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Preliminary communication

Structural Integrity of Pressure Vessel Heads Made by Incremental Sheet Forming from High-Quality Steel P460 NL1

Nedeljko VUKOJEVIĆ*, Zlatan IŠTVANIĆ, Fuad HADŽIKADUNIĆ, Nenad GUBELJAK, Amna BAJTAREVIĆ-JELEČ

Abstract: The fabrication of pressure vessel heads with large diameters necessitates the production from a starting sheet composed of two sections with weld joint. Subsequent plastic deformation may influence changes in the mechanical properties of the sheet, particularly the welded joint. The subject of this research is the effect of incremental plastic deformation (known as Incremental sheet forming) and post weld heat treatment on the mechanical properties of the heat-affected zone in the welded joint, as well as an assessment of the structural integrity. One of the goals of the work is to show that in certain circumstances heat treatment is not necessary. The researches focus on destructive and semi destructive testing of samples extracted from an actual pressure vessel head structure. The material of the vessel head is steel grade P460 NL1, and the heads are manufactured in two thicknesses: 6 mm and 14 mm. The results of the structural integrity assessment are presented in the form of a FAD diagram.

Keywords: incremental sheet forming; post weld heat treatment; residual stress; steel grade P460 NL1; structural integrity; welded vessel heads

1 INTRODUCTION

Incremental sheet forming (ISF) is a metal forming process characterized by intense local deformation. During ISF, a tool follows the surface shape of the workpiece, inducing small deformations in the material and gradually shaping it into the toroidal form. This technique was developed in Japan, with the earliest published works in the field of gradual forming emerging in the early 1990s, primarily by Japanese researchers [1, 2]. Recent studies have also explored ISF processes involving aluminum alloys [3, 4].

The mechanical action of the press tool alters the initial workpiece, leading to surface layer hardening due to large plastic deformations, which can initiate cracks [5]. Under certain conditions, this plastic forming, combined with increased part thickness and residual welding stresses, may result in brittle fractures. The press tool's generates significant residual stresses [6], and the welding process itself contributes to these stresses, which can reach yield stress levels.

Since the press tool does not exert continuous pressure across the entire surface of the vessel head, its localized action results in varying material properties. This non-uniform distribution of properties raises safety concerns under operational loads. Variations in sheet thickness and the number of pressing operations can yield various effects on the basic material [7-10]. Notably, the number of pressing operations and the tool radius significantly influence on the residual stress orientation and size [11].

The vessel heads are typically manufactured as a single piece; however, standards permit welded versions for heads that exceed the standard dimensions of basic sheets. The selected material is high-quality steel for pressure vessels, specifically grade P460NL1. The sheets are welded using a double-sided full penetration butt weld for both selected thicknesses of 6 mm and 14 mm. While it is uncommon to weld 6 mm sheets in this manner in practice, this approach was adopted for the experiment.

2 EXPERIMENTAL RESEARCH

The focus of the tests is on the heat-affected zone (HAZ). The heads undergo post-weld heat treatment (PWHT) through normalization to reduce residual stresses. The experimental researches include testing of mechanical properties supported by structural integrity assessemt based on fracture mechanics parameters.

The specifics of the experiment are:

- The basic plates are round and made of sheet metal from 12 segments,
- The dimensions are limited according to the technological capabilities of the presses for plastic deformation,
- Initial sheet thicknesses are partially changed after plastic deformation,
- All welded joints are double sided full penetration butt weld,
- All specimens for testing are taken transversely to the longitudinal axis of welded joint,
- Vessel heads are heat treated.

The test results are presented in Tab. 5 [12].

2.1 Production Method and Material Properties

The chemical properties of the steel sheet for the vessel heads are presented in Tab. 1.

