4. Spot weld fatigue durability performance evaluation through the use of Finite Elements Analysis and Design for Life Cycle

4.1. Introduction

In this chapter it is discussed how a design for the life cycle (DFX) can be included used to investigate sheet metal joining through electric resistance spot welding (ERSW). ERSW is still the most widely used process for car body building, where an average vehicle has around 5,000 spot welding points in its structure. In this sense, the spot welding project is critical to the final product performance and it must be done in a way that can assure both quality and durability of the vehicle, already taking into consideration the fact that the spot weld mechanical properties related to fatigue and rupture resistance are much lower when compared to other available welding techniques like MIG welding for example. These properties have a direct impact on the fatigue durability and at crashworthiness, with very strong requirements for the welding process, as a significant part of the structural strength is passing through those spot welds. Within this scenario, the correct application of FEA techniques is very important to assure that the projected joints and spot weld disposition meet the product targets in terms of safety and durability. The objective of this work is to review the mechanical properties of the spot weld related to its fatigue strength and the FEA methods applied during the product development to assure that the durability performance target of the vehicle will be met. It has also been reviewed how the assembly process affects the FEA results in the cases of joint misalignment and indentation of the spot weld, where significant performance reduction can be expected. Another aspects, like crashworthiness performance of the spot welds, are not covered in this paper, however the correct application of the FEA techniques described herein are expected to improve these different aspects of the final product as well.

4.2. Car Body in White (BIW) and its welding process of assembly

The automotive industry is all over the world facing the challenge of bringing more diversity in their products, at the same time cutting costs and keeping the quality demanded by the customers in terms of vehicle performance. The ability to assemble a wider variety of products in the same assembly line associated with the automated processes available today is a key factor for the success of these strategies. General Motors do Brazil (GMB) plant in São Caetano do Sul is an example of the successful application of this strategy, currently producing many different vehicles simultaneously in the same assembly line. The same flexibility of these automated assembly lines is also crucial for bringing new models faster to the market. Since the early 1970's, robotic resistance welding has been applied to assembly lines (General Motors installed the first robotic-integrated body assembly line at its Lordstown in USA, plant in 1970), but only more recently the associated equipment costs have been reduced in a way to be competitive to manual handcraft in emerging markets like Brazil. Lane [61] summarizes papers related to robotic welding systems, giving special attention to robotic resistance welding (spot welding) processes.

Metal sheets used in car bodies are usually joined with the spot welds [62]. The spot welds are formed during spot welding process. This process employs the electrodes, which squeeze the plates under certain force and conduct high electric current through them. The Joule heat melts the base metal and forms a fused area, which holds the sheets together. Among the various types of the available welding processes (Figure 4.1 [63]), spot welding allows especially high automation levels and faster operation time compared to other welding options, being specifically suitable for thin sheet metal welding, as noted by [64].

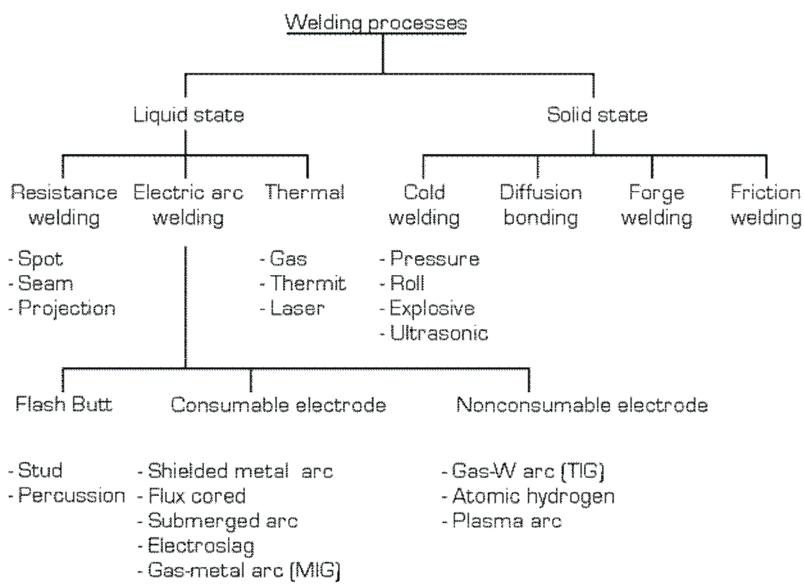


Figure 4.1. *Classification of welding processes [63]*

Taking all these advantages into consideration, the spot weld mechanical properties, remarkably fatigue properties, are considerably inferior compared to other welding options due to its nature of a very small connection area between the welded surfaces and appreciable stress gradients in the spot region. In this sense, it is important to design the spot weld locations in such a way to avoid putting them into heavily stressed areas of the sheet metal under the dynamic loading of the vehicle running on uneven roads – these effects will be discussed in more detail later on this chapter.

ERSW indentation problems might occur, and one way of verifying the geometric stress concentrations due to these indentations are through the Finite Elements Method. 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 attempt in simulating the residual thermal stresses resulting from thermal contraction was made since the RBE-approach is unreliable for the detailed time-dependent stress and/or temperature analysis within the spot weld. This effect occurs due to the spot weld cooling and the analysis can be performed using the fictitious temperature gradients based on experimental analysis or detailed simulations of the welding process such as in Lindgreen [65]. However, in the present analysis such procedure cannot be used, since the geometric variation due to the electrode indentation in the sheets cannot be represented using plate elements.

