Fatigue testing of welded joints with special consideration of component geometry

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Abstract: The development of new steel grades and their application in automotive industry demands more than the knowledge of base material characteristics, although knowledge of joining properties is essential because the customer requires a proof of compatibility for his whole process chain. Besides properties established under quasistatic loads, the knowledge of the strength of components under fatigue loads is relevant for component design. But the properties of components cannot be predicted by testing standardized specimens due to their complex geometries and different kinds of service loads. To simplify the transfer of results from laboratory scale tests to components it is necessary to use component-type specimens. The contribution at hand shows the development of a component type specimen to test materials for chassis components, which is closely designed to meet the geometry of a real component. After that, results of test series with the introduced specimen geometry will be shown and compared to results achieved with standard specimens. To be able to explain the differences of the results of both specimen geometries, FE-calculations will be performed to identify the stress distribution under tensile loads for each specimen geometry. The stress distribution will afterwards be compared with the location of first damages and possible optimisations will be presented.
Keywords: fatigue tests, component type specimens, assembly type specimens, hot rolled strip, chassis components

Introduction and motivation

Handling characteristic is one of the main sales pitches for cars. To achieve characteristics, which evoke the costumer’s enthusiasm, the chassis components are one of the key features. But not only the driving pleasure, but also safety of cars is mainly related to the quality of chassis. Therefore, a lot of efforts have to be invested in the development of chassis and extensive testing is necessary, until a new chassis is released. It becomes evident that the choice of materials for chassis components is a responsible task and has to be done carefully. Chassis components are mainly made of steel and aluminium. To substitute known steel grades with new developments, it has to be ensured that the new material fits to already existing process chains and that the usage properties of the materials match all requirements. As fatigue is an important factor, tests performed only with the base material, are not sufficient. The contribution at hand will show the differences in using standardized specimen geometries and the differences which may occur when component type specimens are used.

Determination of properties using standard samples

If new steel grades are in development, mechanical properties have to be determined to estimate, if these steel grades will have the potential to enter the market successfully. The first tests, which are already performed after the first trial melts are made, are in most cases tensile tests with dog-bone specimens. In these tests, basic properties like yield strength, tensile strength and ultimate strain are determined. These properties will then be used to perform first benchmarks with the requirements and already existing steel grades. An example of such a comparison is shown in the figure below, where results from steel grades are shown, which are often used in chassis components (Figure 1). These steel grades are the hot-rolled steels S355MC, an air-hardening steel in initial and air-hardened state and a bainitic steel.

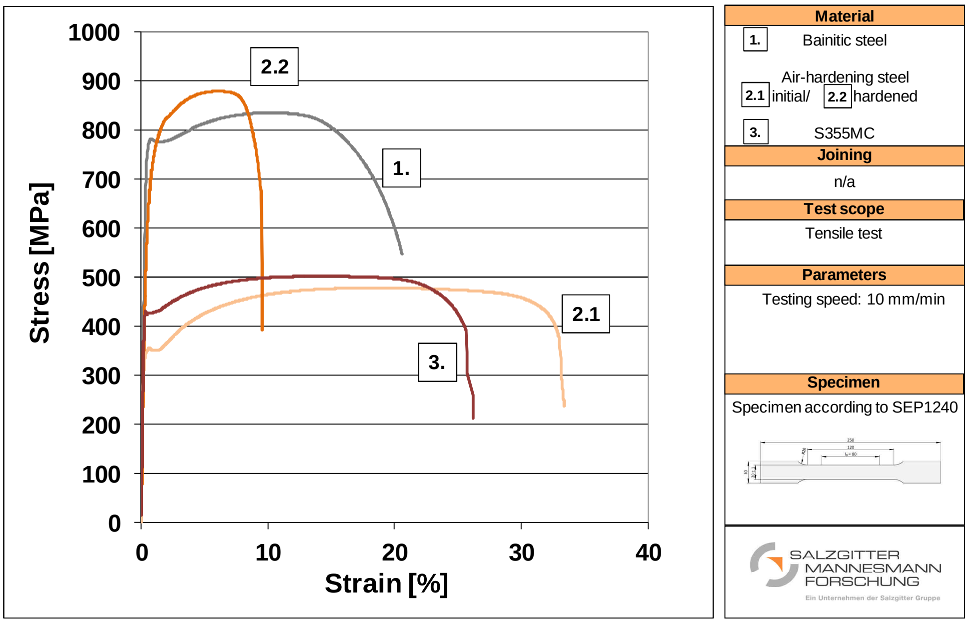

Figure 1: Stress strain curves of hot rolled steels: S355MC, air-hardening steel (initial state and air-hardened state) steel and bainitic steel