Table 1 Chemical properties of the basic material

t, mm	Element, %								
	C	Si	Mn	P	S	Al	Cr	Ni	Mo	Cu
#6	0.17	0.40	1.55	0.010	0.003	0.028	0.04	0.04	0.004	0.02
#14	0.18	0.56	1.67	0.016	0.003	0.032	0.04	0.52	0.003	0.04

The carbon equivalent was calculated using the Ito-Bessyo equation [13]:

$$C_E = C + \frac{Mn}{20} + \frac{Mo}{15} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{V}{10} + \frac{Cu}{20} + \frac{Si}{30} + 5B \tag{1}$$

The carbon equivalent for the treated vessel heads is shown in Tab. 2.

Table 2 C-equivalent

Thickness	C_E Acc. material certificate	C_E Acc. Eq. (1)
#6 mm	0.47	0.26
#14 mm	0.52	0.30

Materials have good weldability and in both cases, the EN ISO4063-121 (EPP/ UP) welding technology was used [14].

Tested vessel heads are manufactured using incremental sheet forming (ISF) from round plates derived from welded sheets. A notable phenomenon observed is sheet thinning, which is especially pronounced in thicker sheets. This thinning results in an increased thickness toward the outer edges of the head due to material extrusion, particularly during the production of the toroidal part. The incremental deformation of the round plates is carried out on a hydraulic press equipped with an interchangeable tool and adjustable pressure force. Plastic deformation was made using the press type P2MF 200x4 "Sertom", Milano, Italy, as shown in Fig. 1

Table 3 Welding procedure

Additional and auxiliary material		Preheating temperature	≥100 °C
Manufacturer	ESAB Ok Auto rod 13.40	Interlayer temperature	200 °C
Classification	EN14171-A-S3Ni1Mo	Post weld heat treatment	930±40 °C
Type of lining	÷	Mode of operation	Manual
Wire diameter	∅3.0 mm	Max. pass width / layer number	15 mm/2 for t = 6 mm 22÷24 mm/2 for t = 14 mm
Drying treatment	2 h/350 °C	Cleaning technique	Grinding and brushing
Powder type	OK-Flux 10.62	Other things	÷

Figure 1 ISF production process

Post weld heat treatment (PWHT) is performed by heating up to 930±40 °C. After a 0,5-hour heating period, the vessel heads were gradually cooled in the air.

2.2 Testing Specimens

A section of the vessel head featuring a welded joint in the center was selected for testing, as illustrated in Fig. 2. Samples were extracted from the cylindrical part of the heads, specifically from areas where plastic deformations are most pronounced. The samples were removed as curved plates from the vessel.

Figure 2 Specimens extracted from the vessel head

To assess the properties in the plastic deformed heat-affected zone (HAZ), test specimens were taken in a direction transverse to the longitudinal axis of the welded joint, as shown in Fig. 2.

2.3 Hardness Testing

Hardness testing was conducted to identify significant differences and their potential influence on other mechanical test results. Measurements were performed using a ZWICK device for hardness and micro-hardness testing. The hardness tests were carried out on the cross-section of the butt-welded joint using the Wickers test method, with a load of 10 kg (HV1) at a test temperature of 22 °C, in accordance with the standard BAS EN ISO 6507-1:2018 [15]. The test results are presented in Tab. 5. Hardness testing was executed on the cross-section of each sample, and the results, along with a typical schematic representation of the impression locations, are illustrated in Figs. 3 and 4.

