Fatigue failure analysis of three-layer Zr–Ti/Zr–Steel composite plates: an insight into the evolution of cracks initiated at the interfaces

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Abstract

Initiation and evolution of fatigue cracks at the interfaces in three-layer Zr–Ti/Zr–Steel composites is herein examined by in situ optical microscopy for the first time. Specimens cut out from three composite plates comprising Zr 700, Ti Gr. 1, and P265GH steel layers have been subjected to uniaxial fatigue cyclic loading. It is found that mechanical property mismatch between layers and defects at the interfaces can reduce the fatigue life of composite plates. An insight into the evolution of cracks initiated at the interfaces reveals that (1) most of the cracks grow into adjacent layers along two distinct planes, and (2) these cracks could lead to the fatigue failure of composites. One of these planes coincides with the adiabatic shear band orientation found in Ti Gr. 1 and Zr 700 layers. The interfaces in multilayer metallic composite could have excellent fatigue strength depending on their structural properties.

Keywords Layered structures · Explosive welding · Fatigue · Mechanical testing · Joints/joining · Adiabatic shear bands

1 Introduction

Multilayer composition of different materials plays a crucial role in specialised industrial equipment. Each layer provides a specific functionality, and the arrangement of the layers fulfils the design requirements. Such multilayer metallic composites may serve as structural and electrical transition joints applied in shipbuilding, (Al – steel) [1, 2], cryogenic pressure vessels [3, 4] including hydrogen storage, automotive industry [5–7], and electrical applications (Cu – Ti) [8,

9]. Moreover, in chemical process equipment, the multilayer plates provide excellent corrosive resistance even at high temperatures by applying layers made of titanium, zirconium alloys [10] or stainless steel [11]. The dissimilar physical properties of metallic materials used in a multilayer composite make the process of joining the layers challenging or even impossible using conventional welding techniques [12, 13].

Explosive welding is a high-velocity impact process that enables the welding of dissimilar materials. It is a solid-state welding process where the energy of an explosive charge accelerates a flyer plate that collides with a base plate, thereby forming the bond [14]. The bond formation process is extremely complex and far from being fully understood and modelled [15]. The welding process is mainly controlled by two parameters, i.e., the amount and type of explosive charge and the predetermined distance between the welded layers, called stand-off distance. Estimating these two parameters for a required material layer composition is the key to a successful welding process.

In some cases, an interlayer is introduced between primary materials to improve the welding process and obtain a product with better mechanical properties [10]. The explosively welded composite is first inspected by a non-destructive ultrasonic examination [16], and then material samples are cut out for mechanical tests. The conventional mechanical experiments include the tensile-shear test, peel

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test, bending test, impact test, and microhardness tests [17, 18]. The results of such tests are used to optimise the welding and heat treatment parameters [19, 20]. Mechanical tests under fatigue loading are much less frequent. The characteristic feature of the interfacial bond is its periodic deformation (described by wave height and length) that remarkably depends on the welding parameters [21, 22]. For higher explosive welding parameters, the locally melted areas may be formed, including brittle intermetallic compounds and shrinkage cracks [23, 24]. For significant Young's modulus mismatch between layers, the interfacial wave profile creates stress concentration and additional shear stress components. This feature together with the possible existence of shrinkage cracks and brittle compounds in the interfacial zone make this zone a potential site for fatigue crack initiation. Additionally, the locked-in residual stress [25–27] may accelerate or block the initiation and evolution of fatigue cracks.

Despite the detection of traits for the fatigue crack initiation in explosively welded metallic composites, only few studies concerning this problem can be found in the literature. Some of them analysed the effect of the heat treatment on the fatigue life of bimetallic plates subjected to cyclic bending [28–30]. In these studies, the bond interface Steel/Ti was parallel to a neutral plane of bending, and the interface was located a few millimetres away from the specimen surface where the highest stress was generated, implying that, although the multilayer composite carries the cyclic loading, the bond interface is less deformed and stressed than the specimen surface of the homogenous material. Thus, the cracks preferably initiate on the specimen surface, with subsequent propagation into the material through the bond interface, and that is confirmed by observations reported in [29–31]. The crack propagation behaviour into the interface could be modified owing to the mismatch of the material layers properties [32, 33]. More insights into the fatigue behaviour of the interfacial zone and the effects of such a zone on the fatigue life are provided by the results of tests with a nominal uniform distribution of the strain or stress along the specimen cross section.

Note that the adjective 'nominal' implies neglecting the stress–strain disturbance due to the wavy profile of the bond interface. Nominal uniform strain distribution could be assumed in multilayer plates with force applied in the parallel direction to the interface. For different Young's moduli of material layers, the stress distribution is not uniform. When the force is applied in a perpendicular direction to the bond interface, the nominal uniform stress distribution is assumed.

