Numerical analyses on welded joints at high-strength steels
Richard Stroetmann*, Thoralf Kästner
Technische Universität Dresden, Institute of Steel and Timber Construction, Germany
Richard.Stroetmann@tu-dresden.de, Thoralf.Kaestner@tu-dresden.de

ABSTRACT
The numerical modelling of welds requires profound knowledge due to the material and the geometric heterogeneity. Microstructural changes in the heat-affected zone lead to local changes in the mechanical properties that can affect the load bearing and deformation behaviour. The necessary material laws can be determined both experimentally and mathematically. For a more precise consideration of the deformation capacity and the softening material behaviour, it may also be necessary to consider damage-mechanical material models. Numerical calculations of experimental tests to determine the mechanical properties of welds are used to investigate these aspects.

Keywords: Welds, high-strength steels, numerical analysis, material modelling

1 INTRODUCTION
In order to evaluate the load bearing and deformation behaviour of welded joints with numerical calculations, detailed knowledge of the geometry and local mechanical properties of the weld metal, the heat-affected zone and the base material is required. Of particular interest are the execution parameters of the weld, which have a significant influence on the microstructure and thus on the mechanical properties (cf. (1)). Especially in the heat-affected zone, the local mechanical properties differ considerably from those of the base metal, depending on the peak temperature attained. Within the framework of the numerical recalculation of experimental tests for the determination of the mechanical properties of welded joints, various aspects regarding the material and geometry modelling of welded joints are discussed. Furthermore, a new test specimen for the determination of the mechanical properties of welds is presented.

2 METHODS OF EXPERIMENTAL EXAMINATIONS OF WELDED JOINTS

2.1 Test specimen for the examination of the mechanical properties of welds
As part of the AiF-FOSTA research project P1020, the two thermomechanically rolled steels S500ML according to EN 10025-4 and S700MC according to EN 10149-2 as well as the two quenched fine grain steels S690QL and S960QL according to EN 10025-6 were selected for experimental investigations. All materials were supplied with a plate thickness of 20 mm. The choice of the filler metals depends on the mechanical properties of the base metals. The focus of the examinations was on undermatching welds. The solid wire electrodes G35 and G42 according to EN ISO 14341 as well as G62, G79 and G89 according to EN ISO 16834 were used for metal active gas welding.
In order to determine the mechanical properties of the welds, a test specimen was developed as part of a comparative test based on EN ISO 14341 as well as G62, G79 and G89 according to EN ISO 16834 were used for metal active gas welding. In order to determine the mechanical properties of the welds, a test specimen was developed as part of a comparative test based on EN ISO 14341 as well as G62, G79 and G89 according to EN ISO 16834 were used for metal active gas welding. In order to determine the mechanical properties of the welds, a test specimen was developed as part of a comparative test based on EN ISO 14341 as well as G62, G79 and G89 according to EN ISO 16834 were used for metal active gas welding.
the selected specimen contour and thickness, the force-transmitting weld area is defined. Figure 1 shows a schematic representation of the specimen and the measuring range before and after the test.

![Schematic representation of the specimen geometry (left) and the test area before and after the test (right)](image)

To determine the mean stresses in the weld $\sigma_w$, the machine force $F$ is divided by the net cross-sectional area $S_0$ in the unloaded state (see equation 1). The mean strains $\varepsilon_w$ in the measuring range are determined as the ratio of the elongation $\Delta L$ at the time of evaluation to the initial measuring length $L_0$ (cf. equation 2). Yield strength and tensile strength of the weld were determined in accordance with EN ISO 6892-1.

$$\sigma_w = \frac{F}{S_0} \quad (1)$$

$$\varepsilon_w = \frac{\Delta L}{L_0} \quad (2)$$

The welds were produced in a specially designed test stand consisting of a six-axis welding robot and a synchronized rotating table. For reasons of comparability, the electrical power of the welding process was chosen to be approximately constant for all tests. The adjustment of the specified cooling times $t_{8/5}$ was achieved by modifying the welding speed and the preheating temperature. In the tests specimens with the dimensions $b_0 = 15 \text{ mm}$, $t = 5 \text{ mm}$ and $d = 5 \text{ mm}$ and a weld opening angle of $90^\circ$ were examined. The selected measuring length was $L_0 = 25 \text{ mm}$. The tests were carried out displacement controlled with a displacement rate of $0.5 \text{ mm/min}$.