One can clearly see that the bainitic steel has a high tensile strength compared to the air-hardened steel, by comparable ultimate strain at the same time. The potential of these steel grades becomes clear in comparison with a conventional steel S355MC. For design engineers and computational engineers, these properties can only be a first indication to estimate the suitability for a certain application. For them, the properties under dynamic loadings are even more important, as for engineering in general, moving masses are expected to be the rule rather than the exception. In addition, components in real applications are often welded.

To be able to show the influence of welding on the properties of steels, the approach to compare welded samples made from different steel grades seems obvious. To make a first assessment it seems to be sufficient to choose a simple specimen geometry to keep the initial expenses small. To estimate the usage properties and with it the properties under fatigue of steel grades with regards to joining, SEP1220-5 offers a standardized procedure for gas metal arc welding. After the welding process the specimen is cut into smaller specimens with a width of 45 mm. After specimen preparation fatigue tests shall be performed using 10 specimens according to ISO 18592. The tests are performed at room temperature. The results given were prepared with each specimen tested with different load

amplitudes. The load ration R is defined as 0.1. As abort criteria a decreasing testing frequency of 0.3 Hz or reaching a number of cycles of N = $2 \cdot 10^6$ was chosen, depending on what criterion was reached first.
That the described approach does not deliver significant results will become evident, if one considers the results in Figure 2 and the fracture patterns in Figure 3.

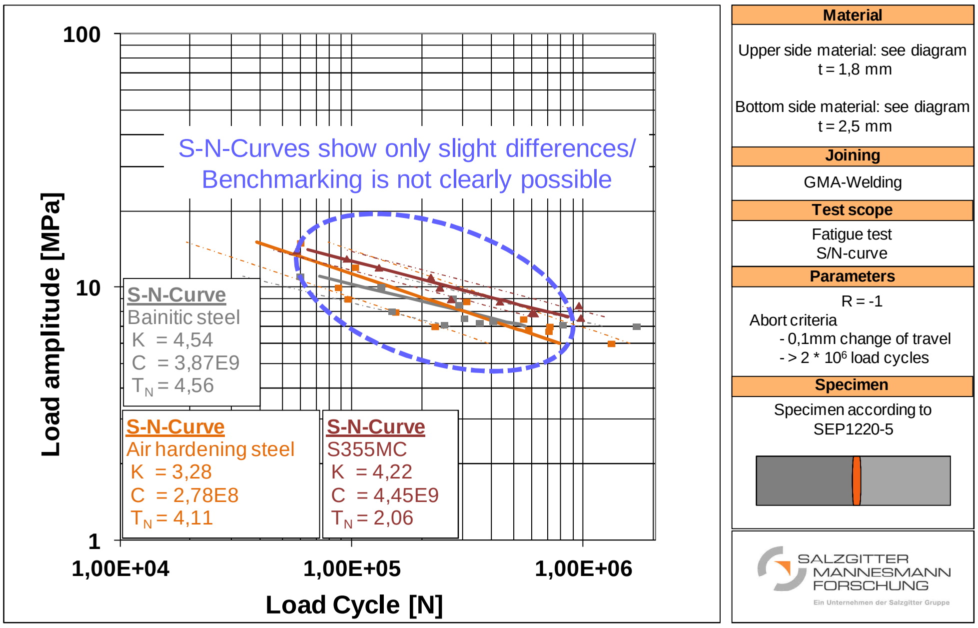

Figure 2: Fatigue strength of different steel grades welded according SEP1220-5

The figure shows the fatigue strength of the three hot rolled steel grades, which were already discussed above, as welded joints. Due to the scattering, comparable inclinations of the fatigue curves and comparable stress-levels, a differentiation between the steel grades is hardly possible. Looking at fracture patterns does not allow a differentiation as well.