Snizek et al. [28] conducted fatigue tests on AA2519/AA1050/Ti6Al4V three-layer plate under cyclic uniaxial loading in a direction parallel to the interface. The study concluded that the performed heat treatment increased the fatigue life at a higher loading amplitude regime (in a range

of $2 \cdot 10^4$ – 10^5 cycles), while the fatigue life above 10^5 cycles remained unchanged. Szachogluchowicz et al. [34] tested the same AA2519/AA1050/Ti6Al4V three-layer plate but under low-cyclic-fatigue regime. It was observed that the fatigue crack started at both interfaces and propagated perpendicular to loading direction accompanied by layer delamination. The performed heat treatment increased the fatigue life and moved the location of crack initiation to surface of the AA2519 layer.

Karolczuk et al. [35] tested Ti Gr. 1–S355N steel bimetallic plates under cyclic uniaxial loading with the force parallel to the bond interface. They found that 20% of the specimens failed from fatigue crack initiated at the interface, while the remaining cracks initiated in the steel. The longest fatigue life was detected in the specimen with exceptional flat interface. The tests conducted under the controlled force signal revealed significant ratcheting phenomena (a progressive cyclic increase in the strain mean value) at lower fatigue life regime. Böhm et al. [36] tested structural transition joint cladding consisting of four layers of A5083, A1050, Ti Gr. 1, and Grade D steel, under a random force signal applied in the perpendicular direction to the bond interface. Among the six tested specimens, two failed in the Ti Gr. 1 – Grade D steel interface owing to the partially unwelded area. Becker et al. [37] analysed the fatigue strength of aluminium to steel transition joint (S355/Al 1050/Al 5754) under uniaxial cyclic loading under different values of stress ratio $\sigma_{\min}/\sigma_{\max}$, with force in the perpendicular direction to the bond interface. Additionally, cyclic torsion tests were conducted. It was reported that, under tension–compression loading, 99.9% of specimens failed at the interface between S355 steel and 1050 aluminium alloy. On the other hand, under cyclic torsion, the cracks were initiated at the interface of Al 1050/Al 5754.

However, the studies mentioned above did not reveal the exact location of the fatigue cracks and their orientation and evolution even if detected at the interfaces. Further, effects of the stress rising features of the bond interface (interface morphology and mechanical property mismatch of welded layers) on the fatigue crack initiation and the reduction in the fatigue life of multilayer plates were not analysed. In this regard, the main aim of this study is to provide experimental insights into both the fatigue failure and the evolution of fatigue cracks initiated at the interface. Additionally, the effects of the interfacial wave height and the mechanical property mismatch between the bonded materials on the fatigue life of Zr 700 – Ti Gr. 1/Zr 700 – P265GH steel multilayer metallic plates are herein analysed. The multilayer plates with a zirconium alloy with outstanding corrosive resistance could replace the solid structures with cost-effective benefit [10]. A thorough search of the relevant literature yielded no research on the multilayer plates with zirconium layer subjected to the fatigue loading.

The purposes of the study are achieved by fatigue tests conducted on specimens cut out from explosively welded plates under three different cases of welding conditions. The tests have been performed under uniaxial cyclic loading with force applied parallel to the interfaces. During the fatigue test, the selected specimens have been periodically observed by means of an optical microscope to detect early fatigue cracks and examine their evolution.

2 Experiments

2.1 Materials in as-delivered condition

Three plates made of different materials in as-delivered condition have been used in explosive welding. The basic mechanical properties of the applied material, i.e., Zr 700 zirconium alloy (~99.5 wt% of Zr + Hf), Ti Gr. 1 titanium alloy (~99.5 wt% of Ti), and P265GH steel (~0.15 wt% of C), are presented in Table 1. The properties have been obtained based on the tensile tests conducted in accordance with EN-10002-1 standard. The Young's modulus values E reported in Table 1 were found by linear fit of registered stress-strain signals in the elastic strain regime. The strain has been measured using a mechanical extensometer with a gauge length of 50 mm. The microstructure of Zr 700 alloy reveals α phase grains of sizes between 70 μm and 170 μm (Fig. 1a). Titanium alloy Ti Gr. 1 is characterised by the presence (Fig. 1b) of equiaxed grains of α phase. The microstructure of P265GH pressure vessel steel depicted in Fig. 1c reveals equiaxed ferrite grains 10–20 μm in size and band formation of perlite grains 4–11 μm in size.