### 2.2 Accompanying studies to determine local mechanical properties

The welding process induces an energy input in the base metal, resulting in microstructural transformations in the heat-affected zone that can significantly alter the mechanical properties. To determine the local mechanical properties of welded joints, miniature tensile specimens were taken from selected weld metals and heat-affected zones as well as from the base metals. The sampling positions were defined based on macro-sections of the welded joints. This is shown schematically in Fig. 2.

![Fig. 2. Positions of the miniature tensile specimens (left and centre); Miniature tensile specimen after testing (right)](image)
During the preparation of the specimens, care was taken to ensure low heating in order to avoid the occurrence of secondary crystallization processes. The specimens were produced with a width of \( b_0 = 3 \) mm and a thickness of \( t = 1.5 \) mm in the test area. The test was carried out with a displacement rate of 0.5 mm/min. Fig. 2 shows a specimen after the test.

In addition to the described experiments, dilatometer tests were carried out at the TU Chemnitz. The base metal samples are subjected to a temperature-time cycle based on MSG-welding, which can be specifically adjusted via the peak temperature \( T_{\text{max}} \) and the cooling time \( t_{8/5} \). The individual areas of the HAZ can thus be examined with regard to the changes in the mechanical properties. Five peak temperatures \( T_{\text{max}} \) in the range from 600 to 1350 °C with seven cooling times \( t_{8/5} \) from 1.5 to 25 s were examined. The dimensions of the dilatometer specimens in the test area are identical to those of the miniature tensile specimens, so that the results can be compared.

3 NUMERICAL MODEL OF THE WELDED TEST SPECIMEN

Before the numerical models were created, the weld geometries were determined. Systematic measurements of the welds were carried out for various structural boundary conditions and execution parameters. For this purpose, macro-sections were produced and digitized. For the butt welds of the test specimen, 20 levels were introduced from the upper edge of the base metal in the direction of the plate thickness with a distance of 1 mm each. Using these, the width of the weld metal was measured (Fig. 3). Subsequently, the mean widths of the individual levels in the respective population were determined. Assuming a weld that is symmetrical in the longitudinal and transverse directions of the weld, the result obtained are 10 coordinates that are used to define the geometry. A linear course was assumed between these coordinates. Fig. 3 shows an example of the measurement of a weld cross section. For the measurement of the areas of the HAZ having a transformed microstructure, additional differentiation was made with respect to the examined base metals. The subdivision of the HAZ into the areas coarse-grain zone (1350°C > \( T_{\text{max}} \) > 1100°C), fine-grain zone (1100°C > \( T_{\text{max}} \) > 900°C) and intercritical zone (900°C > \( T_{\text{max}} \) > 700°C) was carried out. The proportions of the respective zones in the total width were determined using the Rosenthal heat conduction equation. Based on the defined temperature intervals, the proportions of coarse-grain zone were determined to 31 %, fine-grain zone to 26 % and intercritical zone to 43 % of the HAZ. The specimens in the dilatometer were subjected to only one welding cycle. The consideration of further thermal influences on the HAZ by multi-layer welding was not taken into account in the modelling. The geometry model was meshed with 20-node solid elements with a quadratic trail function. Each node has three degrees of freedom in the \( x \), \( y \) and \( z \) direction. Due to the complex geometry of the welds, the model was meshed with the tetrahedral modification of the used element (Fig. 3).

![Fig. 3. Measurement of a weld cross section (left); Meshing of a weld (right) with the areas base metal (blue), intercritical zone (yellow), fine-grain zone (green), coarse-grain zone (orange) and weld metal (violet)](image-url)
The flow functions of the materials were determined based on the miniature tensile and dilatometer tests carried out. A modulus of elasticity of 210,000 N/mm² was determined for the linear-elastic range of the flow functions and a Poisson's ratio of 0.3 was defined for all ranges. The determination of the true stresses ($\sigma_T$) and true strains ($\phi$) from the test data was carried out in accordance with equations 3 and 4 until the uniform strain, which represents the upper limit of the range of definition of the functions, was reached.

