner-Mindlin plate elements without bending-torsion coupling. Normal and frictional contact between plates were simulated using simple adaptive gap elements. Loading transfer from one plate to another was simulated using a RBE-type approach where rigid and beam elements were combined. No effort in simulating residual thermal stresses resulting from thermal contraction was made since the RBE-approach is unreliable for detailed time-dependent stress and/or temperature analysis within the spot weld. Owed to the spot weld cooling is performed using fictitious temperature gradients based on experimental analysis or detailed simulations of the welding process such as in LINDGREEN [4]. However, in the present analysis such procedure cannot be used because of the geometric variation owed to the electrode indentation in the sheets cannot be made using plate elements.

The indentation severity can be determined by ultrasonic techniques. In the Quality Technological Center (CTQ) at DaimlerChrysler, Brazil, the ultrasonic technique is used in spot weld joints to determine these indentations, through the measure of the medium thickness of the spots.

This technique has the first experiments dated about 1986, in Germany, and it differs basically from the conventional technique by the use of a special transducer, that possess a water column between the piezoelectric crystal and the piece to be tested, eliminating the undesirable effect of the "dead zone", defined as the area of strong turbulences in the end of the transducers, disabling the measurement of small thickness.

The technique consists basically on a non-destructive rehearsal, where the equipment generates an electric pulse to a piezoelectric crystal that receives the pulse and vibrates, generating sound waves in the range of 0.5 up to 30 MHz, inaudible for the human being. Those waves penetrate in the material to be tested, and they contemplate when finding the bottom of the piece or any other reflector, generating signs that are amplified properly and, after codified, exhibited in graph form or image, making possible to an operator properly trained the identification of which signs represent a eventually flaw in the material.

Objectives: The present work seeks to determine the parameters for approval of low-carbon steel sheets spot weld joints through ultrasonic techniques, comparing the indentations previously measured by ultrasonic techniques to pre-stabilished acceptance parameters as the results of fatigue tests of sheets welded in three points. The results were analysed using residual stress measurements in both 3 points, and simulation by FEM of the joints.

Experimental procedure: Starting from lower carbon steel sheets of 1.5 mm thickness, with the chemical composition showed in the table I and the nominal mechanical properties showed in the Table II, 3-point joints were obtained in specimens of 50 width mm and 110 mm length, as showed in Illustration 1.

Table I. nominal chemical Composition of the studied steel (weight %).

Element	C	Mn	P	S	Al
weight %	0,08	0,45	0,03	0,03	0,02

Table II. Mechanical properties of the studied steel.

Modulus of elasticity (GPa)	207
Yield strength (MPa)	195
Tensile strength (MPa)	304
Total elongation in 50 mm (%)	49.2
Hardness (HV)	100

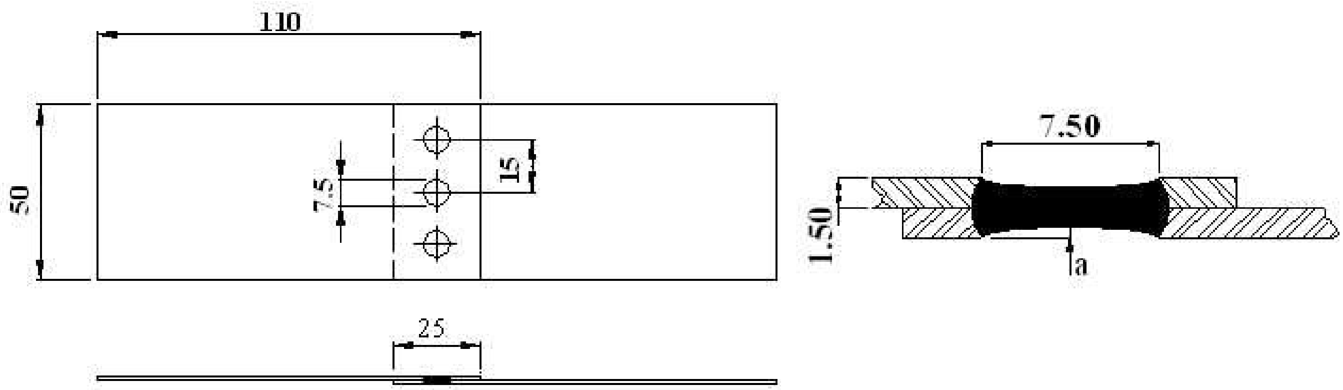

Illustration 1. Welded specimen in study and spot weld geometry.