Besides all these factors, if the surfaces to be joined are not designed in a way to assure the contact between them prior to the welding process, allowing gaps between the parts, additional pre-stresses may arise during the welding process that can compromise further the fatigue durability of these joints.

Finally, the intensive usage of CAD/CAE tools to analyse the more convenient spot weld location and distribution and the optimum shape of the interface of the parts to be welded through spot welding, as well as a mean for deeper understanding of the possible effects of a wrong assembly in the vehicle performance, is a key factor to produce reliable and robust products. Here, a big number of techniques to represent spot welds with Finite Element (FE) software have been studied like those presented by Rossi in [66]. Besides that, specific software is needed to calculate the excitation loads for the structure and its final durability performance, like the one presented by Vilela and Gueler [67].

4.3. Electric Resistance Spot Welding process (ERSW)

The spot welding working principle, as described by Okumura & Taniguchi in their book [64], is represented here in the Figure 4.2: the two metal sheets to be welded are kept in contact through two cooper electrodes, while a very intense electric current passes through this electric circuit for a short period of time.

The passage of this intense electric current through the circuit releases heat in the contact interface between the two metal sheets that are being welded by means of electric resistance. The surfaces are then melted and the pressure kept between the sheets is enough to create the spot weld. The heat release also happens between the metal sheets and the electrodes, but these are internally cooled down in a way to avoid its fusion or the fusion of the sheet metal surface in contact with it.

Although which sketch shows the application of the spot welding bonding two metal sheets, the same principle can be applied to bond three or even four metal sheets in some rare cases, but special care should be taken in this case for the thicknesses involved and the electric current needed, since these designs are more susceptible to gap induced pre-stresses and lack of weld penetration, as we will discuss further in this paper. As previously mentioned, one of the biggest advantages of the spot welding process is the possibility of assembly automation and flexibility through the usage of different programming for different vehicles in the same assembly line.

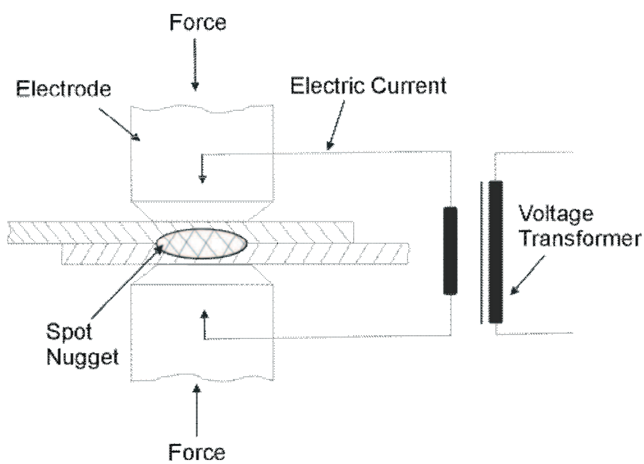


Figure 4.2. *ERSW (spot welding) working principles [64]*

A robotic ERSW system is comprised of a robot arm, robot control, resistance welding equipment (transformer, cable assemblies and electrodes), welding control, product positioning jig and fixturing system, system controller (if required) and other associated peripheral equipment, such as safety clutches, safety interlocks and gates and tool changing hardware. There are many robotic arm configurations available for assembly plant usage (Lane [61]), and the choice is based on the flexibility and velocity required for the system. These characteristics are usually conflicting and the manufacturing engineer has to choose the best option also based on the economic constraints of a specific project or assembly plant. Product positioning is especially critical for the spot weld fatigue properties, since the pre-existent gaps that are forced by the spot welding process will turn into additional pre-stresses that reduce the already not so good fatigue strength of the spot welds. Experience in the automotive industry has resulted in the need to achieve as little product dimensional variation as possible and to design tools and fixtures in such a manner as to minimize the dimensional variations resulting from part location and clamping. Besides that, usually it is usual that the sheet flanges being welded are not much wider than the formed spot weld nugget diameter itself. As it is not desirable to locate the nuggets on the edge of these flanges to avoid possible loss of welding area and consequently mechanical properties of the joint, the accurate location and positioning of the workpiece are absolute requirement.

4.4. ERSW spot weld fatigue properties

The welding process consists of the union of two different pieces of metal through a localized melt. During the welding process, the metal is heated and further cooled in the welding area, leading to thermal expansion and contractions in the material. As these effects are extremely localized in the welding area, thermal induced pre-stresses are generated in the weld region that reduces significantly the fatigue resistance of these areas. Figure 4.3 illustrates how these residual stresses vary for a welded plate. In a spot weld, the effect is more accentuated and a bigger gradient of residual stresses is to be expected, as the dimensions are smaller compared to a weld chord as shown in Figure 4.3.

Lindgreen [65] studies residual stress through measurements made to identify some stress regions near from the spot weld, as a base for the FE analysis. These measurements were made under Bragg’s law, principle of X-Ray diffraction, using a Rigaku MSF-3M X-Ray diffractometer. The test practice consisted in a 4-angle testing, where the X-ray is emitted through a beryllium transmitter and received by a chromium target. The residual stresses were measured in 3 regions, described in Figure 4.4.

