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Elastic-plastic behaviour of welded joints during loading and unloading of pressure vessels

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Abstract

In this paper elastic-plastic behaviour of welded joints during loading and unloading of pressure vessel has been analysed. Two stage pressuring process has been applied in previous experimental investigation and simulated using the finite element method. The effect of residual stress and strain has been analysed.

Keywords: elastic-plastic behaviour; welded joints; pressure vessel; static loading-unloading; structural integrity

1. Introduction

The penstock built during the late seventies in the scope of reversible hydro power plant “Bajina Basta” (HPP BB) required innovative design and extensive experimental research to verify its structural integrity, [Sedmak et al. (2011)].

To most important aspect of design was the decision to produce one penstock instead of two, as would be required if a mild structural steel had been used. For only one penstock the application of structural steel of yield strength level 700 MPa was inevitable. This requirement was satisfied by HT80, weldable, quenched and tempered, low alloy high strength (HSLA) steel, with ultimate tensile strength above 800 MPa. Anyhow, selection of this HSLA steel opened a new problem. Namely, the plate thickness in the penstock most stressed part was calculated to be slightly above 47 mm, which was the upper limit in plate fabrication, [Sedmak and Sedmak (1995), Sedmak et al. (2011)] Therefore, two full scale prototypes of this penstock were made in order to gather the data about its integrity, one tested in the static loading-unloading sequence, and the other one impact loading (explosion). The

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overall behavior of a welded penstock under load was analyzed based on this approach, allowing an evaluation of crack significance and "fitness-for-purpose" assessment.

In this paper elastic-plastic behaviour of welded joints during loading and unloading of pressure vessel has been analysed by using the Finite Element Method (FEM) to simulate experimental results, briefly presented as well, whereas more details are given in [Tatić et al.].

2. Pressure vessel full-scale model

The most important data for the full-scale model of the penstock are given. The welded joints, longitudinal (L) and circular (C), as shown in Fig. 1, were produced by shielded metal arc welding (SMAW) and submerged arc welding (SAW) processes. Typical chemical composition of SM 80P steel plates and its weld metals is given in Table 1, and mechanical properties in Table 2.

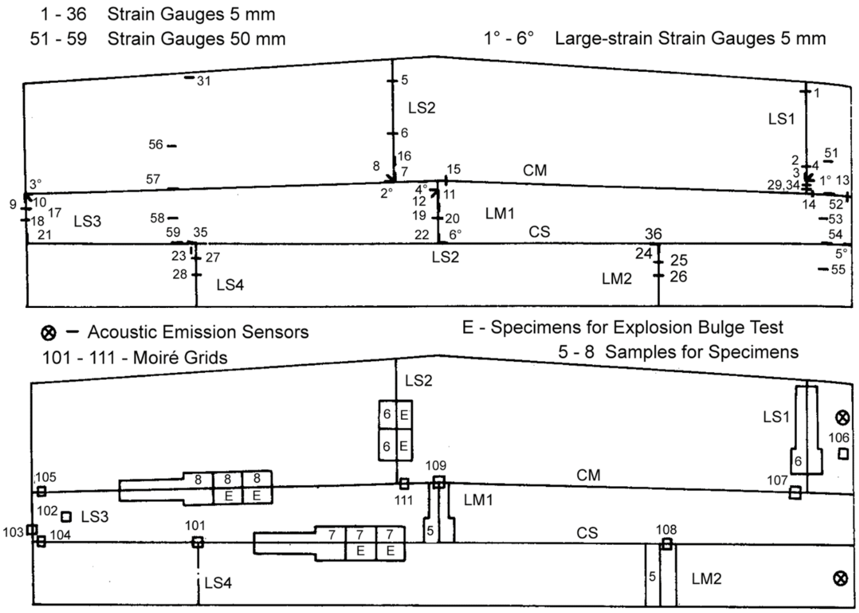

Fig. 1. Instrumentation and specimens sampling in the penstock model static pressure test