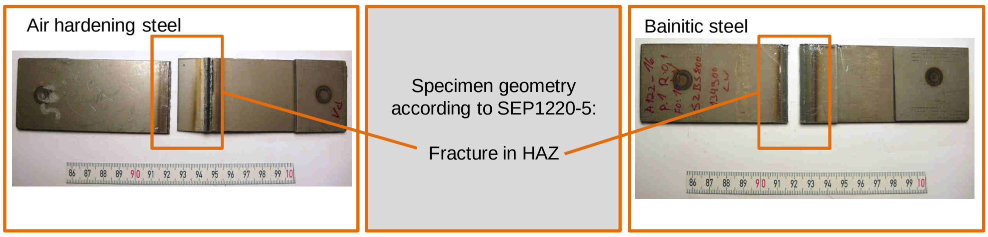

Figure 3: Fracture patterns of air hardening steel and bainitic steel after fatigue tests; joining technology MAG-welding

All specimens from all steel grades show a failure in the heat affected zone of the weld on the side of the sheet metal with the lowest sheet thickness. Here, a metallurgical notch with a coarse grain can be found. As the results show, this metallurgical notch has a higher influence on the fatigue strength as the strength of the base material. The positive properties of the bainitic steel and the air-hardened steel, which could be turned out by testing the base materials, cannot be seen in welded joints. Therefore, this approach proofs not to be suitable for a qualified material choice for a specific application with complex geometries and loadings. With regards to fatigue strength calculations this becomes even truer.

Development of a component type specimen

To be able to perform tests resembling the situation in chassis components and to be able to perform calculations using a local concept, it is of importance to be able to determine local stresses on a specimen, which are comparable to those stresses appearing on real components. This cannot be done using a simple overlapped specimen, because here only shear stresses will be applied to the materials and weld seams and no complex loadings. Therefore, to be able to simplify the determination of input parameters for fatigue life calculations, the BMW group developed a component type specimen which was derived from the geometry of a chassis frame (Figure 4) [1]:

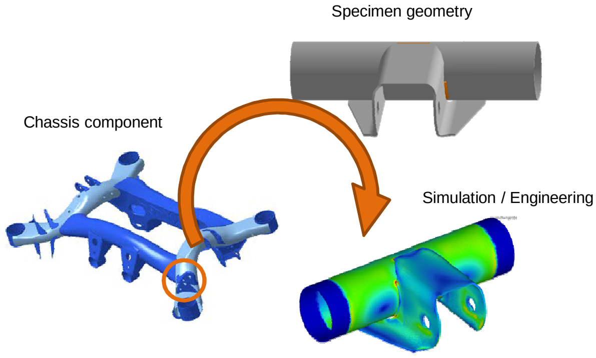

Figure 4: Development of a component type specimen, which can be used for determination of input parameters for fatigue life calculations [2]

The specimen consists of a pipe and a flange, which is longitudinally welded to the pipe. The ends of the pipe will be fixed during testing, whereas the cyclic load will be applied to the flange of the specimen. Five weld seams connect flange and pipe. Three of the weld seams are orientated in a longitudinal direction to the pipe, whereas two weld seams are orientated circumferential. Using this weld seam setup, different stress conditions and stress distributions can be assessed using one specimen and complex loading situations can be simulated.

Test setup and results for component type specimens

The specimen itself is clamped into a clamping device. The cyclic load is applied to the flange and then transferred by the weld seams to the pipe. The test will be performed force-controlled with a force ratio R = 0.1. As abort criteria a change of punch travel of Δt = 0.1 mm was chosen or reaching a number of cycles of $N = 2 \cdot 10^6$, depending on what criterion was reached first. For the tests, three specimens were tested on five load levels. The S-N-curves can be seen in the figure depicted below (Figure 5).