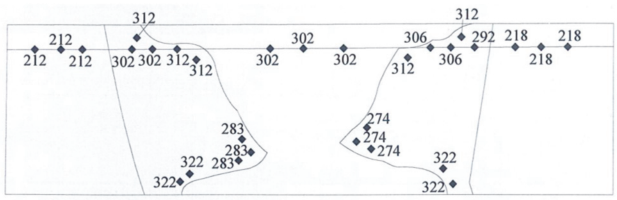

Figure 3 Scheme of hardness testing before PWHT - sheet #14 mm

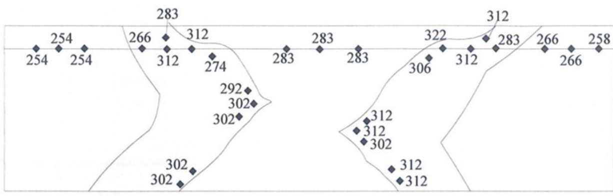

Figure 4 Scheme of hardness testing after PWHT - sheet #14 mm

2.4 Tensile Testing Procedure

Tensile tests were conducted at temperature of +16°C. The test procedure follows the standard BAS EN ISO 6892-1:2017 B [16], using test specimens whose geometry is specified by the standard BAS EN ISO 4136:2014 [17]. The specimens were prepared with a transverse groove cut in the heat-affected zone (HAZ). A typical force-elongation diagram for a 14 mm sheet is presented in Fig. 5, and the test results sts are summarized in Tab. 5.

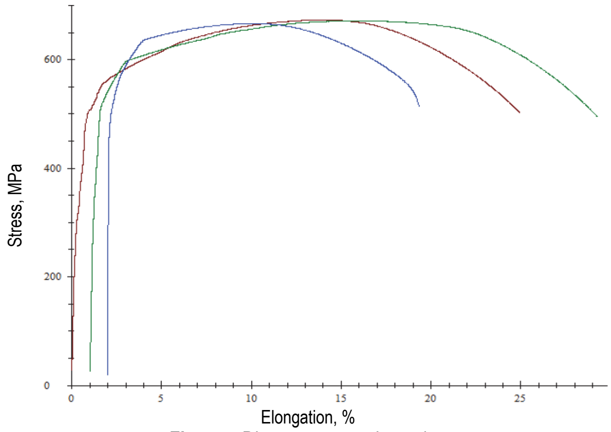

Figure 5 Diagram stress-elongation

2.5 Impact Testing Procedure

Impact tests were conducted at temperature of +20 °C. The test procedure followed the BAS EN ISO 148:2016 [18] standard using standard test specimens as specified in BAS EN ISO 9016:2012 [19]. Testing was performed on a Charpy pendulum with a capacity of 300 J. The results of the total impact energy testing are presented in Tab. 5.

The tests measured the total energy absorbed by the impact both before and after heat treatment. The strengthening effect from plastic deformation resulted in a decrease in toughness. Overall, the values of total impact energy for the heat-affected zone (HAZ) indicate a significant tendency toward brittle fracture, as shown in Tab. 5.

2.6 Determination of Residual Stress

Residual stresses were measured using the semi destructive treatment in accordance with ASTM E837 [20]. Measurements were conducted in the heat-affected zone (HAZ), which includes a narrow area adjacent to the strain gauge position (strain gauge type 1-RY61-1.5/120 was used), selected to determine residual stress values at sites of significant plastic deformation, as shown in Fig. 6. The measurement results are presented in Tab. 5.

Figure 6 Residual stress measuring position on vessel head

It is important to note that measurements were made primarily in the HAZ or in zones close to it, with a relatively limited number of data points for this type of analysis. The values of the principal residual stresses were recalculated using Mohr's circle equation. The recalculated principal stresses were oriented to align with the directions of the primary operating stresses in both the meridional and circular directions. The circularly oriented part of residual stress ($\sigma_{res\text{-}c}$) was used for further analysis in the structural integrity assessment.

2.7 Determination of Fracture Toughness, K_{Ic}

Experimental determination of J_{Ic} (critical J-integral) was done in accordance with the following standards ASTM E399 [21] and ASTM E1820 [22]. Due to the fact that the conditions of a plane-state of deformation were not achieved (acc. Eq. (2)), instead of applying linear-elastic fracture mechanics, it was decided to use elastic-plastic fracture mechanics.

$$B \geq 2,5\left(\frac{K_{Ic}}{R_T}\right)^2 \tag{2}$$

Using the determined value of the critical J_{Ic}-integral, the critical SIF (stress intesity factor) for a plane strain state of deformation (K_{Ic}) was recalculated based on the following equation:

$$K_{Ic} = \sqrt{\frac{J_{Ic} \cdot E}{1-\nu^2}} \tag{3}$$

Tests were conducted on two samples taken from the vessel heads. From each vessel head, a compact tension (CT) specimen was prepared, as illustrated in Fig. 7. These specimens had the same nominal width W and height H but differed in thickness B, adjusted according to the head's thickness. In order to obtain test specimens with parallel sides, the actual thicknesses of the test CT-specimens were 11 and 3 mm.