Table 1. Chemical composition of SM 80P steel and of MAW and SAW weld metals

Element		C	Si	Mn	P	S	Cu	Cr	Ni	Mo	V	B	C_{eq}
SM 80P		0.10	0.30	0.90	0.01	0.008	0.24	0.48	1.01	0.47	0.03	0.0016	0.5
Weld metal	MAW	0.06	0.53	1.48	0.011	0.005	-	0.24	1.80	0.43	-	-	-
	SAW	0.07	0.37	1.87	0.01	0.011	-	0.44	0.13	0.73	-	-	-

Table 2. Mechanical properties of SM 80P steel and of MAW and SAW weld metals

Material	Direction	Tensile			Charpy impact test	
		Y.S., MPa	U.T.S., MPa	Elongation	vE_{-40}, J	vT_{rs}, °C
SM 80P	rolling	794 - 755	804 - 834	24 - 29	156 - 224	-92
	cross rolling	794 - 755	795 - 834	22 - 23	60 - 147	-58
Weld metal	MAW	722	810	22	99	-5
	SAW	687	804	23	78	-18

Figure 2 shows the instrumentation on the developed model mantle, with the scheme of specimens cutting [Tatić et al.].

Pressurizing of the model had been performed in two stages. In the first loading (FL) stage the pressure reached 90.2 bar (σ_t = 399 MPa), corresponding to working pressure, then model was held under pressure of 73.5 bar for two hours. After unloading (UL), model was tested by the pressure of 120.6 bar (σ_t=533 MPa) in the second loading (SL) stage, close to the total working and water hammer load.

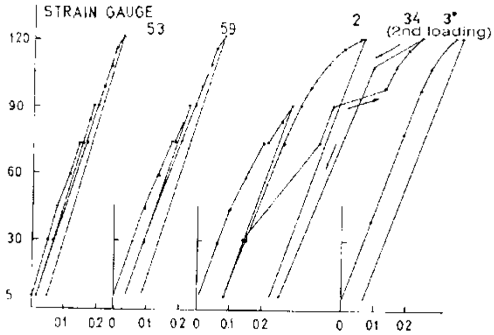

Fig. 2. Typical relationships between pressure and strain

3. Results and discussion

Finite element analysis (ABAQUS) of full-scale model of penstock has been performed and presented in the following form: Von Misses stresses distribution, (FL-UL, SL-UL), Von Misses stress-strain curves (FL-UL, SL-UL), Von misses stress-pressure curves (FL-UL, SL-UL), Pressure-von Misses strain curves (FL-UL, SL-UL) and Hoop stresses-strain curves (FL-UNL, SL-UL).

3.1. Pressure vessel without RS

Figure 3 shows, the von Misses distribution of finite element model for first load as calculated in ABAQUS software, the highest stresses was in weld joint (LSI SAW), and the base metal at that same side. This concentration of stresses is due to the geometry of model.