The welding parameters were altered in order to obtain two different groups of samples, referenced to the spot weld indentation, showed in Illustration 1 as dimension a, in both sides of the spot welded joint point. The indentations were measured by ultrasonic technique using a 20 MHz, 4,5 diameter mm transducer, with water column [5], as showed in the Illustration 2. After this procedure, the welded specimens could be divided in two samples:
Sample A: specimens where the indentation did not surpass 20% of the joint thickness
Sample B: specimens where the indentation has joint thickness between 20% and 40%

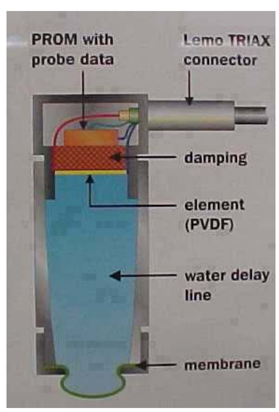

Illustration 2. Schematic representation of the used transducer.

Residual stress measurements: Because temperature changes can expand or contract a metal volumetrically, either directly through thermal expansion or indirectly through phase changes, residual stress are used when heat is put into or taken out of a metal inhomogeneously. A common example where residual stress resulted from effects or thermal expansion includes spot welding [5].
In this study, residual stress measurements were made to identify some stress regions near from the spot weld, as a base for the FEM analysis, in both A and B samples previously described.
These measurements were made under Bragg's law, principle of X-Ray diffraction, using a Rigaku MSF-3M diffratometer, showed in Illustration 3. The test practice consisted in a 4-angle testing, where the x-ray is emitted through a beryllium transmitter, received by a Cr target. The residual stresses where measured in 3 regions, described in Illustration 4.

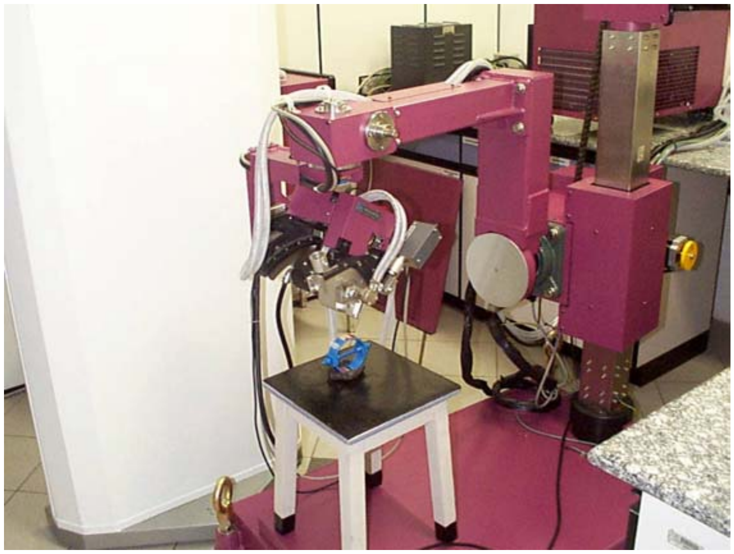

Illustration 3. Rigaku MSF-3M diffratometer X-Ray Analyser

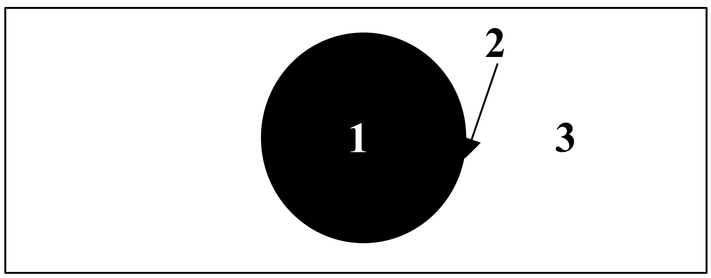

Illustration 4. Selected regions for residual stress measurements

The two samples, were submitted to controlled cyclic load, varying it from zero to 14 kN, in order to determine the number of cycles to the fracture. Such tests were performed in a universal testing machine MTS, servo-controlled, of 250 kN of maximum capacity, showed in the Illustration 5. The load reversion frequency in the tests was 8 Hz.

Illustration 5. MatLab-FEI 's universal testing machine MTS

Finite Elements Method modelling: Since the purpose of the analysis is to identify the critical stress concentration points as well as the resulting time-dependent stresses around spot welds, no effort was made to simulate residual thermal stresses arising from the non-uniform cooling of the spot welds. LINDGREN [4] showed that, in FEM simulation of spot welding process of low carbon steel sheets with 1mm thickness using specific FEM codes, residual stress were observed ranging from -75 MPa to 75 MPa depending on the conditions of the simulation.

