Investigations of stress state in cracked steel specimens and wide plates containing laser beam welds

J. Heyer and P. Langenberg* and W. Dahl

Department of Ferrous Metallurgy, RWTH University of Technology Aachen, Germany

ABSTRACT: *The results of combined experimental investigations and 3D-FE analysis on pre-cracked fracture mechanics steel specimens and wide plates with overmatching laser beam weldments (LBW) under quasi-static loading will be presented. From fracture mechanics experiments the crack initiation has been obtained. At these points stresses and strains for the loading state at crack initiation were determined in the FE analysis. Analysing the stress state, the occurring pop-ins in fracture mechanics testing in comparison to the wide plate behaviour could be explained. Further it was found that the tendency for the often observed crack path deviation in LBW is increased at higher loads. The constraint in the plate with LBW can be estimated by evaluation of the homogenous material configuration conservatively, especially for higher loads.*

INTRODUCTION

Laser beam weldments (LBW) in ferritic steels show some special features in comparison to conventional weldments. The weld is often only some few millimetres in width and the weld metal strength can be more than double of the base metal strength. If the overmatching weld contains a crack, these properties can lead under external quasistatic or dynamic loads to the often observed crack path deviation of the growing crack into the base metal. This phenomenon is most distinct in wide plates and thin fracture mechanics specimens and less in thick fracture mechanics specimens [1], [2]. The crack path deviation possibly enlarges the region of applied load of a structure when ductile crack growth is allowed, because the resulting crack path extension corresponds to a higher energy release and increases the structures resistance to fracture.

Experiments have shown a difference in the behaviour of fracture mechanics specimens and wide plates with laser beam weldments at the same

* Corresponding author: IWT Aachen, 52068 Aachen, Germany
Tel.: +49-241-9632320 Fax: +49-241-9632329
peter.langenberg@i-w-t.de

moderate test temperature (e.g. room temperature) and under quasistatic load. In fracture mechanics specimens sudden load drops (pop-in's) due to local cleavage initiation often occur, while in the wide plates no pop-in's are observed and the cracks always initiated in a ductile manner [3]. Since the only conditions that have been changed from one test to the other are specimen geometry and loading mode, the resulting stress fields in the structures should be responsible for the change in failure behaviour (constraint effect). A high constraint means a high hydrostatic stress state and can be expressed by stress triaxiality [4] as the ratio of hydrostatic stress σ_m and equivalent stress σ_v:

$$h=\sigma_m/\sigma_v \qquad (1)$$

Usually the constraint in a structural component is less than the constraint in fracture mechanics specimens, because the specimens are designed to give lower bound fracture toughness values. Though generally the fracture mechanics value for ductile crack initiation J_i was often found not or hardly to be dependent on constraint [5], the constraint gives nevertheless valuable hints concerning the failure of a structure, because it increases the risk for cleavage failure and promotes together with the plastic deformation the development of damage [6].

In the current work, the stress state in a wide plate with a laser beam weldment under an increasing load is investigated and compared with the stress state in homogenous weld and base metal plates. From these investigations conclusions are drawn concerning the constraint state. Furthermore the crack tip loading at initiation of a crack (the weldments resistance against crack initiation) is known from experimental tests on fracture mechanics specimens containing laser beam weldments performed in [3]. For this initiation state, characterised by a critical J-Integral, the stress and deformation state both in a fracture mechanics specimen and a wide plate are compared.

FINITE-ELEMENT-ANALYSIS (FEA)

The experimental tests, which are the base of the current Finite-Element-Analysis (FEA), were performed within the European Brite Euram Project ASPOW and are documented in [3]. Two different specimen geometries were investigated numerically: a compact tension C(T) specimen and a centre cracked wide plate under tension M(T). The dimensions are given in

fig. 1. Both specimen types were cut out from the same welded plate of a quenched and tempered C-Mn steel EMZ450. The thickness of the welded plate was 12mm and has been kept as specimen and wide plate thickness. The weld seam was produced by laser beam welding. In both specimen types the crack was located in the centre of the weld seam.