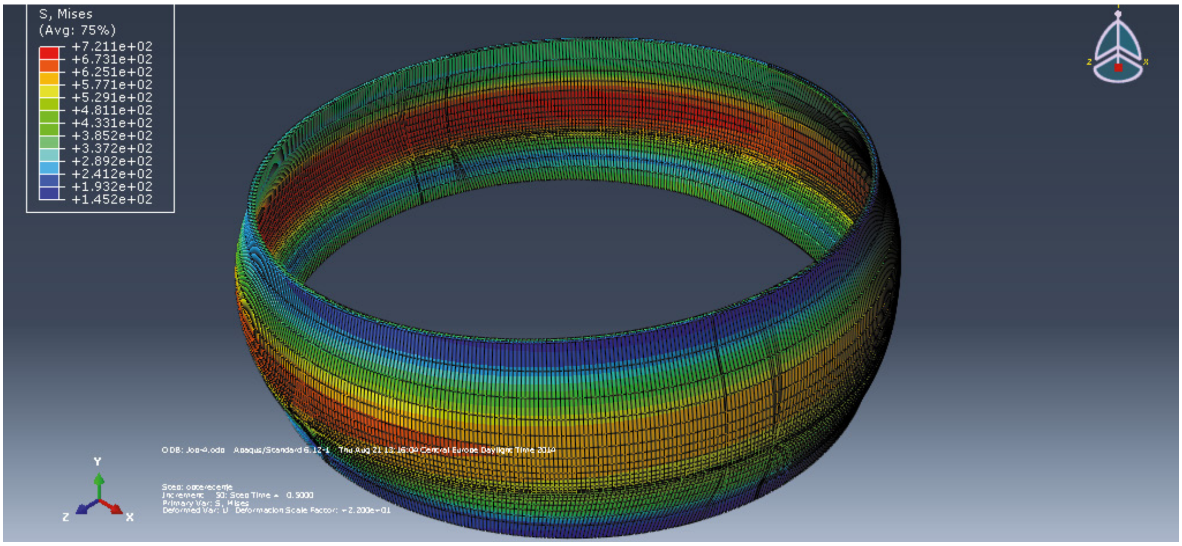

Fig. 3. von Misses stresses distribution of FE model of first load, (P =14.5MPa)

As indicated in figure 4, the plastic strain initiate just in the weld joint (LS1 SAW), this behavior is due to the lower yield strength of joint and its location in the stress concentration region.

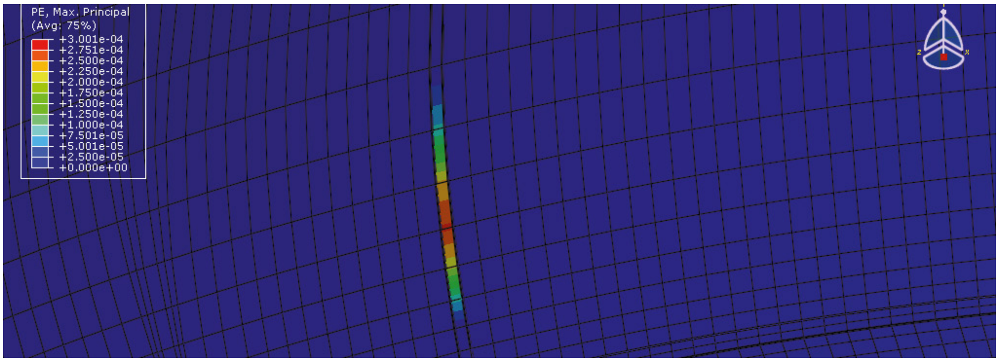

Fig. 4. plastic deformation of FE model (FL-UNL, P=14.5MPa).

As the internal pressure increased in the second load of FE model the level of von Misses stress will increased, and the distribution of stress has been not changed compared to the first load except the behavior of weld joint (LS1 SAW), which is has stress lower than base metal at that side of stress concentration region due to the effect of initiation of plasticity as indicated in figure 5.

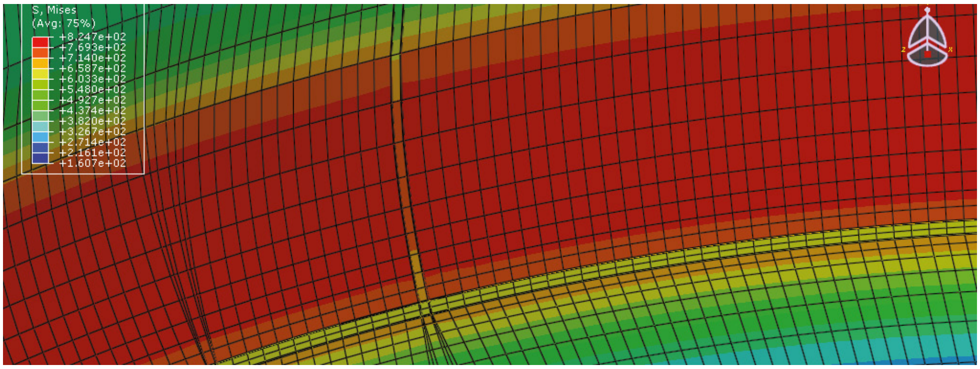

Fig. 5. von Misses stresses distribution of FE model of second load, (P=18.5MPa)

As illustrated in figure 6, the level of von Misses stresses have been exceeded yielding of base metal and weld joints at that side of stress concentration region and the plasticity initiated and spreads in base metal and weld joints in this area.