Table 4.1 shows the residual stresses' values founded in the selected regions, confirming Lindgreen's theory of tensile residual stresses in the region 3 of Figure 4 (at the steel sheet, near the spot weld) and compression residual stresses at the heat affected zone and in the centre of the spot weld (respectively regions 2 and 1 of Figure 4.4).

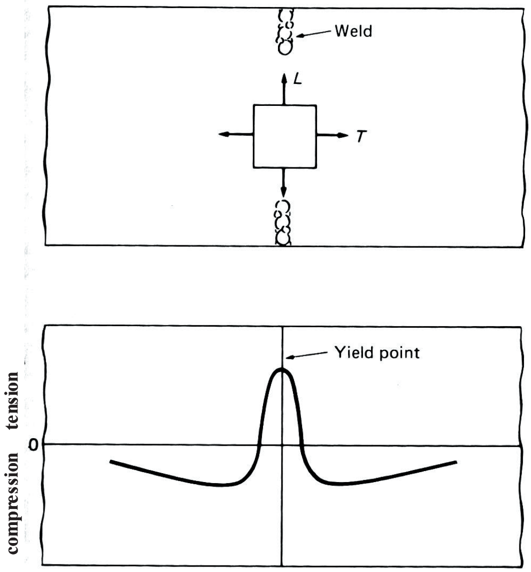


Figure 4.3. *Longitudinal residual stresses in a welded plate (Dieter [63])*

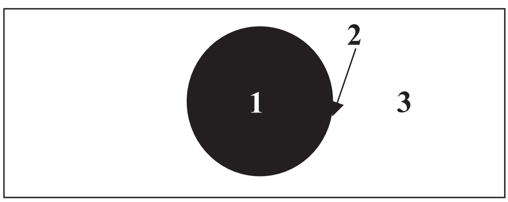


Figure 4.4. *Lindgreen [65] selected regions for residual stress measurements*

Table 4.1. *Lindgreen [5] residual stress measurements*

Region	Spot centre (1)	HAZ (2)	Sheet (3)
Average Residual Stress (MPa)	-13.35	-13.73	18.79

The material selection for the welding influences the final result of the weld mechanical properties. The so-called "*weldability*" of a specific material is a complex technological property that combines many basic properties. The melting point of the material, together with the specific heat and latent heat to fusion determine the heat input necessary to produce fusion. A high thermal conductivity allows the heat to dissipate and therefore requires a higher rate of heat input. Besides that, a high thermal conductivity will lead to a faster cooling and more problems with weld cracking in this sense. The higher the thermal expansion of a material, the higher the residual stresses will be in the weld location, jeopardizing further the mechanical and fatigue properties of the weld. Rapid cooling of alloy steels in welding can result in brittle martensite formation and consequent crack problems. According to Dieter [63], a usual limitation of carbon composition in the structure to avoid this kind of problem is about 3%. If higher carbon concentration in the base material proves to be necessary for the high strength associated with these materials, special care with pre-heating and cooling velocity is demanded for the welding process.

It is interesting to notice that these effects are so important, that the weld fatigue properties are much more correlated with the weld process itself than the fatigue properties of the plain materials that are being welded to each other. Figure 4.5 shows a typical degradation of the fatigue strength of low-carbon plain steel subjected to GMAW - MIG welding and spot welding.

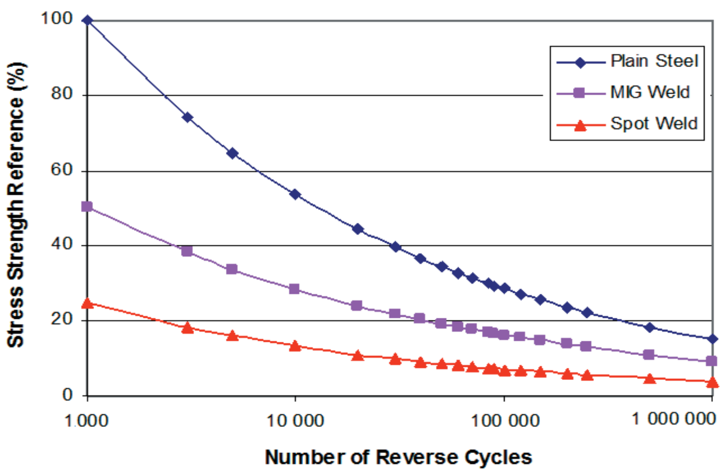


Figure 4.5. *Fatigue strength degradation due to welding process*

The fatigue curves shown in Figure 4.5 consider only the residual stresses due to the thermal characteristics of the welding process, not taking into consideration the pre-stresses caused by misalignment of the welded flanges or spot weld indentation problems, as it will be studied further in this book. It is important to mention here the correct usage of the DFMA methodology will allow the designer to propose parts that are less susceptible to matching problems that may cause the pre-stress effect.

4.5. ERSW - spot weld analysis by Computer Aided Engineering (CAE)

4.5.1. Spot weld indentation effect

One of the defects that can happen in spot welds is the deep penetration of the electrode, resulting in indentations in the sheet surfaces [63]. 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.