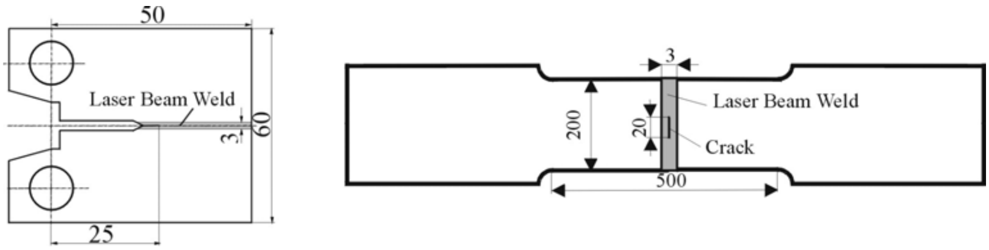

Fig. 1: Investigated geometries and their dimensions, left: C(T), right: M(T)

Resulting stress-strain-curves of base and weld metal from tensile tests (microtensile for weld metal) at room temperature served as input for the FEA. Input yield strength was 470MPa for base metal and 633MPa for weld metal, which results in a mismatch factor between both materials of 1.5 (overmatching). The base metal showed discontinuous yield behaviour in contrast to the weld metal. For both weld and base metal the same elastic properties were used: 210GPa for Young's Modulus and 0.3 for Poisson ratio.

Three-dimensional FE-models were generated. Due to symmetry only a quarter of the C(T) and an eighth of the M(T) was modelled. The weld seam was idealised as a rectangular strip with a width of 1.5mm. The FEA were performed with the FE-code ABAQUS/Standard [7]. Element type used was a 3D solid element of second order (20 nodes) with reduced integration. The crack tip was modelled with collapsed elements and was therefore infinite sharp in the initial state. The analysis was performed using second invariant flow rule (Mises) and large deformation theory.

In the experiments, the crack growth in the C(T) initiated ductile as well as cleavage (from different specimens) approximately at δ_5=0.2mm (for δ_5 definition see [8]). When this value of δ_5 was reached in the FEA, the J-Integral, stress triaxiality h and equivalent plastic strain ε_v^{pl} in the centre of the specimens (half thickness) were calculated. The stress triaxiality h was defined with equation (1). For the same critical J-Integral the local stresses and strains were determined in the M(T) plate.

RESULTS AND DISCUSSION

Fig.2 shows the force-displacement-curves of the M(T) plate with LBW from experiment [3] and FEA in comparison to FEA results for homogenous base and weld metal. In general the agreement between the 3D-FEA and the experimental curve is quite well. The overall LBW plate behaviour is similar to the base plate's, so the loading of the overmatched LBW plate can estimated by the homogenous base plate conservatively, which is recommended in [9].

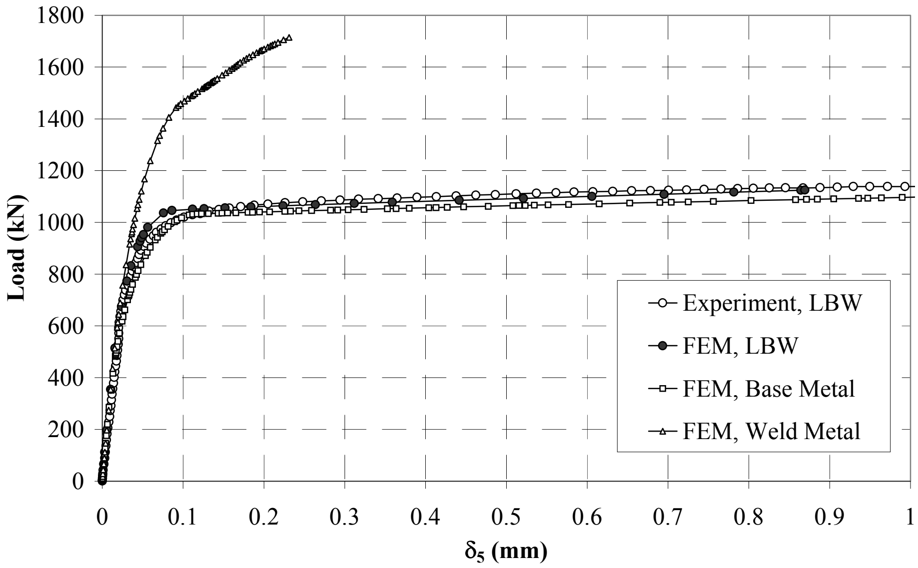

Fig. 2: Experimental and numerically calculated load vs. δ5 for the M(T) with LBW and homogenous material