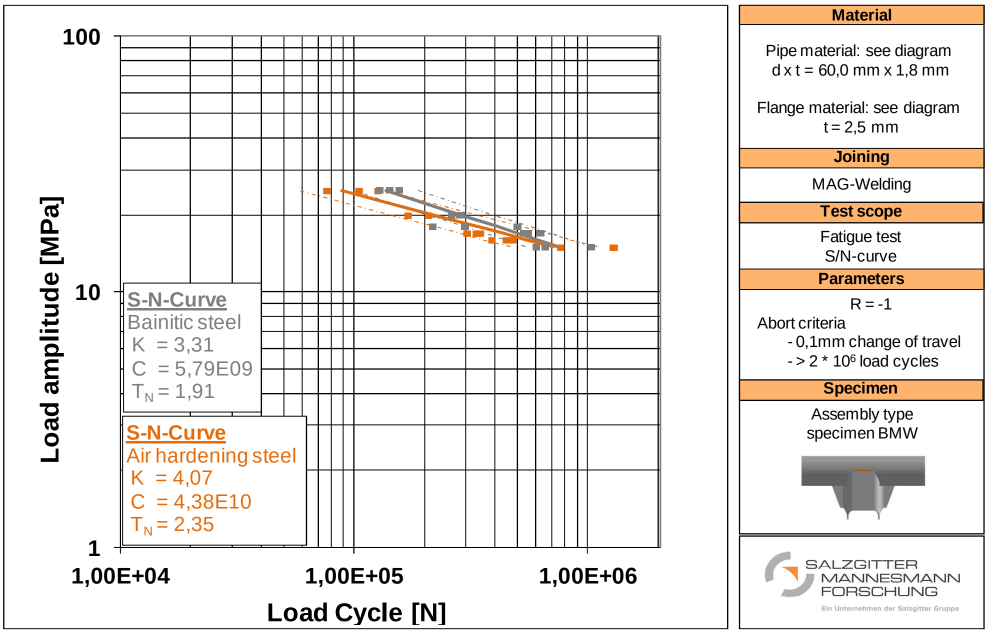

Figure 5: Comparison of fatigue strength of component type specimens made from different steel grades and aluminium

One can see that the S-N-curves of specimens made from air-hardened steel show an exponent k = 3.7, what is similar to the exponent of the S-N-curve of the bainitic steel, which has a value k = 3.3. Using load amplitudes which lead to a failure of the specimens near to low cycle fatigue, the bainitic steels shows slightly higher load cycles until failure. But comparing the results at lower load amplitudes, close to the abort criterion of $N = 2{\cdot}10^6$ and taking into account the scattering of the results, both steel grades are able to reach comparable load cycles.

Looking at the appearances of fracture confirms the results mentioned above (Figure 6).

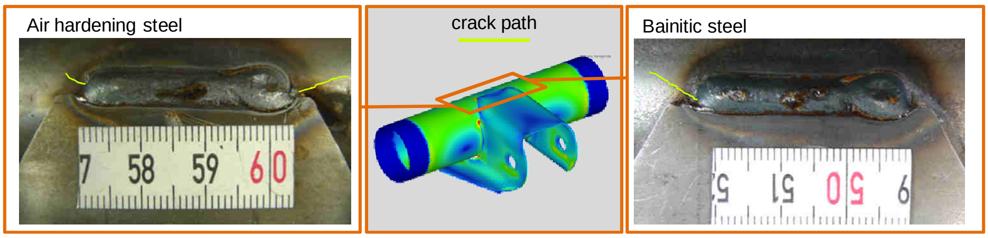

Figure 6: Fracture patterns of air hardening steel and bainitic steel after fatigue tests using component type specimens (upper weld seam); joining technology MAG-welding

Regardless of the used steel grade, the failure starts always in the area of the metallurgical and geometrical notch at the end or the beginning of the weld seam. In addition, one can see cracking at the bottom side of the specimens, starting from the notch at the end of the weld seam and propagating into the flange material (Figure 7).