A study was performed, where the welding parameters were altered in order to obtain two different groups of samples, referenced to the spot weld indentation, showed in Figure 4.6 as dimension “a”, in both sides of the spot welded joint point. The indentations were measured by ultrasonic technique using the 20 MHz, 4.5 mm diameter transducer, with water coupling [65].

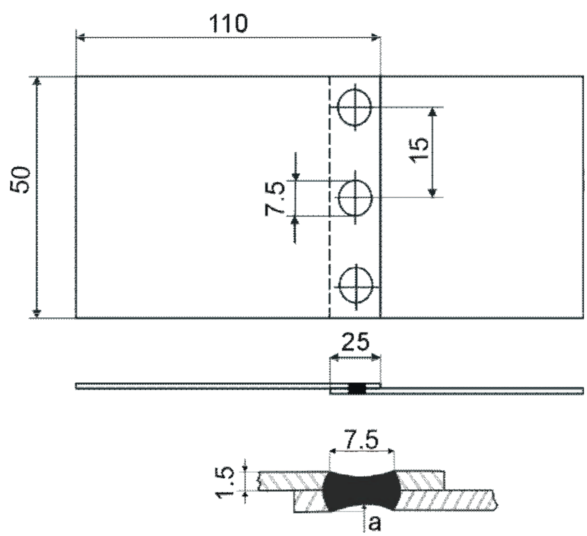


Figure 4.6. *Welded specimen in study and spot weld geometry*

After this procedure, the welded specimens could be divided in two samples:

Sample A: with indentation values did not exceed 20% of the joint thickness.

Sample B: with indentation values between 20 % and 40 % of the joint thickness.

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. Lindgreen [65] showed that, in FE simulation of spot welding process of low carbon steel sheets with 1.0 mm thickness using specific FE 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 Goodman criteria for example [62]. 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®. Kinematic friction coefficient between steel plates was assumed to be 0.25. The spot weld itself was modelled in the plate simulation via RBE and spider techniques. 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 the time-dependent heat-transfer problems and cannot be used in obtaining residual stress in the interior of the spot weld. The applied loading was simulated with the sinusoidal wave varying from 0 to 14 kN. Once the influence of material cushioning in spot welded fatigue behaviour it is still little known, 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 1.25 s. These parameters correspond to 10 cycles of load application.

The results of this simulation with a mesh parameter of 0.8 mm and non-structured meshes show that the stress developed inside the joint concentrates heavily near the external surfaces of the spot, the fact being 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 Figures 4.7 and 4.8.

The results for the solid elements simulation are presented in Figure 4.9 for mean and alternate von Mises stress. It is noticed that, for indentation levels between 0 % and 15 %, the results show a discreet rise in the stress level and for an indentation between 15 % and 50 %, the stress levels increase even more.

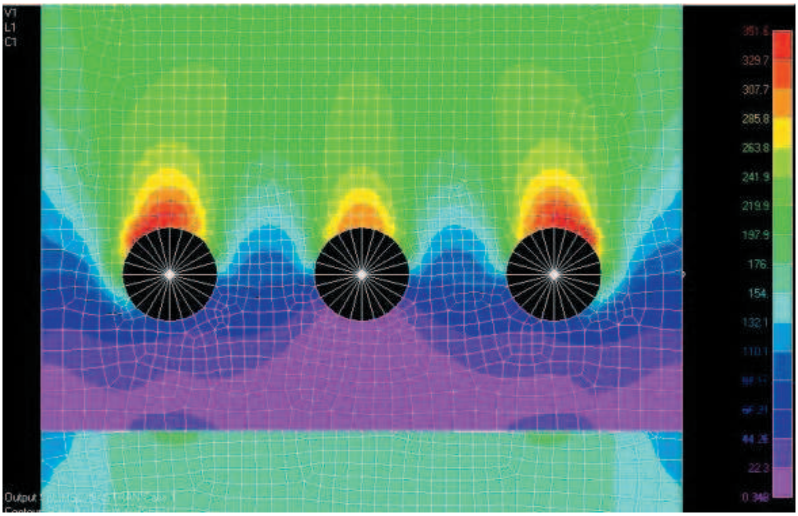


Figure 4.7. *Results of the simulation through FE for the maximum principal stress ($\sigma_{maxPR} = \sigma_{medPR} + \Delta\sigma_{PR}$) with plate elements, showing stress concentration area in the outermost spots*

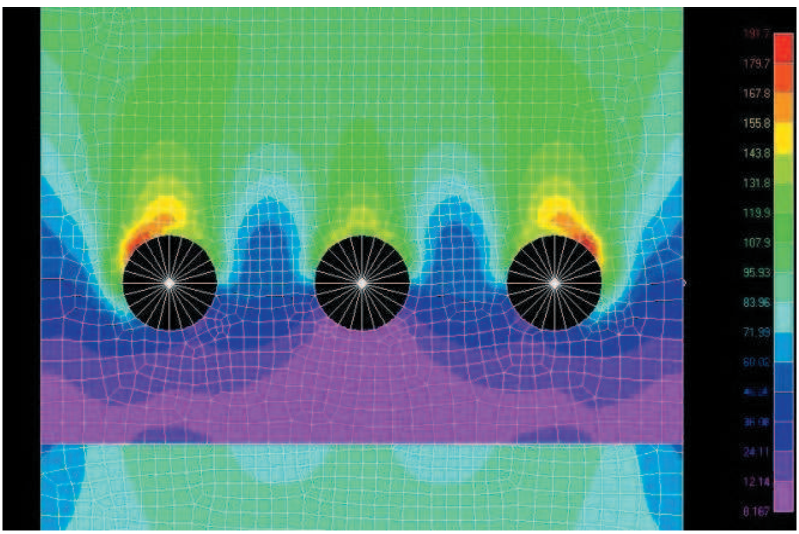


Figure 4.8. *Results of the simulation through FE for the von Mises Stress with plate elements, showing area of σ_{med} concentration in the outermost spots*