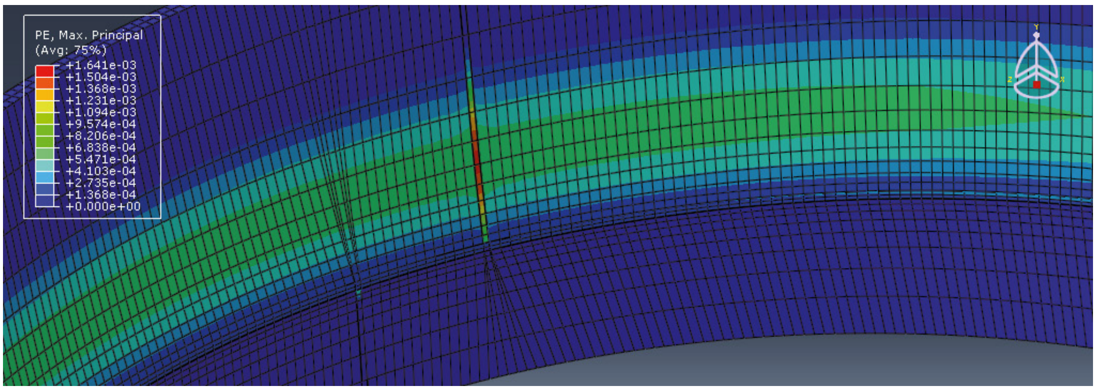

Fig. 6. plastic deformation of FE model (SL-UNL, P=18.5MPa).

3.2. Results without RS (FL-UNL, SL-UNL).

Figure 7 illustrates the behavior of von Misses stress-strain curve of weld joint (LS1) for FL-UN and second load-unload, this behavior showed the linearity of stress-strain curve of loading and unloading behavior for first and second load.

Figure 8 shows the behavior of von Misses stresses with loading and unloading, as the pressure increasing the von Misses stresses increasing until the yield point of the weld joint, then the changing of Von Misses stresses will be lower, for unloading the behavior will be linear, until the effect of residual stresses then will be non-linear.

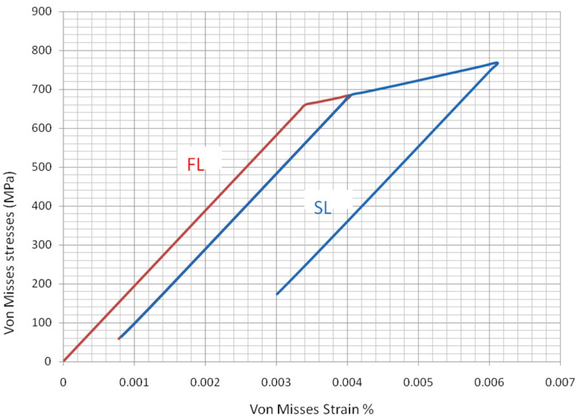

Fig. 7. Von Misses stress-strain behaviour LS1 SAW without RS as calculated in ABAQUS.

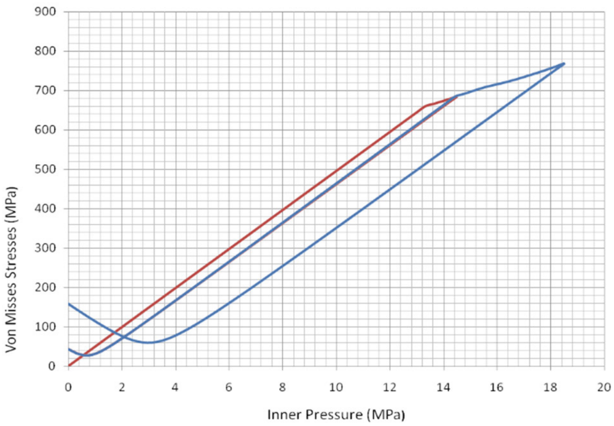

Fig. 8, Von Misses-Inner Pressure behaviour of WM LSI SAW as calculated in ABAQUS.

