Low-cycle fatigue behaviour of laser welded high-strength steel DOMEX 700 MC

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Abstract. The article presents the results of research on low cycle fatigue strength of laser welded joints vs. non-welded material of high-strength steel DOMEX 700 MC. The tests were performed under load controlled using the total strain amplitude ε_{ac}. The operating principle of the special electro-mechanic fatigue testing equipment with a suitable clamping system was working on 35 Hz frequency. Fatigue life analysis was conducted based on the Manson-Coffin-Basquin equation, which made it possible to determine fatigue parameters. Studies have shown differences in the fatigue life of original specimens and laser welded joints analysed, where laser welded joints showed lower fatigue resistance. In this article a numerical analysis of stresses generated in bending fatigue specimens has been performed employing the commercially available FEM-program ADINA.

Keywords: low-cycle fatigue, laser, welding, high-strength steel

1 Introduction

Static or quasistatic loading is rarely observed in modern engineering practice, making it essential to the engineer to implications of repeated loads, fluctuating loads and rapidly applied loads. By far, the majority of engineering design projects involves machine parts subjected to fluctuating of cyclic loads. Such loading includes fluctuating or cyclic stresses that often result in failure by fatigue. The most difficult aspect of fatigue is to detect the progressive changes in material properties that occur during cyclic stressing and the failure may therefore occur with no apparent warning. Also, periods of rest, with the fatigue stress removed, do not lead to any measurable healing or recovery from the effects of the prior cyclic stressing. Thus the damage done during the fatigue process is cumulative and generally unrecoverable [1]. Fatigue failure is an extremely complex physical process which is governed by a great number of parameters related to, for example, local geometry and material properties of the structural region surrounding the crack growth path. It is commonly recognized that it is impossible for a physical model to account for all fatigue

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influencing parameters, thus a lot of approximate models have been conceived for practical fatigue assessments. In every stadium of fatigue cumulative damage dominates a definite mechanism controlled by more or less known and verified rules [2, 3]. There exists a stage of micro-plastic process in the total volume of material with a following stage of fatigue crack nucleation and stage of their growing with a more or less detailed zoning. Despite of this research no results have been achieved, which could be considered as successful ones.

Fatigue failure investigations over the years have led to the observation that the fatigue process actually embraces two domains of cyclic stressing or straining that are significantly different in character, and in each of which failure is probably produced by different physical mechanisms. One domain of cyclic loading is that for which plastic strain occurs during each cycle. This domain is associated with high loads and short lives or low-cycle fatigue. The other domain of cyclic loading is that for which the strain cycles are largely confined to elastic range. This domain is associated with lower loads and long lives, or high cycle fatigue. Low-cycle fatigue is typically associated with cycle lives from one to about 10^4 or 10^5 cycles, and high-cycle fatigue for lives greater than about 10^4 or 10^5 cycles [1, 4]. In recent years, it has been recognized that the fatigue failure process involves three phases. A crack initiation phase occurs first, followed by crack propagation phase and finally, when the crack reaches a critical size, the final phase of unstable rapid crack growth to fracture completes the failure process. The modelling of these phases has been under intense scrutiny, but the models have not yet been developed in a coordinated way to provide widely accepted engineering design tools. The basic premise of the local stress-strain approach is that the local fatigue response of the material at critical point, that is, the site of crack initiation is analogous to the fatigue response of a small, smooth specimen subjected to the same cyclic strains and stresses. The cyclic stress-strain response of the critical material may be determined from the characterizing smooth specimen through appropriate laboratory testing [5, 6].

To properly perform such laboratory tests, the local cyclic stress-strain history at the critical point in the structure must be determined, either by analytical or experimental means. Thus valid stress analysis procedures, finite element modelling or experimental strain measurements are necessary, and the ability to properly account for plastic behaviour must be included. In performing smooth specimen tests of this type, it must be recognized that the phenomena of cyclic hardening, cyclic softening and cycle-dependent stress relaxation, as well as sequential loading effects and residual stress effects that may be experienced by the specimen as it accumulates fatigue damage are presumed to be the same as at the critical point of the structure member being simulated. Since, including all these factors in a test is inconvenient, inaccurate and expensive, the use of finite element method has become a powerful tool to calculate the cyclic stress-strain response of any structure or mechanical component. The finite element method is especially used in the ground vehicle industry where discontinuities of the geometry such as notches and holes produce difficulties to calculate the local cyclic stresses and strains, which are essential to predict the fatigue life of any structure or component [7, 8].