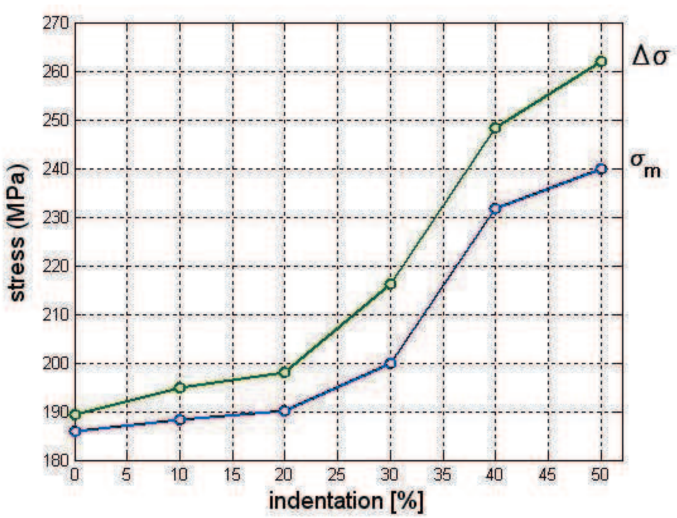


Figure 4.9. *Maximum main stress components variation in function of spot weld indentation – FEM simulation with solid elements*

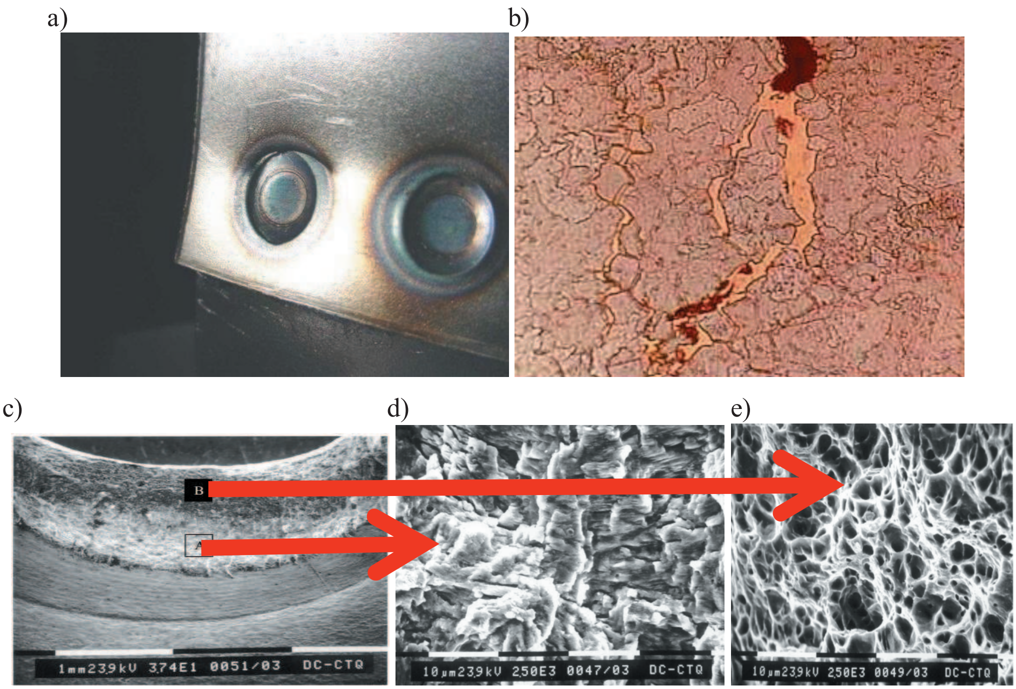


Figure 4.10. *Experimental proof of crack appearance at von Mises maximum stress area. a) external appearance, b) microstructure of a crack (c, d and e) MEV of the fracture surfaces*

It was possible to observe that fatigue cracks nucleated in the areas of maximum equivalent von Mises stresses calculated in simulation by FE, and that the propagation of such cracks happened in the direction of the maximum main stress also calculated by FE, as showed in Figure 4.10, compared to Figure 4.8.

It is interesting to notice the great increase in stress concentration in the spot weld due to higher levels of indentation. It was observed that 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, it can be said that, although the plate elements are widely used in the simulation of welded joints, the FE 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 desired stress in the analysis. In this particular case, residual stresses were considered low, and could be neglected in the FE calculation.

4.5.2. Flange misalignment effect

Pre-stresses will also appear if the flanges to be welded present gaps prior to the welding due to problems in the surfaces' matching – Figure 4.11 illustrates this situation.