The behaviour of von Misses strain with inner pressure as calculated in ABAQUS is illustrated in figure 9, this behaviour showed linearity during loading and unloading with a little bit changing during plasticity.

The behaviour of hoop stress-strain curve as indicated in figure (5-8), the yielding for first load starts at 13.34 MPa of inner pressure (531.5 MPa of hoop stresses), while for second load the plastic deformation initiated at 14.8 MPa of inner pressure (586.1 MPa of hoop stresses).

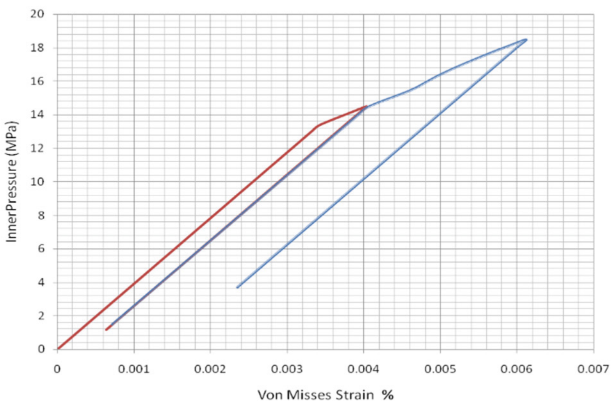

Fig. 9. Pressure-Von Misses strain of LS1

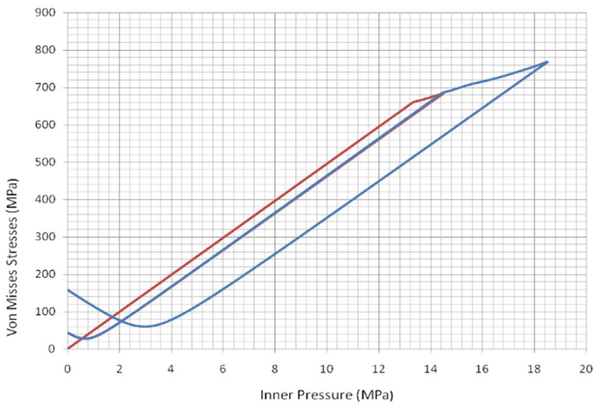

Fig. 8, Von Misses-Inner Pressure behaviour of WM LSI SAW as calculated in ABAQUS.

3.3. Results for FL (with RS).

Figure 11 shows von Misses stresses distribution, the highest stresses has been in weld joints at the stress concentration side, due to the effect of initial residual stresses (40% of yield strength) stresses and the shape of geometry of model. Figure 12 shows the initiation of plasticity after FL, in LS1, due to the lower yield point and its location. Figure 13 shows von Misses distribution in SL, with the maximum in weld joints at the concentration stresses side with a considerable increasing of von Misses stresses in base metal at that side.As the inner pressure increased for second load the plastic strain initiated in the other weld joints at the shorter side CMAW, LS3 SEW

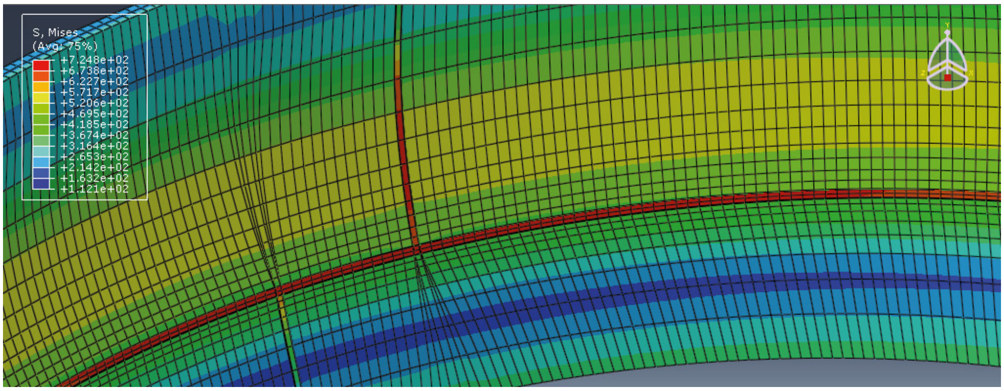

Fig. 11. Von Misses stresses distribution of FE model for first load with RS (P=11.2MPa)