$$\sigma_T(\varepsilon) = (1 + \varepsilon) \cdot \sigma$$  \hspace{1cm} (3)

$$\phi(\varepsilon) = \ln(1 + \varepsilon)$$  \hspace{1cm} (4)

To consider larger strain ranges, the flow function is extrapolated using the Hollomon equation (equation 4). The constants $k_H$ and $n_H$, to be determined are material-specific characteristic values. Accordingly (4), the Hollomon flow function can be described as a straight line in a double-logarithmic diagram. The gradient of the straight line describes the constant $n_H$, the intersection with the $y$-axis the constant $k_H$. The strain range for the determination of the Hollomon constants was determined for the examined materials by comparative calculations. Starting from the uniform strain, this range lies from 0.1 to 1 % in negative coordinate direction. The necessity of a differentiation of the strain ranges results from the differently distinctive hardening behaviour.

To extend the parameter range examined with miniature tensile specimens, the Hollomon constants were determined on the basis of the weld yield strengths $f_{wy}$, which were determined within the scope of the investigation of the mechanical properties of the weld, using the equations of Eichler (5) (cf. equations 6 and 7).

$$\sigma_T(\phi) = k_H \cdot \phi^{n_H}$$  \hspace{1cm} (5)

$$n_H(f_{wy}) = -0.1897 \cdot 10^{-3} \cdot f_{wy} + 0.2291$$  \hspace{1cm} (6)

$$k_H(f_{wy}) = 0.7206 \cdot f_{wy} + 553$$  \hspace{1cm} (7)

In order to consider the softening material behaviour, the damage mechanical model according to Gurson (6) with the extensions of Tvergaard and Needleman (7) (GTN model) was used. This model represents an extension of the plasticity theory in which the von-Mises flow criterion is modified as a function of the void volume fraction. With this material model, it is possible to consider the influence of void fraction as well as void growth and void coalescence as processes of ductile failure on the load-bearing and especially deformation behaviour. The input variables for the GTN model are determined by metallographic investigations as well as numerical unit cell and comparative calculations.

## 4 COMPARISON OF THE NUMERICAL RESULTS WITH EXPERIMENTAL TESTS

For comparison of the results of numerical simulations with experimental tests, a quarter of the flat tensile specimen (Fig. 1) was modelled. The applied symmetry boundary conditions are shown in Fig. 4. In the area of the load application (red frame), the displacements in $y$ and $z$ direction were set to zero. The load was applied by a displacement $v$ in $x$-direction. From this, the reaction force was calculated, which was used to determine the mean stress in the net cross-section (see equation 2). The strain was determined analogously to equation 3 using the relative displacements in the measuring range. The measuring points for determining the relative displacement were selected analogously to the measurements in the experiments. The stress-strain curves of the numerical models are therefore integral characteristic curves. The results of three tests for the material combination S690QL-G42 with a cooling time $t_{8/5}$ of 12 seconds and an opening angle of $90^\circ$ are plotted as solid lines in the stress-strain diagram in Fig. 5. These are compared with the results of the numerical calculation using the experimentally determined flow function, the flow function calculated according to Eichler’s equations and the experimental flow function with the GTN model.
When using the experimentally determined flow function, a very good agreement of the stress-strain curve is achieved until the fracture strain is reached. Due to the neglect of the softening material behaviour, an ideal plastic material behaviour is formed locally with increasing deformation. For strains above the elongation at break, there is no affinity between the experimentally determined and the numerical re-calculated stress-strain curves.

Using the GTN model, a porosity is calculated for each element as well as the associated softening. Until the uniform strain is reached, the numerical simulations without and with the GTN model show only small differences in the load-bearing and deformation behaviour. This is due to the low proportion of primary voids in the matrix material. With increasing deformation, however, the affinity of the progressions decreases, since the influence of element porosity due to void growth and the formation of secondary voids becomes more important. In the area of elongation at break of the experimentally determined stress-strain curves, numerical simulation with the GTN model does not achieve any convergence. The numerically determined course ends there. This is in good agreement with the experimentally determined stress-strain curves, since from this point, a strong drop of the mean stress occurs and the fracture occurs continuously in the deformation-controlled test.