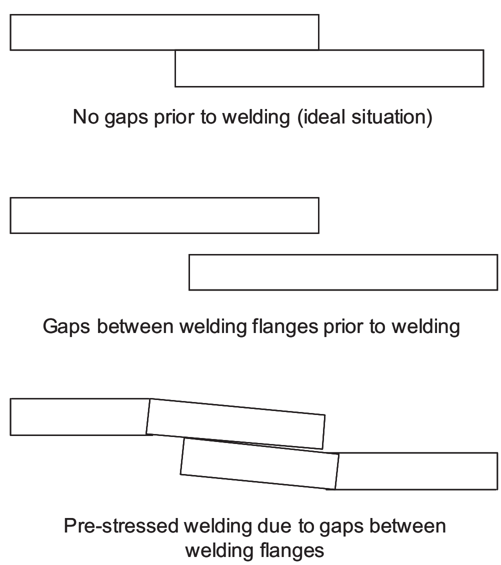


Figure 4.11. *Flange matching problem induced pre-stress*

If this matching problem situation occurs during the assembly of the parts prior to the welding process, there will be a tractive pre-stress acting in the welded area that will jeopardize further the fatigue properties of the weld. Different approaches to evaluate the effects of a tractive pre-stress in the fatigue properties of a material are available in the literature – Figure 4.12 shows the comparison for some of these existent approaches.

In the plot of the Figure 4.12, the horizontal line has the mean stress value (pre-stress S_m) and other material properties, like yield strength (S_{yt}) and ultimate strength (S_{ut}). The vertical line contains the original fatigue strength value for a given number of cycles without the pre-stress effect (S_e) and the corrected fatigue strength due to the existence of the pre-stress (S_a – in the example above calculated using the Goodman criteria).

The Soderberg criterion considers that the fatigue strength will be affected by the ratio of the pre-stress over the yield strength of the material – this has proven to be a very conservative criterion in most cases. Goodman criterion on its turn, considers that the fatigue strength will be affected by the ratio of the pre-stress over the ultimate strength of the material. Finally, Gerber proposes that even the Goodman criterion can be sometimes conservative and that a specific material would have its fatigue strength also based on its ultimate strength, but following a quadratic curve. The criterion to be used depends on the material properties, but the Goodman criterion is the one that shows the best overall good correlation for pre-stresses acting on weld points, especially spot welds.

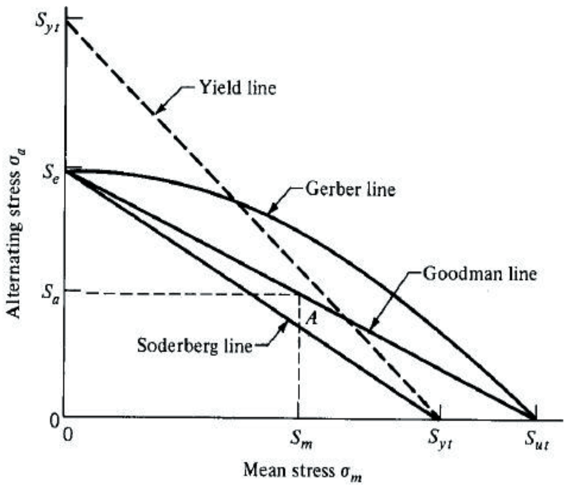


Figure 4.12. *Methods to evaluate the effects of a tractive mean stress in the fatigue strength of a material*

The only way to accurately quantify the existent pre-stress of the weld assembly here is to simulate its effect through the use of the finite element software, since practical measures are usually limited to quantify the existent gap between the welding flanges. The final pre-stress value will strongly depend on the geometry of the parts to be welded, including their thicknesses. An example here was studied using ARCAN device, as described by Kavamura [68] (see Figure 4.13), to produce a gap between two welded plates of 1.50 mm thickness each.

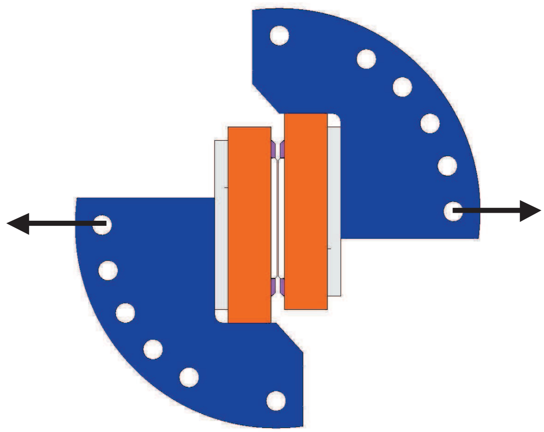


Figure 4.13. *ARCAN device (Kavamura & Batalha [68-69]) simulated to verify assembly misalignment induced pre-stress effects*

Table 4.2. *Assembly Misalignment induced Pre-Stress Effects on Spot Weld Fatigue Life*

Misalignment (mm)	Misalignment (% of plate thickness)	Pre-Stress (MPa)	Fatigue Resistance Stress Reduction Factor	Fatigue Life Reduction
0.00	0%	0	1.00	0.0%
0.05	3%	15	1.05	20.8%
0.10	7%	31	1.10	37.9%
0.15	10%	46	1.16	52.0%
0.20	13%	62	1.22	63.4%
0.25	17%	77	1.29	72.5%
0.30	20%	93	1.38	79.7%
0.35	23%	108	1.47	85.3%
0.40	27%	124	1.57	89.6%
0.45	30%	139	1.69	92.8%
0.50	33%	155	1.83	95.2%
0.55	37%	170	2.00	96.9%
0.60	40%	186	2.20	98.1%
0.65	43%	201	2.45	98.9%
0.70	47%	217	2.75	99.4%
0.75	50%	232	3.15	99.7%

The linear FE analysis has performed with MSC Nastran® in order to understand the sensibility of the gap in the fatigue performance of the spot weld and the results are summarized in the Table 4.2 and Figure 4.14, considering the material with ultimate strength of 340 MPa using the Goodman criteria.