Once determined via numerical or experimental methods, such residual stresses can be readily incorporated as mean values in the conventional stress approach of fatigue via both Goodman or Gerber criteria [2]. The joint was simulated using both Reissner-Mindlin quadratic plate elements without bending-torsion coupling and quadratic solid elements in time-domain. Considering the expected deformation pattern of the asymmetric joint, one can expects the existence of normal and frictional contact as the test progresses. Mechanical contact between plates was simulated via simple gap elements available in MSC-NASTRAN®. Cinematic friction coefficient between steel plates were assumed to be 0.25. The spot weld itself was modelled in the plate simulation via RBE and spider techniques described by ZHANG [6]. Both techniques use a combination of beam and rigid elements to transfer loading form one plate to another. However this technique gives very unreliable results in simulating time-dependent heat-transfer problems and cannot be used in obtaining residual stress in the interior of the spotweld. The applied loading was simulated via a sinusoidal wave varying from 0 to 14 kN. Once it is still little known the influence of material cushioning in spotwelded fatigue behaviour, the material was modelled as linear viscoelastic with 1.0% of hysteretic reduction. The time simulation was performed using 20 points by period for a frequency of 8 Hz for a total simulation time of 1.25s. These parameters correspond to 10 cycles of load application.

The results of this simulation with a mesh parameter of 0.8mm and non-structured meshes show that the stress developed inside the joint concentrates heavily near the external surfaces of the spot, fact experimentally validated. The results for mean (σ_m) and alternate ($\Delta\sigma$) von Mises stress obtained with zero indentation and solid modelling were 187 MPa and 192 MPa respectively. The results for plate modelling differ somewhat of those but exhibit the same pattern around the spot weld. The results for plate modelling are presented in illustrations 6 and 7. The results for the solid elements simulation are presented in illustration 8 for mean and alternate von Mises stress. It is noticed that, for indentation levels between 0% and 15%, the results show a discreet elevation in the stress level and for an indentation between 15% and 50%, the stress levels increase more heavily.

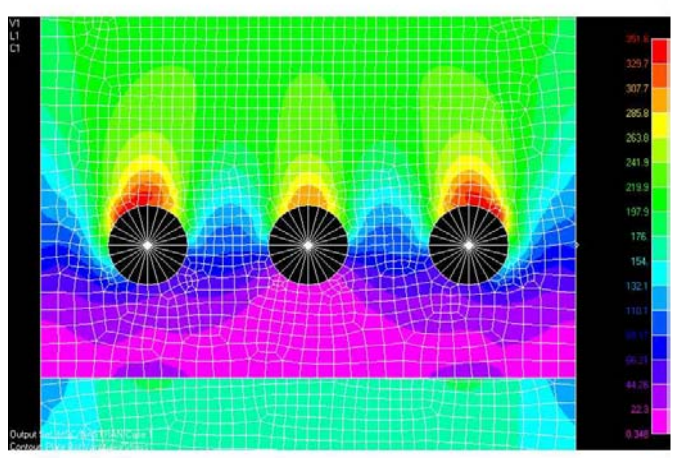

Illustration 6: Results of the simulation through FEM for the maximum principal stress ($\sigma_{maxPR} = \sigma_{medPR} + \Delta\sigma_{PR}$) with plate elements, showing stress concentration area in the most external spots.

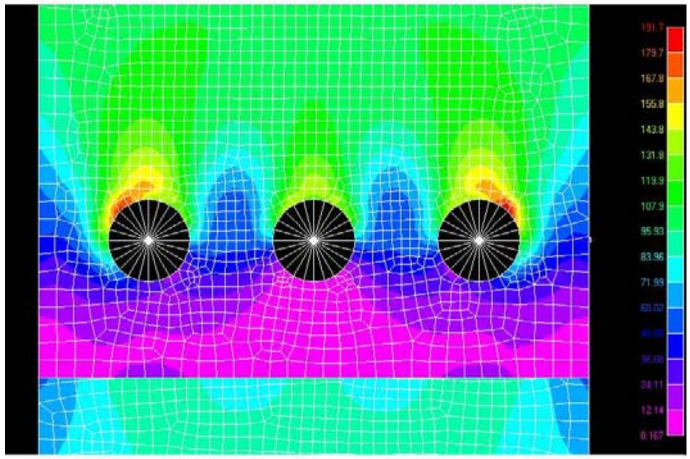

Illustration 7: Results of the simulation through FEM for the von Mises stress with plate elements, showing area of σ_{med} concentration in the most external spots.

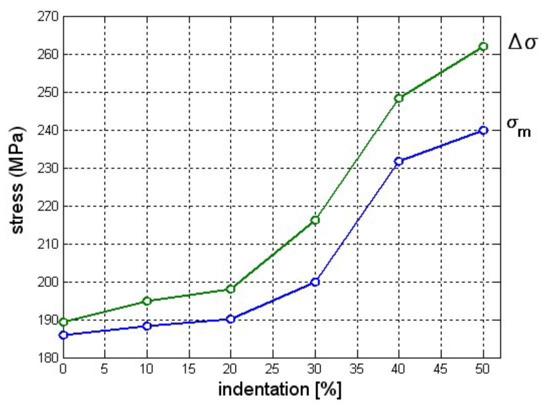

Illustration 8: Maximum main stress components variation in function of spot weld indentation. Results of the simulation through FEM with solid elements.