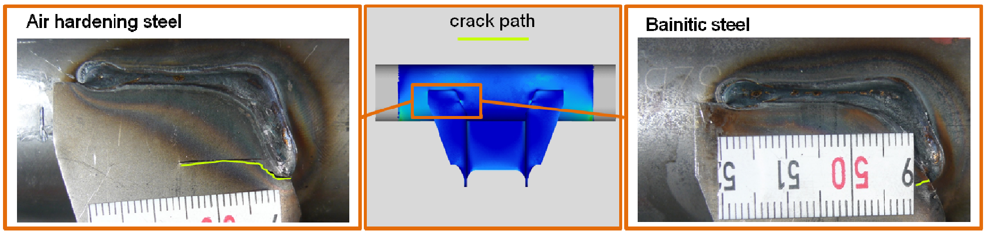

Figure 7: Fracture patterns of air hardening steel and bainitic steel after fatigue tests using component type specimens (upper weld seam); joining technology MAG-welding

The analysis of the fracture patterns shows that the influence of the base material is negligible compared to the influences of welding. The positive potential which could be shown on the base material cannot be transferred into component properties. Therefore, it has to be the aim to adjust the welding processes and the joint geometries in a way, so that the positive properties of the steel grades become visible. To be able to perform optimisations, the knowledge of stress distributions is important. Thus, FE-calculations were performed.

Visualisation of stress distribution and optimization using FEM

Basing on the results shown above and after the discussion of the fracture patterns, simulations with the method of finite elements were performed to be able to analyse the stress distribution in the pipes and into the weld seem. Aim of these investigations was to determine whether it will be possible to identify weak points of the specimens and if corrective measures can be derived.
The simulations were done with the software ANSYS Mechanical 17.1. An isotropic elastic-plastic material model and tetraeder elements type 187 with midside nodes were used. To achieve an adequate weld seam geometry, they were modelled according to the geometries of the experimentally welded specimens and meshed with an element size down to 0.1 mm. The applied load of 20 kN was applied in tension and compression direction and was realistically transferred only by the weld seam cross-sections. The ends of the tube were fixed according to the experiment. The weld seams were modelled without heat influence like heat affected zones and therefore have the same material properties like the base material properties. Below one can see the evaluations of the simulation of the component type specimen (Figure 8). The analysis of the stresses show that the highest compressive stresses occur on the upper weld seam and, to be more precise, at the notch at the beginning and end of the weld seam in the pipe sided heat effected zone. Comparably, the compressive stresses on the flanges of the bottom side and the side seams of the specimen are low. If one compares the compressive stresses with the tensile stresses, one can see that the areas with the highest stresses are the notches at the beginning and at the end of the weld seams, too. But, looking at the upper side of the specimen, the tensile stresses here are much higher than the stresses under compression. The stresses in the flanges on the bottom side of the specimens and in the side seams are significant higher then under compression as well. A comparison of the stresses in the pipe and in the flange itself with the stresses in the area of the notches shows that these stresses are clearly lower. This domination of thermal notches and material notches related to the welding process shows clearly that the full potential of new steel grade developments can only be used, if the boundary conditions are adjusted properly.

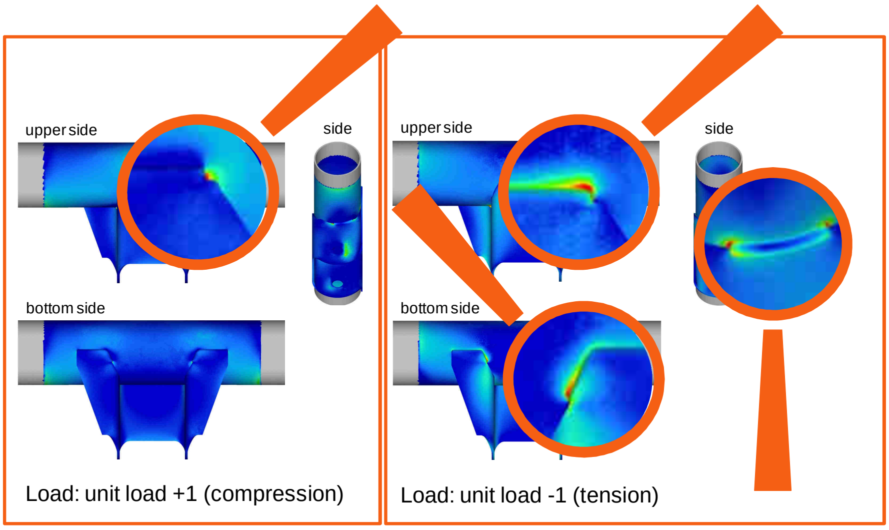

Figure 8: Simulation of stress distribution of welded component type specimen

This means that the design of components has to be adjusted to the characteristics of specific steel materials and that it is not appropriate only to substitute existing materials by new ones. One approach may be to move the notches, on which the stress concentrations occur, in areas of the specimen, where they can be assumed as not critical. The next picture shows such an approach (Figure 9).