4.6. Durability performance analysis by CAE

As previously mentioned, only through the intensive usage of CAD (Computer Aided Design) and CAE (Computer Aided Engineering) tools it is possible to analyse effectively the adequate spot weld distribution in a structure in terms of its fatigue durability performance. It is not the purpose of this book to go deeply into this aspect of the problem, but some points can be highlighted here.

In order to make the correct stress determining possible on the spot weld locations, the structure must be described as a 3D CAD model that contains all relevant aspects for the upcoming FE (Finite Element) software analysis, like overall dimensions, thicknesses, radii and correct spot weld location;

The FEM software representation must reproduce the physical behaviour of the spot welds in terms of stresses for a given loading condition of the structure, in order to be possible to use these values for a fatigue life calculation. Many different approaches exist in the literature, like those shown in [65].

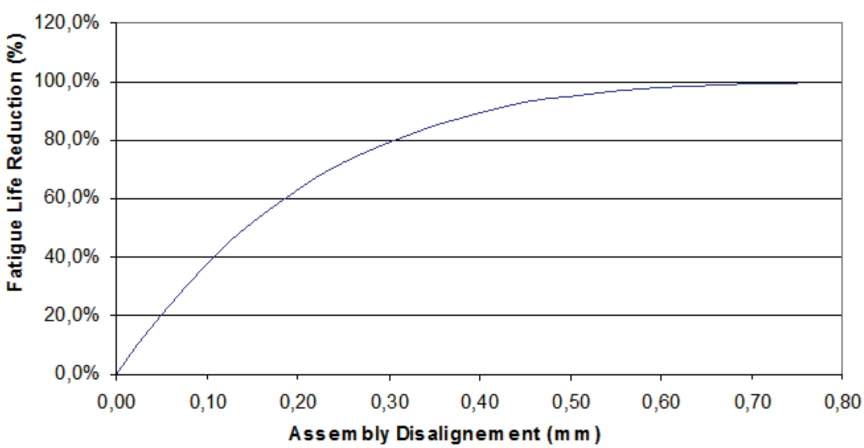
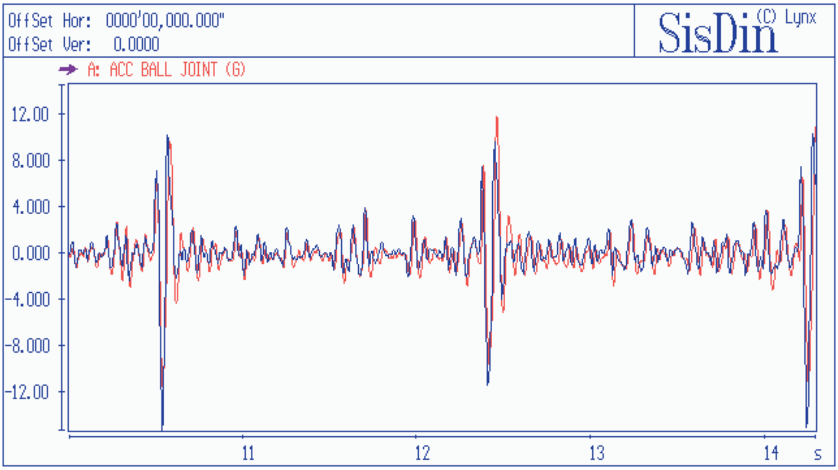


Figure 4.14. *Assembly misalignment induced pre-stress effects on spot weld fatigue life*

If the process or the part shape does not allow the elimination of pre-stresses during the assembly of the structure, these pre-stresses need to be quantified through the same FE tool, in order to be used to adjust the fatigue properties that will be considered for the fatigue life calculation.

For example, if it is known that a certain amount of gap exists at some flange welding point during the assembly, this value can be used as an initial forced displacement in the FE software to calculate the pre-stresses caused by it.

a)



b)

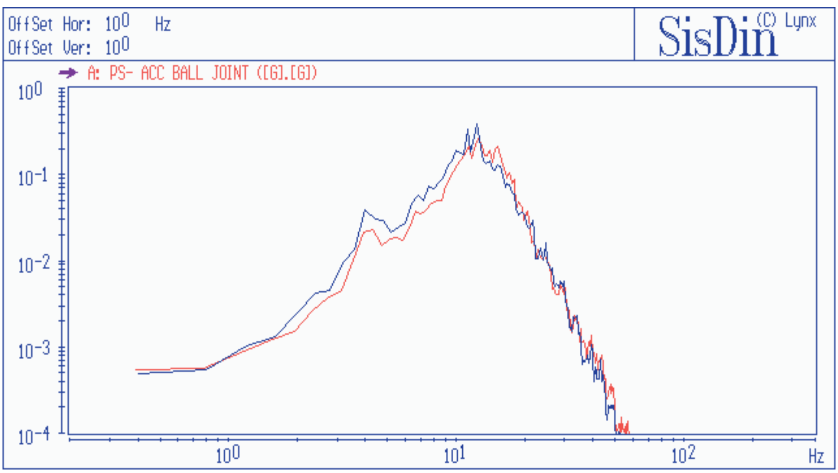


Figure 4.15. *Small vehicle front suspension control arm ball joint acceleration time history (a) frequency spectrum (b) red: measured, blue: simulation. Vilela & Gueler [67]*