Fig. 3 shows the maximum stress triaxialities h_{max} in the ligament and at the fusion line of the M(T) plate in the plate centre (half thickness) for plate configurations with the LBW, homogenous base and weld metal with increasing J-Integral. For the ligament it can be seen that the initial stress triaxiality at low loads is similar for all three configurations. With increasing load the gradient of h_{max} in the LBW ligament is steeper than in the homogenous cases and reaches lower absolute values. In the laser beam weld, the plastic zone starts to develop at the crack tip, and for low loads the loading state is the same as in homogenous weld metal plate. At a certain load, in this case at J=7N/mm, in the LBW configuration a second plastic zone develops at the fusion line in the base metal (**fig. 4**), which leads to a relaxation of stress state at the crack tip. In contrast to this phenomenon, at the fusion line in the LBW h_{max} increases in the softer base metal to a higher level than in the homogenous base metal plate at the same location (imaginary fusion line). Both the ligament and fusion line h_{max} reach almost constant values at higher loads. Due to the concentrated development of plasticity and increased stress triaxiality at the fusion line together with the relaxed constraint at the crack tip the crack path deviation should become more likely at higher loads.

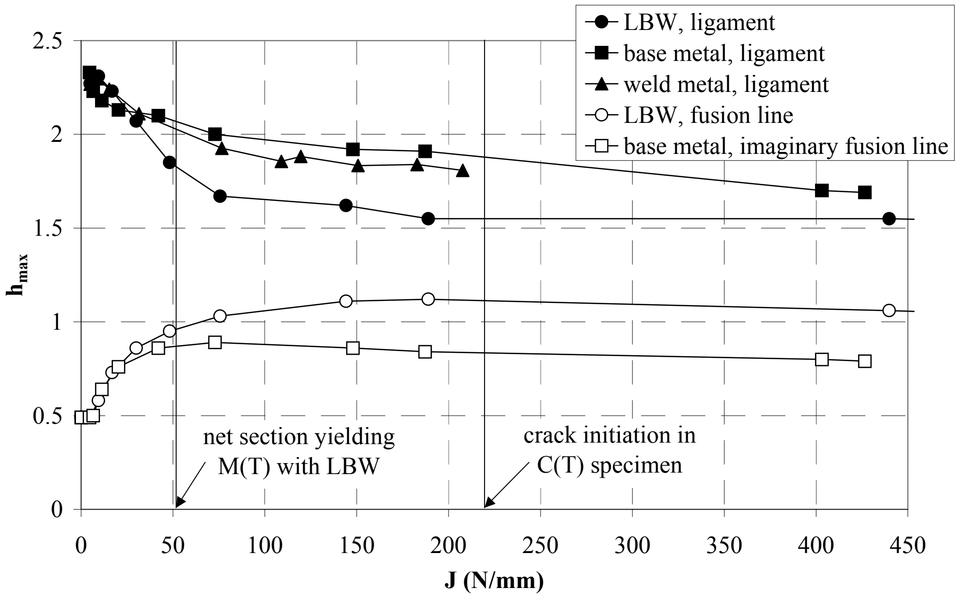

Fig. 3: Maxima of stress triaxiality vs. J-Integral in M(T) for LBW and homogenous material in the ligament and at the fusion line at base metal side

The crack initiation in the C(T) LBW specimen took place at δ_5=0.2mm which corresponds to a J-Integral of 220N/mm calculated from FEA. From **fig. 3** it is clear that the initiation in the wide plate takes place in the region of constant stress triaxiality state beyond net section yielding. This means that the onset of ductile fracture in the plate will be controlled by plastic strain.

However, at J=220 N/mm h and ε_v^{pl} are determined in both the C(T) and M(T) in the ligament (**fig. 5**). It can be seen that in the C(T) both h and ε_v^{pl} are much higher than in M(T). Assuming the location of ductile crack initiation is at the crack tip, this could mean that the initiation in the M(T) will take place at higher loads. The high stress triaxiality in C(T), which won't be reached in the M(T), can give an explanation for the frequently occurring pop-in's in the C(T): The cleavage fracture resistance of some brittle zones of the structurally heterogeneous LBW is exceeded.