Results And Discussion: Table III shows the founded values of residual stresses in the selected regions, confirming LINDGREN's theory [4] in the two specimens, as described before, confirming the presence of residual stresses in the point 3 of Illustration 4 (at the steel sheet, near the spot weld) and compression residual stresses at the heat affected zone and in the center of the spot weld (respectively points 2 and 1 of Illustration 4).

Region	Spot weld center (1)	Heat affected zone (2)	Sheet (3)
Average Residual Stress (MPa)	-13,35	-13,73	18,79

Table III: Residual stress measurements

Table IV brings the medium values and respective standard deviation of the number of cycles to the fracture for the two samples, tested under constant load, varying the loads between zero and 14 kN. It is noticed that the samples with indentations of up to 20% of the joints thickness result in life in fatigue of the sample 30% larger than life found in the sample where the indentation lies between 20 and 40% of the joint thickness.

Besides, it is noticed in Table IV that the standard deviation of the fatigue life of the sample with indentation up to 20% it is equal to 9% of the medium life, while for the sample where the indentation lies between 20 and 40% of the joint thickness the standard deviation corresponds to 35% of the medium life. Such facts show the deleterious effect of indentation increase in fatigue life of the components, and demonstrate that the parameter used in the ultrasonic measurements (to accept spots with up to 20% of nominal thickness reduction of the joints) for such spot welded joints guarantees better safety in the mechanical project.

Sample groups	Fatigue life (cycles)
Up to 20% of nominal thickness joints reduction	24663 ± 2316
From 20% to 40% of nominal thickness joints reduction	18935 ± 6647

Table IV. Medium values and respective deviation-pattern of the number of cycles to the fracture for the two groups of samples, tested with loads from zero to 14 kN.

It was possible to observes that fatigue cracks nucleated in the areas of maximum equivalent von Mises stresses calculated in simulation by FEM, and that the propagation of the same ones felt in the direction of the maximum main stress also calculated by FEM, as showed in Illustration 9, compared to Illustration 7. It is interesting to notice the great increase in stress concentration in the spot weld according to higher levels of indentation. It was observed although the results with plate elements follow the same patterns observed in the simulation with solid elements, although they are not capable to simulate the spot indentation. In the wider aspect of the analysis, can be said that, although the plate elements are widely used in the simulation of welded joints, the FEM analyst should evaluate carefully the indentation level of spot found in practice and take in account the portion of the stress concentration due this indentation before specifying the wanted stress in the analysis. In this particular case, residual stress are considered low, and can be discharged in FEM calculation.

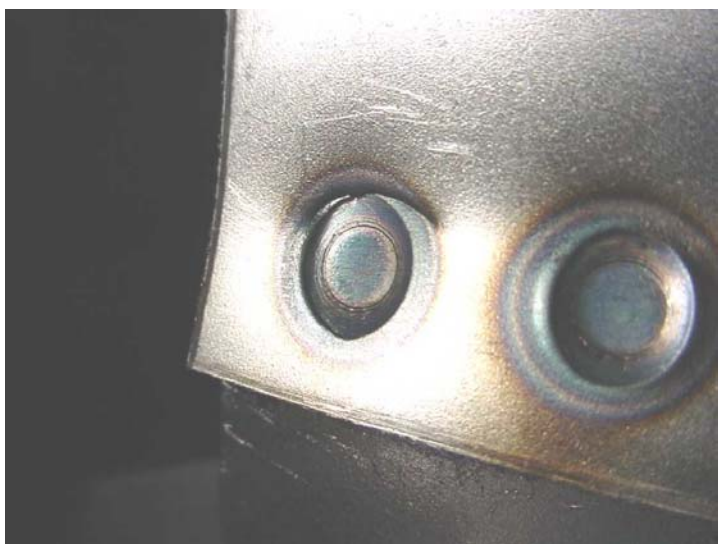

Illustration 9: Experimental proof of crack appearance in von Mises maximum stress area.

Conclusions: Of the present work can be ended that:

- The ultrasonic measurements parameter used - to accept spot welds with up to 20% of nominal thickness reduction of the joints - guarantees to the studied committees better safety in the mechanical project, once the medium fatigue life of the joints with this characteristic it is higher; besides, such parameter guarantees smaller dispersion in fatigue life.
- FEM is a powerful tool in stress determination in structural elements that allows determination of the variation in time of stress found in complex geometries. Besides, the current results of the

FEM were, at least qualitatively, experimentally proved, considering the low residual stresses found.

References:

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