Another approach to take into account a certain permissible amount of pre-stress during the assembly is to design the structure with a pre-determined margin of safety over the desired durability performance – this approach has the drawback of leading for non-optimized designs in terms of mass (and the consequent costs);

A software capable of calculating the correct durability loading environment for a specific vehicle must be used, taking into consideration the durability environment desired for a specific project (road profiles and desired mileage) and the vehicle dynamic characteristics (masses, inertias and suspension set-up).

This part of the CAE process is crucial, as the required accuracy for the loads in the fatigue calculation is high, usually with only 2% to 3% error margin allowed to allow a durability performance evaluation with less than 20 % difference to the physical test results. The VPG (Virtual Proving Ground – Vilela and Gueler [67]) software performs this task at GMB, and an example of the loads correlation obtained is shown in Figure 4.15.

The dynamic loads calculated for the vehicle need to be combined with the FE stresses for the structure in order to calculate the fatigue damage for a specific point.

VPG is used to combine these dynamic loads with the FE stresses to produce stress time histories that are analysed through the rain flow method and the cumulated damage is computed for each critical point of the structure, being related to the material fatigue properties selected for that point (spot weld fatigue curve adjusted by the assembly induced pre-stress for example).

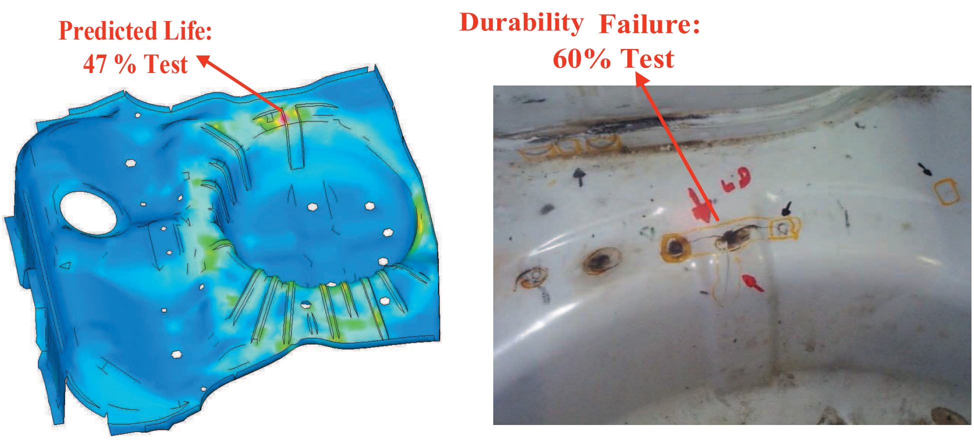


Figure 4.16. *Correlation between simulation and durability test for a rear floor region under development (Vilela and Gueler [67])*

The final information for the analyst engineer is then summarized in terms of "lives" for the durability procedure run. An example of correlation of this process is show in Figure 4.16.

Using these CAE tools, it is possible to predict the structural fatigue performance for the spot welds. When a performance lower than desired is obtained with this process, it is possible to propose the necessary adjustments before or simultaneously to the tooling development, avoiding additional costs at the vehicle validation phase. On the other hand, if the observed durability performance is much higher than the project requirement for its life cycle, there is an opportunity for cost reduction in the project without penalties to the final customer in terms of product quality.

4.7. Conclusions

This chapter has reviewed the aspects related to the spot weld design aiming the fatigue durability performance through the use of the FEA, DFMA and Design for Lice Cycle methodologies.

It has been seen that, although an interesting option of welding joint for the current automated manufacturing/assembly plants, the spot welds have inferior mechanical properties compared to other welding options and this characteristic needs to be considered in order to achieve a good design with the necessary quality for the final customer. The mechanical properties of the spot welds have been reviewed, including the effects of the excessive indentation and assembly misalignment induced pre-stresses in the weld performance.

The FE analysis is a powerful tool in stress determination in structural elements, allowing the determination of the variation in time of stress found in complex geometries. Besides, the current results of the FE analysis were, at least qualitatively, experimentally proved. After that, the durability performance evaluation through the use of CAE methods has been described, and the some examples from GMB current practice were shown.

Finally, the application of the DFMA and Design for Life Cycle methodologies specially aimed to improve the spot weld design on automotive applications has been discussed, point important best practices in this regard. Based on all the exposed points, it is expected that a spot weld design that follows the DFMA and Design for Life Cycle methodologies will certainly have the benefit of achieving a good compromise in terms of product quality for the final customer, allied to a higher productivity in the assembly plant and lower time-to-market for new projects that will ultimately mean lower costs and more competitive products in the market.