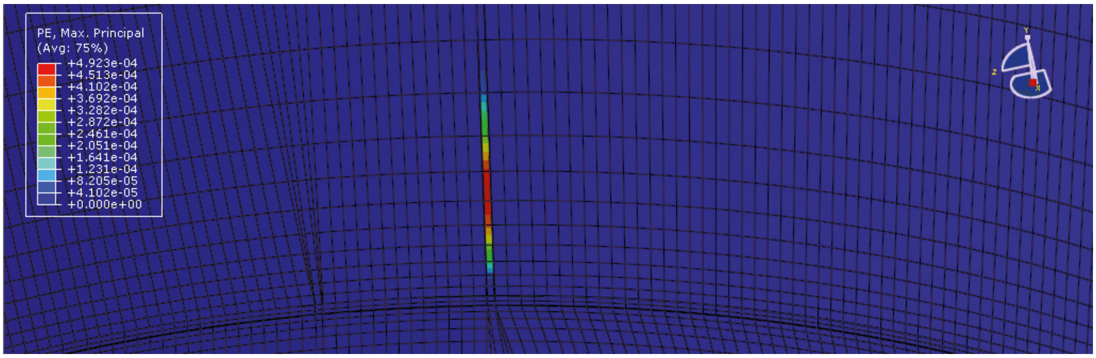

Fig. 12. plastic strain of WM LS1 SAW after FL (P=11.2MPa).

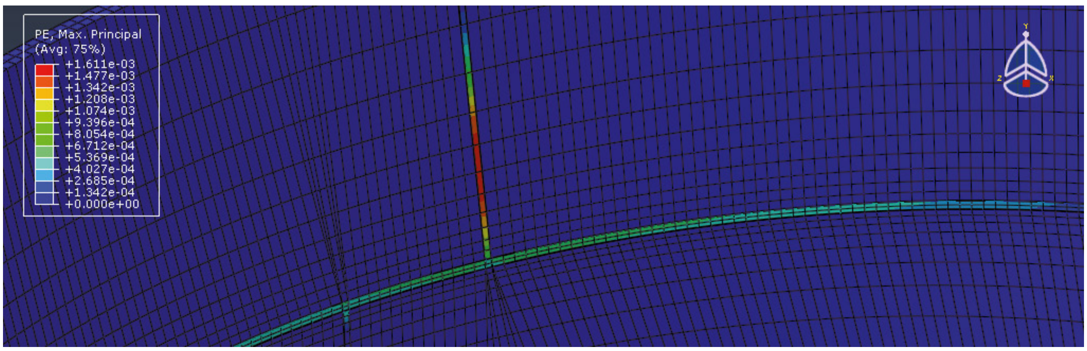

Fig 13. Von Misses distribution of FE model for SL with RS (P=14.4MPa).

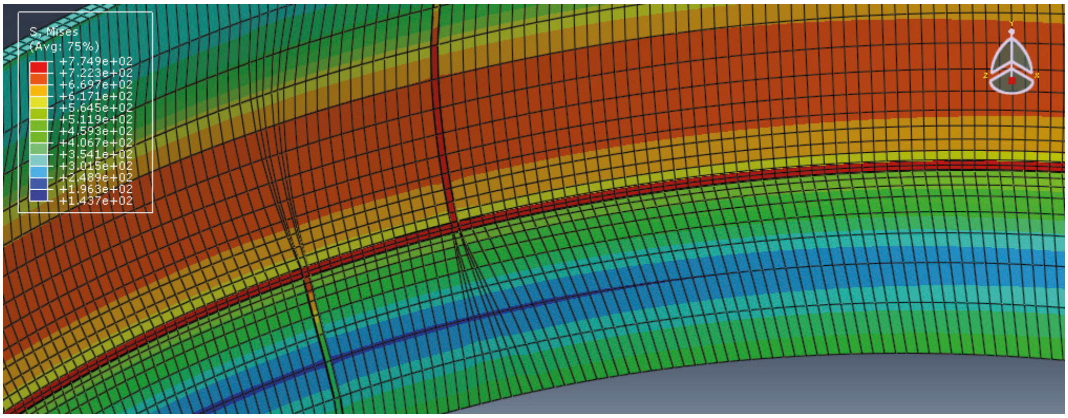

Fig. 14. Plastic strain of WM LS1 SAW after SL (P=14.4 MPa)