The calculation results with the *Eichler* flow function show good agreement of the load-bearing and deformation behaviour with the tests up to elongation at break. However, the load-bearing capacity is slightly overestimated. In the present study, the deviation is 4.6 %. The reason for this is the use of the experimentally determined weld yield strength \( f_{\text{wy}} \) and the influence of the specimen geometry on this value. Numerical calculations with other material combinations and cooling times \( t_{8.5} \) also show a slight excess strength of the models with the *Eichler* flow function. These are systematic deviations, since the weld strength is determined in the experiment under the notch effect of the central hole and...
the associated three-dimensional stress condition. This fact can be taken into account by a corresponding correction of the weld yield strength $f_{wy}$ from the flat tensile tests, so that the use of these flow functions for parameter studies by numerical simulations is possible in good approximation.

5 SUMMARY, OUTLOOK AND ACKNOWLEDGMENT

The load-bearing and deformation behaviour of welds is influenced in many ways. For numerical calculations, comprehensive knowledge of the weld geometry and the mechanical properties of the individual areas of the weld is therefore required. While a realistic representation of the geometry can be carried out based on the measurement of macro-sections, it should be noted when determining the local mechanical properties that these can only be determined in the form of integral values. The execution of dilatometer tests offers a possibility to examine the different mechanical properties of the areas of the HAZ and to derive flow functions.

With the application of the *Hollomon* function, very good results could be achieved with the load-bearing behaviour of the presented, experimentally examined welds. The consideration of the deforming material behaviour with the GTN model led to a very good description of the deformation behaviour in the area of the elongation at break.

The use of the flow function with the calculation approaches according to *Eichler* based on the experimentally determined weld yield strengths also provided good agreement with the test results. Within the scope of the re-calculations, a low systematic over-strength was determined, which is attributable to the specimen geometry. However, with a corresponding correction by $f_{wy}$, it is still possible to carry out parameter studies with these flow functions.

In addition to the presented test re-calculations, parameter studies at transverse and longitudinal fillet welds are currently being carried out as part of the ongoing AiF-FOSTA P1020 research project in order to expand the parameter space examined experimentally. The results of these studies are used to calibrate a new design model for welded joints of high-strength steels (cf. (1)).

The IGF project 19043 BR/P1020 “Economic welding of high-strength steels” of FOSTA – Forschungsvereinigung Stahlanwendung e.V., Düsseldorf, is promoted within the programme for the promotion of Industrielle Gemeinschaftsforschung (iGF), funded by the Federal Ministry of Economics and Energy on the basis of a resolution by the German Parliament. The authors of this paper are very grateful for this funding and would like to thank all the industry partners. In addition, thanks to the Centre for Information Services and High Performance Computing (Zentrum für Informationsdienste und Hochleistungsrechnen) of the TU Dresden for the generous provision of computing power.

REFERENCES

1. Stroetmann, Richard et. al., 2018. Welds for high-strength steels – Development of new design rules. In: 40th IABSE Symposium – Tomorrow’s Megastructures. Nantes, 19.-21. September 2018. Zürich: IABSE. pp. S29-57 – S29-64.
2. EN ISO 6892-1. Metallic materials – Tensile testing – Part 1: Method of test at room temperature. Issue 2009-12.
3. EN ISO 4136. Destructive tests on welds in metallic materials– Transverse tensile test. Issue 2013-02.
4. Münstermann, Sebastian, 2006. Numerische Beschreibung des duktilen Versagensverhaltens von hochfesten Baustählen unter Berücksichtigung der Mikrostruktur [Dissertation]. RWTH Aachen. Aachen: Shaker Verlag.
5. Eichler, Björn, 2015. Hochlagenorientierte Werkstoffgütewahl für die plastische Bemessung von Stahlbauteilen [Dissertation]. RWTH Aachen. Aachen: Shaker Verlag.
6. Gurson, A. L., 1977. Continuum Theory of Ductile Rupture by Void Nucleation and Growth – Part I – Yield Criteria and Flow Rules for Porous Ductile Media. Journal of Engineering Materials and Technology.
7. Needleman, A., Tvergaard, V., 1984. An Analysis of Ductile Rupture in Notched Bars In: Journal of the Mechanics and Physics of Solids 36(6), pp. 461–490.