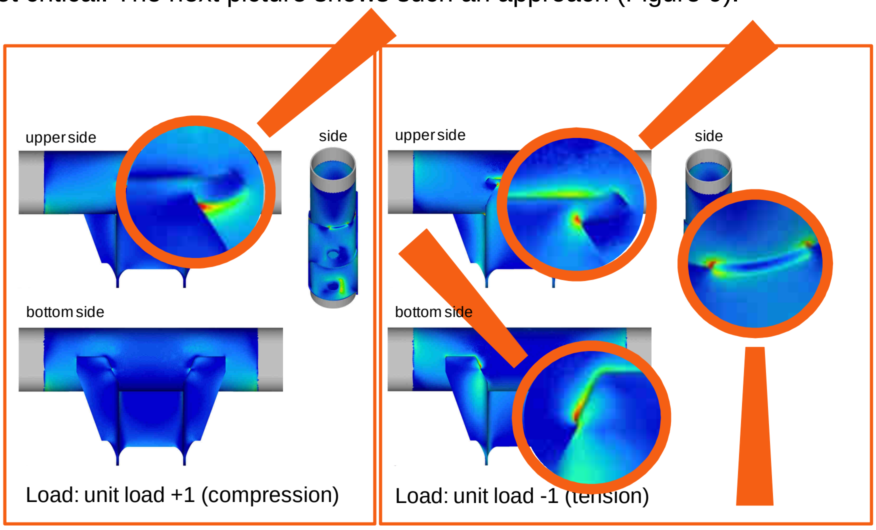

Figure 9: Simulation of stress distribution of component type specimen after fitting of upper weld seam

In this approach, the upper weld seam was elongated with a curved shape to both sides. The aim of this strategy was to move the notches of the heat affected zone and the weld seam start and end in areas of the pipe, where the first simulations turned out stresses under compression and tension are low. By analysing the stresses in the optimised specimen, it is obvious that under compression, the stresses on the upper side and bottom side of the specimen are comparably high

like the stresses in the not optimized specimen. As in those areas no cracks appeared in the cyclic loading tests, it can be assumed that these areas are not critical. Under tension loads one can see that on the upper side of the specimen, the stress concentrations on the pipe side could be significantly reduced in the areas, where cracks appeared in the tests. On the other hand, stress concentrations appeared on the flange side of the weld seam, which were not seen before. As these concentrations are now in the material with a thickness of 2.5 mm, it can be assumed that they will not negatively influence the results of the fatigue tests. The stress distribution in the weld seams of the flange on the bottom side of the specimen is not influenced and stays on the same level as shown with the not optimised specimens.
The chosen approach shows that notches, which are hindering the use of the full potential of new steel grades, can be avoided by adjusting and optimising existing designs. As these optimisations were only done in simulations at the moment, further experiments will have to deliver the proof of concept.

Conclusion

New steel developments are often significantly superior to conventional steel grades. This makes them predestined for new applications. In case of chassis components, bainitic and air-hardening steels show significantly better properties in quasistatic tests and in tensile tests, if one compares the base material properties. This superiority becomes void, if one compares the properties of welded joints using single overlapped specimens. Trying to prove the beneficial properties of new steel grades, test setups have to be used, which allow to represent real conditions on components on the one hand and on the other hand the determination of properties, which can be used for fatigue life calculations, has to be feasible. The BMW group developed a specimen, which is able to achieve these two requirements. But results in fatigue tests show that a differentiation of different steel grades is hardly possible, because the influence of thermal and metallurgical notches, caused by welding, predominate the positive effects of the base material properties. This could be successfully shown by FE-simulations. By analysing the stress distribution in component type specimens, one was able to derive optimisations, which turned out to reduce stress peaks and, therefore, possibly are able to strengthen the positive influence of the base materials. The paper at hand shows that it is not sufficient to just substitute one steel grade by another. The components geometries have to be adjusted in a way that new developed steel grades can show their strength. The derived strategies now have to proof their suitability in further fatigue tests.

Acknowledgement

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