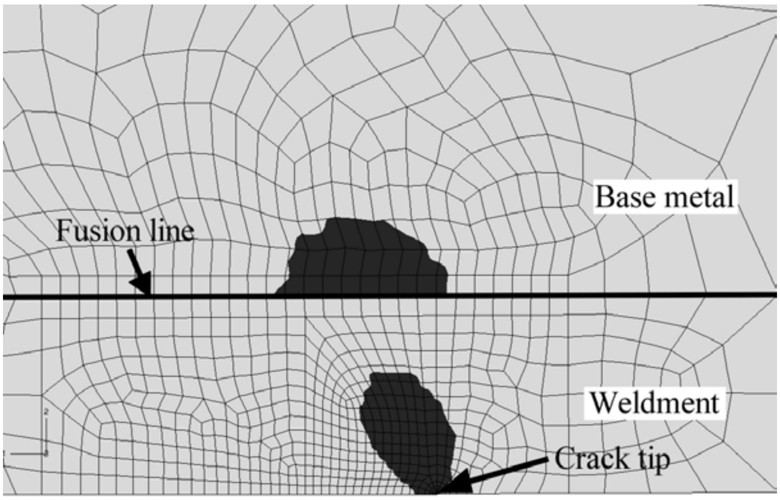

Fig. 4: Plastic zone (dark grey) in M(T) with LBW at J=7N/mm

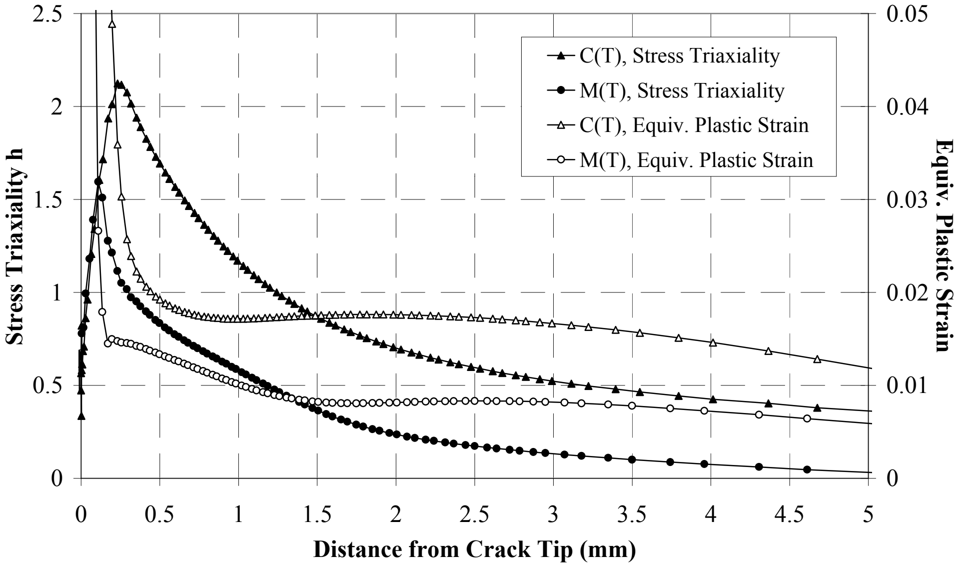

Fig. 5: Distribution of h and ε_v^{pl} in C(T) and M(T) with LBW in the ligament at J=220N/mm (C(T) crack initiation)

Concerning the distributions of h and ε_v^{pl} at the fusion line in C(T) and M(T) (**fig. 6**), the situation is different. The stress triaxiality in the C(T) is still higher than in the M(T), but the plastic strain is much lower. From these findings it is difficult to conclude in which specimen type the tendency of crack path deviation is more distinct, since both h and ε_v^{pl} contribute to damage and ductile crack initiation.