The strength analysis of welded structures does not deviate much from that for other types of structures. Various failure mechanisms have to be avoided through appropriate design, choice of material, and structural dimensions. Design criteria such as yielding, buckling, creep, corrosion, and fatigue must be carefully checked for specific loading conditions and environments. It is, however, the fact that welded joints are particularly vulnerable to fatigue damage when subjected to repetitive loading. Fatigue cracks may initiate and grow in the vicinity of the welds during service life even if the dynamic stresses are modest and well below the yield limit. The problem becomes very pronounced if the structure is optimized by the choice of high strength steel. The very reason for this choice is to allow for higher stresses and reduced dimensions, taking benefits of the high strength material with respect to the yield criterion [9]. However, the fatigue strength of a welded

joint is not primarily governed by the strength of the base material of the joining members; the governing parameters are mainly the global and local geometry of the joint. Hence, the yield stress is increased, but the fatigue strength does not improve significantly. As already stated, the fatigue behaviour of welded joints is random by nature. Very few load-bearing details exhibit such large scatter in fatigue life as welded joints. This is true even in controlled laboratory conditions. As a consequence, it becomes an important issue to take scatter into consideration, both for the fatigue process and for the final life. Furthermore, the in-services stresses may often be characterized as stochastic processes [10, 11]. However, a welded joint has some peculiar features that make some of the subjects and parameters play a much more important role than others [10, 12]. Let us start with an S-N curve for a welded joint and compare it with other specimens. Fig. 1 shows the S-N curves based on tests with one smooth plate, one plate with a bore hole, and one plate with a fillet welded transverse attachment.
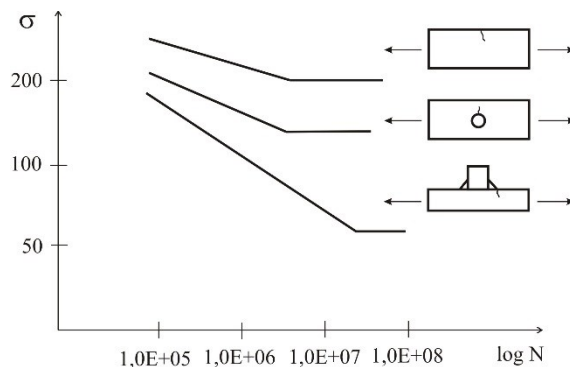

Fig. 1. Fatigue life curves for various details [11]

This type of fillet welded joint is often referred to as non-load-carrying due to the fact that the load is carried straight through the base plate. It is also noted that the applied force is transverse to the welding direction [3, 10]. In the plate, the fatigue cracks can appear anywhere in the longitudinal edges of the plate, whereas they will appear at the inner edges of the bore hole transverse to the applied loading in the specimen with the hole. The latter phenomenon is due to the stress concentration at the edge of the hole. In the fillet welded joint the cracks will appear at the weld toe and grow through the base plate in a direction perpendicular to the applied principal stresses.

The difference between the S-N curve for the specimen with the hole and the S-N curve for the welded joint is rather surprising considering the fact that the bore hole creates a stress concentration factor close to 3 at the edge of the hole. The relatively short fatigue life of welded detail is explained, in the main, by three factors:
- severe notch effect due to the attachment and the weld filler metal,
- presence of non-metallic intrusions or micro-flaws along the fusion line,
- presence of large tensile residual stresses.

2 Test equipment design

The design of experimental equipment is based on a mechanical principle. The constant rotation is generated by excenter and linkage mechanism. By changing of eccentric magnitude it is possible to change a loading magnitude. Also if we change the length of connecting crank on the experimental equipment, there will be a change in the loading cycle

character (proportional-non-proportional loading, bending/torsion loading, etc.) [13, 14]. Power of the device is secured by two synchronic electro motors with frequency converters from 0.5 Hz to 100 Hz. Loading frequencies are identical with the frequency of rotation drive. Synchronization of the electro motors is secured by electronics and allows synchronization of the loading amplitude. The synchronization of electro motors also allows setting the phase shift for individual loading levels. There are also two force measurement systems included in the experimental equipment. These systems may be used for measurement of force values during the loading process. For evaluation of fatigue curves it is necessary to know stress and strain conditions on individual loading levels [12, 15, 16].

3 Experimental material and strain-life data results

Twenty smooth specimens were tested under strain controlled conditions in order to identify the strain-life behaviour of the base and laser welded experimental material. After machining, the specimen surfaces were mechanically polished. The experiments were carried out in an electro mechanic fatigue test machine, developed on University of Žilina.

For evaluation of fatigue curves it needs to know stress and strain conditions on individual loading levels. A sinusoidal waveform was used as command signal. The fatigue tests were conducted with constant strain amplitudes, at room temperature, in air. The specimens were cyclic loaded under strain control with symmetrical proportional bending loading, with a nominal strain ratio, $R_\varepsilon = -1$. The computational fatigue tests were performed under cyclic loading with the zero mean value. Frequency of each analysis was equal to 35 Hz.

Domex cold forming steels are thermo-mechanically rolled in modern plants where the heating, rolling and cooling processes are carefully controlled. The chemical analysis, consisting of low levels of carbon and manganese has precise addition of grain refiners such as niobium, titanium or vanadium. This together with a clean structure, makes Domex Steels the most competitive alternative for cold formed and welded products. The typical mechanical and chemical composition of our experimental material - high strength streel is shown in Table 1 to Table 3. The material used in this research was delivered in the form of a cylindrical shape with a diameter 10 mm. The length of cylindrical bars was 150 mm.