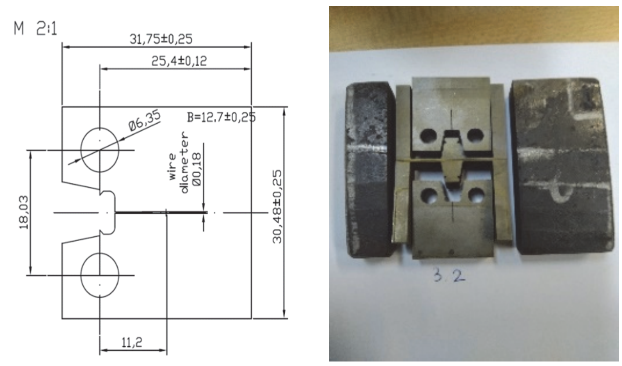

Figure 7 CT- specimens

The conditions for the experimental tests were as follows: The CT-specimens were prepared with a mechanical notch in the heat-affected zone (HAZ), identified as a critical area of the vessel head. For further analysis, experimentaly determined values of yield strength (R_{eH}) and tensile strength (R_m) were taken, as shown in Tab 5.

Testing was conducted using a controlled servohydraulic machine (type INSTRON 1255) with a dynamic/static loading capacity of up to 250 kN, in accordance with [22]. The crack mouth opening displacement was measured by clip gauge. Tests were performed at room temperature with displacement control at a speed of 1 mm/min.

Fig. 8 displays force-displacement diagram for tested CT-specimen with a thickness of 3 mm, illustrating the procedure for testing the fracture toughness using a clip gauge. Clip gauge records displacement ("v" in mm) in the direction of force ("F" in N) application (as known as "Load Line Displacement - LLD").