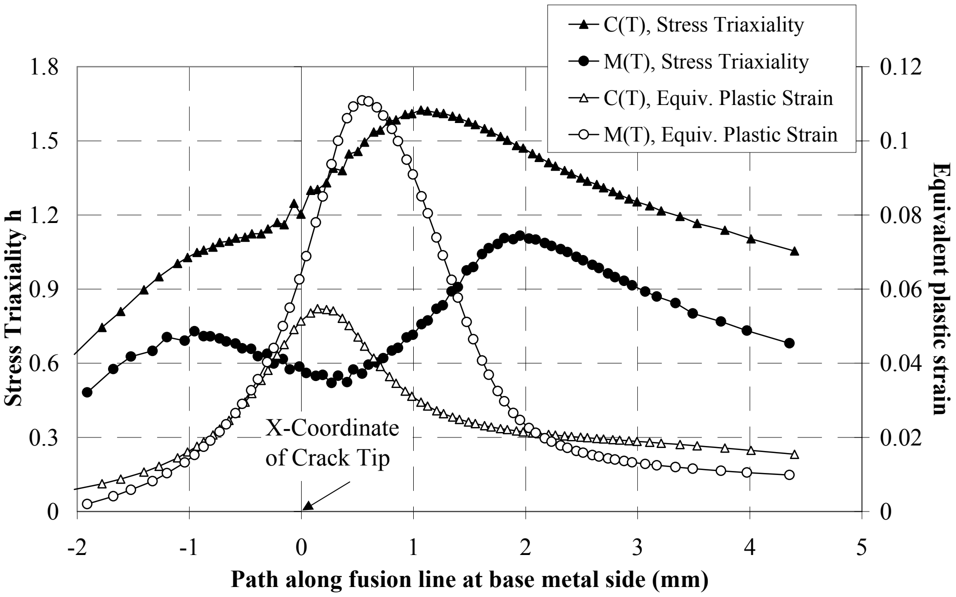

Fig. 6: Distribution of h and ε_v^{pl} in C(T) and M(T) with LBW at the fusion line on base metal side at J=220N/mm (C(T) crack initiation)

CONCLUSIONS

In general, the crack tip constraint in terms of stress triaxiality in overmatching LBW can be estimated by analysing the geometry with homogenous material conservatively. The difference in stress triaxiality between homogenous material and LBW configuration is maximum beyond net section yielding. Due to the relaxed constraint state in the M(T) in comparison to C(T) at the crack tip, the probability of pop-in occurrence decreases in M(T), which makes the safety analysis more conservative in case of valid pop-in's in fracture mechanics testing. Furthermore the reduced stress triaxiality and plastic strain in the M(T) ligament could give a hint that ductile crack initiation in the M(T) weldment occurs at higher J-Integral levels than the critical J-Integral measured in the C(T), which would increase the safety margin for crack initiation in the wide plate. The decreasing stress triaxiality in ligament and increasing triaxiality and plastic strain at fusion line indicate that the likelihood of crack path deviation increases with increasing load.

ACKNOWLEDGEMENTS

This contribution is based on the work done within a project funded by the Deutsche Forschungsgemeinschaft (DFG) (contract No. DA 85/80-1). The Authors would like to thank the DFG for its support.

REFERENCES

1. Senogles, D. J.; Harrison, P. L.; Cardinal, N. (1998) *Analysis of Wide Plate Behaviour of Steel Laser Welds*, European Symposium on Assessment of Power Beam Welds, February 4-5, GKSS Research Center, Geesthacht, Germany
2. Koçak, M.; Çam, G.; Kim, Y.-J., dos Santos, J. F. (1998) *Mechanical and Fracture Properties of Laser Beam Welded Joints*, IIW Doc. XV-996-98, 5th Int. Conf. on Trends in Welding Research, June 1-5, Pine Mountain, GA, USA
3. Insfran, A. C. (1999). PhD Thesis, University of Technology Hamburg-Harburg, Germany
4. Brocks, W.; Schmitt, W. (1995) In: *Constraint Effects in Fracture Theory and Applications: 2nd Volume*, pp. 209-231, Kirk, M.; Bakker, A. (Eds.), ASTM STP 1244, American Society for Testing and Materials, Philadelphia, USA
5. O'Dowd, N. (1998) Nuclear Engineering and Design 184, pp. 77-88
6. Tvergaard, V.; Needleman, A. (2001) In: *Handbook of Materials Behavior Models*, Lemaitre, J. (Ed.), Academic Press, San Diego, USA
7. ABAQUS/Standard User's Manual, Version 6.1 (2000), HKS Inc., Pawtucket, RI, USA
8. Schwalbe, K.-H., Neale, B. K., Heerens, J.; (1994) The GKSS test procedure for determining the fracture behaviour of materials: EFAM GTM 94, Report No. GKSS 94/E/60
9. Koçak, M.; Riekehr, S.; dos Santos, J.; Cardinal, N.; Webster, S.; Kristensen, J.; Borggreen, K.; Klein, R.; Fischer, R. (1999) *Analyis of Fracture Behaviour of Laser Beam Welded Wide Plates*, European Symposium on Assessment of Power Beam Welds, February 4-5, GKSS Research Center, Geesthacht, Germany