Table 1. Chemical composition of high strength steel DOMEX 700 MC (weight %)

C	Si	Mn	Ni	P	S	Cr	Mo
0.06	0.04	1.18	0.04	0.013	0.002	0.03	0.1
V	**N**	**Ti**	**Cu**	**Al**	**Nb**	B	C_{ekv}
0.01	0.004	0.1	0.01	0.039	0.06	0.0001	0.41

Table 2. Mechanical properties of high strength steel DOMEX 700 MC

Ultimate tensile strength	849 MPa
Tensile yield strength	790 MPa
Elongation at fracture	17 %

Table 3. Mechanical properties of laser welded high strength steel DOMEX 700 MC

Ultimate tensile strength	810 MPa
Tensile yield strength	622 MPa
Elongation at fracture	7 %

From experimentally measured values of number of cycles to failure was created uniaxial fatigue curve, which is shown in Fig. 2. For fatigue test interpretation on each

loading levels it is necessary to know the plastic strain amplitude (Manson-Coffin curve) or stress amplitude (Wöhler curve) applied on each cycle loading level. For that it is necessary to analyze the stress and strain maximum values by FEM [11-13].
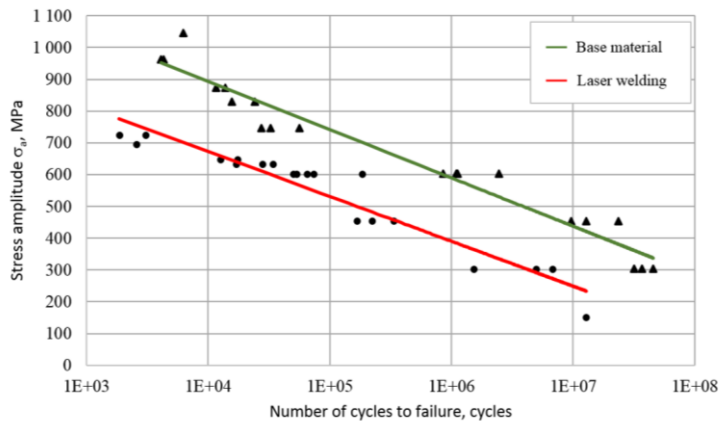

Fig. 2. S-N curves for high strength steel DOMEX 700 MC

The specimen model was created by the finite-element program ADINA. The material was assumed plastic-bilinear; the true stresses were obtained from a real stress-strain graph. The tetrahedron linear element type was automatically generated. The "Load Plot" function was defined by excenter setting with excentricity of 1 mm. At the fix point shell and beam elements were used for hammer simulating. From the computational analysis can be seen that the area with the greatest concentration of stresses or the place with the higher deformation was localized in the middle of the rod radius, see Fig 3.
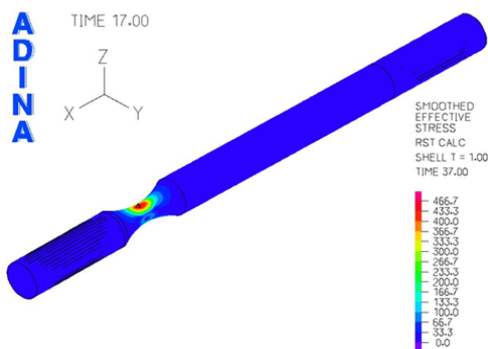

Fig. 3. Result of FEM analysis

Conclusion

In this study, the low-cycle fatigue behaviour of high-strength steel Domex 700 MC smooth bars from the base and laser welding joint condition was experimentally evaluated. Tests were performed under strain controlled conditions bending loading on machined bar specimens by means of a simple loading apparatus that allowed to reach high strain levels. Generally we can say that the results are in good agreement with the results published by other authors [6, 15]. On the basis of the tests performed, the following conclusions were

formulated: The fatigue resistance of both experimental materials increases with decreasing stress amplitude continuously in the cycles of number region. From the comparison of the low cycle fatigue data of the base material and the laser welded joint stat able, that in the case of identical total and plastic strain amplitudes, the welded joint can be tolerate smaller number of cycles until the failure, then the base material. The ratio between the cycle to failure of base material and the welded joint s is decreasing with the increasing of the total and plastic strain amplitudes. Residual stress is an important factor influencing the structural behaviour in all instability failures as well as in fatigue crack initiation and propagation when cyclic service stresses are superposed onto the residual stresses. The presence of residual stresses in engineering components and structures can significantly affect the fatigue behaviour during external cyclic loading. The effect of residual stresses may either be beneficial or detrimental, depending on magnitude, sign and distribution of the stresses with respect to the load-induced stresses. Residual stresses in tension are detrimental and are often in the magnitude of the materials yield strength. The tensile residual stresses will reduce the fatigue life of the structure by increasing the growth of the fatigue crack, while compressive residual stresses will decrease fatigue crack growth rate. The existence of tensile residual stresses in a surface layer accelerates crack initiation reducing fatigue life due to the increase of local mean stress.

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