3.4. Results for weld metal LS1 SEW, (FL-UNL, SL-UNL, with RS)

The behavior of von Misses stress-strain curve of weld joint LS1 SAW with residual stresses is similar to the behaviour without residual stresses, but it yields at lower level of inner pressure due to the effect of residual stresses as illustrated in figure 15.

The behavior of hoop-stress-strain curve of weld joint LS1 SAW with residual stresses showed that, the plastic strain for first load was in direction of axial stresses not in circumferential direction (there is no plasticity for first load in hoop stress-strain curve) as indicated in figure 16, this behaviour is due to the shape of the geometry model (angle of 5º), which is exerted more compression in axial direction.

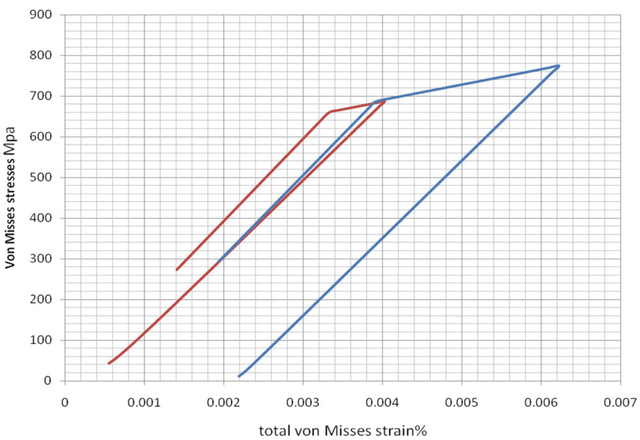

Fig. 15. von Misses stresses-strain curve of WM LS1 SAW with RS as calculated in ABAQUS.

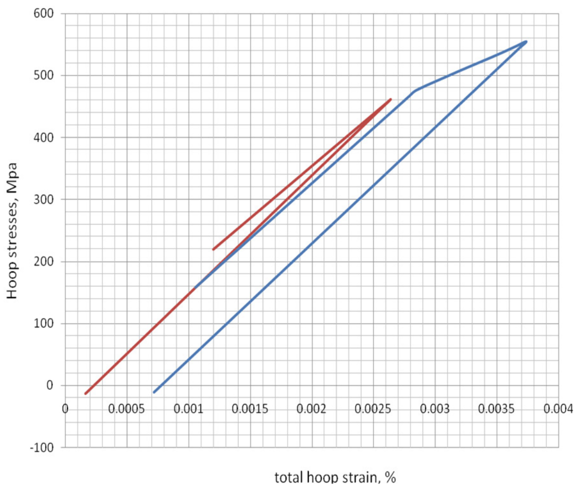

Fig. 16. Hoop stresses-strain of WM LS1 SAW with RS as calculated in ABAQUS

4. Conclusions

Based on the results presented here and in more details in [1], one can conclude the following:

- For the higher heat input $\sigma_{inic}$is always higher, while $a_{un}$is higher in WM, but smaller in HAZ, so the higher heat input is somewhat better.
- The HAZ of microalloyed steel has greater resistance against cracks than the WM, being quite different comparing e.g. to the behaviour of microalloyed steels welded joints.
- High stress levels for initiation of stable crack growth suggest the possibility that the welded structure can operate safely even in the presence of relatively large surface cracks.
- The integrity of heterogeneous welded joints is not affected by the presence of surface cracks because overmatching plays a protecting role, which consists in a small plastic deformation of weld metal even at high loads causing fracture of parent metal. The latest conclusion holds at low temperatures, as well.

Acknowledgements

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