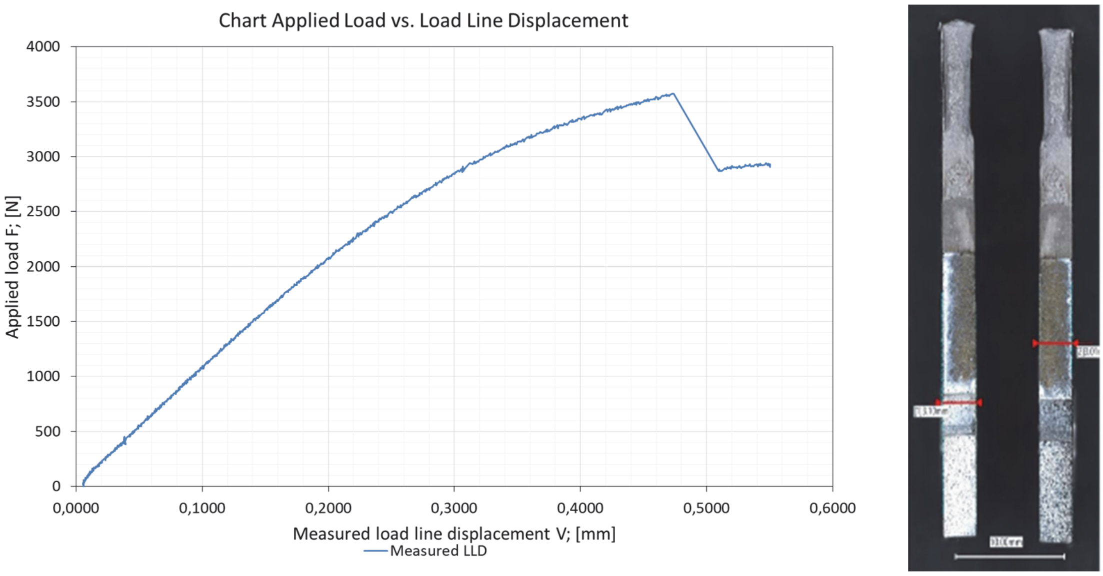

Figure 8 Curve *F*-*v* for specimen #3 mm

The results were processed in accordance with [21, 22]. Fig. 9 shows a typical curve for determining the K_I (fracture toughness) according to the fracture behavior for the CT specimen thickness of t = 3 mm. For specimens with stable fracture behavior, analysis is performed according to [22], while for specimens where instability occurs, analysis is performed according to [21] and the critical value of fracture toughness K_{IC} or K_{IQ}. Critical values of fracture toughness for each tested CT specimen are presented in Tab. 4.

The fracture toughness values defined in this way can be used as critical values for evaluating the structural integrity of vessel heads.

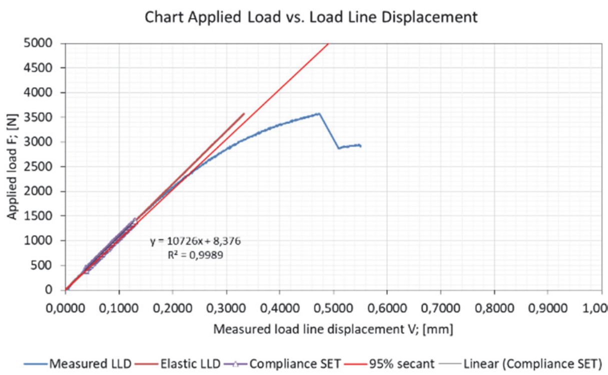

Figure 9 Determination of the fracture mechanics parameter

2.8 Fracture Safety Assessment

Structural integrity assessment of the pressure vessel head is defined using the Failure Assessment Diagram - FAD [23]. This two-parameter approach is more general than the application of the CTOD curve, as it also accounts for plastic collapse. Given that the analysis is performed using a conservative approach, the cracks under consideration are isolated linear surface cracks (semi-elliptical cracks). The analysis focuses on the stresses present in the torispherical vessel head, incorporating the residual stresses resulting from welding.

The Failure Assessment Diagram delineates the boundary between two independent solutions:

- one predicting fully brittle fracture based on the parameter K_r, and
- the other indicating structural failure due to plastic collapse, defined by the plastic analysis parameter S_r.

Brittle fracture parameter, K_r, is calculated according to the equation:

$$K_r = \frac{K_I}{K_{IC}} \tag{4}$$

The plastic collapse parameter, S_r, is calculated according to the equation:

$$S_r = \frac{\sigma_n}{\sigma_F} \tag{5}$$

There are:

- $\sigma_n = \left(1 + \frac{a}{t}\right) \cdot \sigma$, [MPa], the primary stress, internal pressure increased by the stress concentration,
- $\sigma_F = \frac{R_{eH} + R_m}{2}$, [MPa], plastic collapse stress, the mean value of the sum of the yield strength and the tensile strength obtained by tension testing.

The stress intensity factor, that takes into account only the operating loads, is estimated by the equation:

$$K_I = \sigma_{tot} \cdot \sqrt{\pi \cdot a} \,. \tag{6}$$

There are:

- $\sigma_{tot} = \left(\sigma_{\varphi} + \sigma_{res-c}\right)$, [MPa], total stress consists of primary and secondary stress,
- $\sigma_{\varphi} = \dfrac{p_i \cdot L}{4 \cdot t}\left(3 - \dfrac{L}{R}\right)$, [MPa], primary (operating) circular stress on the spherical part of the vessel head, [22],
- σ_{res-c}, [MPa], secondary (residual) stress defined from the equation of Mohr's circle, circular direction,
- $a = t/2$, [mm], crack depth taken as half the thickness of the vessel head,
- p_i, [MPa], operating internal pressure, where the stresses on the mantle are the same for all variants of thicknesses and diameters,
- $L = 0.8D$, [mm], radius of spherical part of the vessel head,
- $R = D/2$, [mm], radius of vessel head,
- $D = 1250$, [mm] and $D = 2500$, [mm], outer diameter of vessel heads,
- t, [mm], vessel head wall thickness, $t = 6$ i 14 mm,
- K_{Ic}, [MPam$^{1/2}$], fracture toughness determined indirectly using J_{Ic} and as values $K_{mat} = K_{IQ}$, presented in the Tab. 4,
- The analysis is carried out for four varieties of vessel heads with the following dimensions ∅1250 × 6, ∅1250 × 14, ∅2500 × 6 i ∅2500 × 14 [mm].

Parameters S_r and K_r are determined using Eqs. (4) and (5), which leads to the equation:

$$K_r = S_r \left[\frac{8}{\pi^2} \ln \sec \frac{\pi}{2} \cdot S_r \right]^{-\frac{1}{2}} \tag{7}$$

The issue arises for cracks oriented in the axial direction of the welded joint, specifically in the meridional direction of the head, where the influence of the curvature of the contour (cross-section) can be disregarded given the dimensions of the head. With these assumptions, the problem simplifies to that of a tensioned plate, where the dimensions are significantly larger than the length of the crack. The total stresses (operating and residual stresses) that contribute to crack opening are in circular direction. Additional input data necessary for determination of integrity assessment of the structure using the "Failure Assessment Diagram" are presented in Tab. 4.

This approach is evidently very conservative, designed to determine the integrity of the structure in the simplest and safest manner possible.

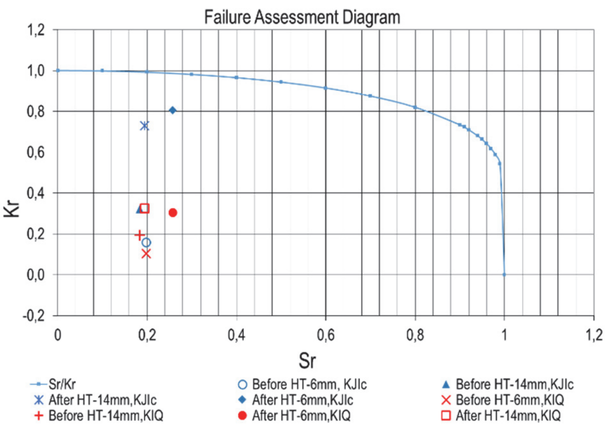

Figure 10 Failure Assessment Diagram - FAD

Table 4 Input data for determination of parameters *Kr* and *Sr*

Dimension	Inner pressure	Primary stress	Secondary stress	Total stress	SIF for σ_{tot}	Fracture toughness	Parameter	Prim. stress *x* stress concentr.	Plastic failure stress	Parameter
D/t / mm	p_i / MPa	σ_{φ} / MPa	σ_{res-c} / MPa	σ_{tot} / MPa	K_I / MPa√m	K_{IQ}/K_{JIc} / MPa√m	K_r for $(K_I/K_{IQ})/(K_I/K_{JIc})$	σ_n / MPa	σ_F / MPa	S_r
Before PWHT										
∅1250#6	1.47	86	12	98	9.5	92.3/60.1	0.1/0.2	129	648	0.2
∅2500#14	1.7	86	28	113	16.8	86.7/52.4	0.19/0.3	129	695	0.18
After PWHT										
∅1250#14	3.43	86	76	162	23.9	73.8/32.9	0.32/0.7	129	662	0.19
∅2500#/6	0.74	86	168	254	24.7	80.7/30.6	0.3/0.8	129	504	0.26

As shown in Fig. 10, all the values of the parameters K_r and S_r, calculated for cracks corresponding to half the thickness of the vessel head sheets (tested samples thickness of 6 mm and 14 mm), are below the limit curve, within the safe area. The results for the samples taken post weld heat treatment are less favorable, positioning them closer to the acceptance limit for both sheet thicknesses.

3 RESULTS

Based on the results of all tests presented in Tabs. 4 and 5 and Fig. 10, the following conclusions can be drawn:

- Better hardness values were observed in the welded joint of the 14 mm sheet compared to the 6 mm sheet.
- The mechanical properties of the samples exceeded the minimum standard values for base material P460NL1, with yield strengths of $R_{eH} = 467$ MPa for the 6 mm sheet and $R_{eH} = 531$ MPa for the 14 mm sheet. Plastic deformation contributed to the material's strengthening, leading to increased yield and tensile strength. However, thermal treatment resulted in a reduction of these mechanical properties. The breaking occurred in the HAZ.
- Compression residual stresses were introduced in a circular direction through pressing. Sheet 14 mm has a lower value of residual stress.

- Generally poor total impact energy properties prior to heat treatment indicate brittle material behavior.
- The K_{JIC} values were relatively low, likely due to the location of the fatigue crack tip in the HAZ. Experimental results show that the measured fracture toughness K_{JIC} did not vary significantly with the thickness of the base material, reflecting a generally negative influence from heat treatment.
- There was a low resistance to the initial cracks.

Table 5 Test results before / after PWHT

Thickness		6 mm	14 mm
Yield strength	R_{eH} / MPa	614/460	636/515
Tensile strength	R_m / MPa	682/547	754/810
Elongation	Δ / %	21.5/20.5	29.5/13.5
Contraction	A / %	9.5/7.5	18.5/6.5
Impact energy	KV / J	15/40	42/57
Hardness HV	*HAZ*	278/244	301/301
Residual stress-circ. direction	σ_{res-c} / MPa	12/168	28/76

4 DISCUSSION

Considering that the K_{IQ} values are significantly higher than the K_{IJC} values, using K_{IJC} as a comparative parameter emphasizes a conservative approach to assessing the integrity of these pressure vessel heads. In both scenarios, it can be concluded that the pressure vessel heads are safe from brittle fracture and plastic collapse, although with a greater tendency toward brittle fracture.

5 CONCLUSIONS

Overall, considering the results of all the tests performed before and after the heat treatment, it can be concluded that the heat treatment did not improve the mechanical properties.

Furthermore, the integrity assessment results presented in the FAD diagram for samples after heat treatment are worse than those obtained prior to treatment. This suggests that the post weld heat treatment was either inadequately selected or improperly executed.

The process of incremental plastic deformation introduced compressive residual stresses, which positively impact the reduction of crack formation and propagation risks. It has been confirmed that the heat-affected zone (HAZ) remains a potential weak point.

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Contact information:

Nedeljko VUKOJEVIĆ, Professor
(Corresponding author)
University of Zenica,
Faculty of Mechanical Engineering,
Fakultetska 1, 72000 Zenica
E-mail: nedeljko.vukojevic@unze.ba

Zlatan IŠTVANIĆ, PhD
Metacomm Jajce d.o.o.,
Bage 5, 70101 Jajce, Bosnia and Herzegovina
E-mail: zlatan.istvanic@gmail.com

Fuad HADŽIKADUNIĆ, Professor
University of Zenica,
Faculty of Mechanical Engineering, Fakultetska
1, 72000 Zenica
E-mail: fuad.hadzikadunic@unze.ba

Nenad GUBELJAK, Professor
University of Maribor,
Fakulteta za strojništvo Maribor,
Smetanova ul. 17, 2000 Maribor,
E-mail: nenad.gubeljak@um.si

Amna BAJTAREVIĆ-JELEČ, Teaching
Assistant University of Zenica,
Faculty of Mechanical Engineering, Fakultetska
1, 72000 Zenica
E-mail: amna.bajtarevic@unze.ba