Table 1 Basic mechanical properties of welded materials in as-received condition

Material	E , GPa	ν , —	$R_{p0.2}$, MPa	R_m , MPa	A , %
Zr 700	101	0.38	216	269	35
Ti Gr. 1	109	0.37	251	325	46
P265GH	193	0.29	268	391	41

2.2 Manufacturing of three-layer metallic composites

Three different explosive welding systems have been applied to produce three-layer composite plates. The systems have been labelled as Case 1, Case 2, and Case 3. For all cases, the P265GH steel has been used as the base plate and the Zr 700 alloy as the flayer plate. The plates with sizes shown in Fig. 2 have been welded in the parallel system using an explosive charge with ammonium nitrate NH_4NO_3 as the main component (the complete constituents are classified). According to the experience of the manufacturing company, the interlayer material is required for the successful welding of zirconium-based materials when the thickness of the flayer plate is greater than 8 mm.

Case 1. A Zr 700 plate with a thickness of 10 mm was cladded to a prefabricated bimetallic plate Ti Gr. 1 – P265GH with stand-off distance $\delta = 10$ mm and detonation velocity $v_D = 2500$ m/s. The prefabricated plates consisted of 14 mm and 2 mm thick layers of P265GH and Ti Gr. 1, respectively.

Case 2. The same as Case 1, except for the stand-off distance, which is equal to 15 mm.

Case 3. Two plates, i.e., a Zr 700 plate with a thickness of 10 mm and stand-off distance of 6 mm to a Zr 700 interlayer

Fig. 2 Explosively welded plate with marked ignition zone and location of specimens for fatigue tests

Fig. 1 Microstructure of the materials in as-delivered conditions: **a** Zr 700 zirconium alloy, **b** Ti Gr. 1 titanium alloy, **c** P265GH steel

plate with a thickness of 3.2 mm, were cladded in a single explosion ($v_D = 3000$ m/s) to the base plate with a thickness of 25 mm. The stand-off distance between the interlayer and the base plate was equal to 25 mm.

The ultrasonic examination [16] did not reveal discontinuities except for the ignition zone (marked in Fig. 2) and in a 20 mm width band around the plate edges. The explosive welding parameters are listed in Table 2. Information concerning residual stresses and monotonic strength properties of composites for Case 1 and Case 2 have been presented in Ref.[38].

2.3 Structural properties of composite plates

The changes in the microstructure caused by explosive welding are mainly observed in the zone approaching the impact surface—the interface. The induced changes, along with the transition of the physical properties between the connected plates, have to be carefully analysed and quantified because of their probable effects on the fatigue lives of the explosively welded plates.

The interfacial area in explosively welded materials is characterised by wavy profile with height depending on the applied welding parameters [39]. The higher the explosive charge and the larger the stand-off distance, the higher the waves and the larger the melted areas observed [40, 41], which is also confirmed in the present analysis (Fig. 3).

Figure 3 shows the profiles of two interfaces for each case analysed. The height H of the interfacial waves is measured using an optical microscope at several points. The mean values, along with the error bands computed as the standard deviation, are shown in Fig. 3. For Case 3, the interface Zr 700 – Zr 700 was not revealed in the

polished analysed sample. The highest interfacial wave was observed for Case 3 between Zr 700 and P265GH steel. Cases 1 and 2 are characterised by a very similar (within the standard deviation) wave height of the interface with P265GH steel. The wave height of the Zr 700 – Ti Gr. 1 interface for Case 2 is approximately 15% greater than that for Case 1.

For some explosive welding systems, melted areas adjacent to the interface are observed. The melted areas could include cavities and intermetallic compounds, which are very hard and brittle compared to the surrounding material. The melted areas could include multiple shrinkage cracks owing to the rapid cooling rate. All these phenomena have been previously detected in the explosively welded composite of Zr – Steel and Ti – Steel and deeply analysed in [42–44]. In particular, the existence of cracks and brittle compounds was considered to degrade the mechanical properties [42, 45]. These phenomena were observed in the interface with steel for all the studied plates (Fig. 4).

The induced material deformation and the creation of new phases is detected through microhardness measurement. The Vickers microhardness measurement $HV_{0.05}$ has been conducted along three lines perpendicular to the interfaces, with the distance between points being 0.06 mm near the interface. The mean value of three measurements with standard deviation as the error band has been computed. The results are depicted in Fig. 5. Additionally, referential hardness values of materials in as-delivered conditions are illustrated as horizontal lines in Fig. 5.

The largest increase (55%) in hardness has been detected for Case 3 at the interface with P265GH steel (Fig. 5c). The steel reference Vickers hardness equal to 177 has increased up to 274. The increase in hardness for Cases 1 and 2 is comparable and equal to 49% and 44%, respectively. From such structural observations, it can be concluded that the interface between Zr 700 and P265GH steel, produced in the process marked as Case 3, is characterised by the highest wave and hardness. Therefore, the above observations anticipate that the interface between Zr 700 and P265GH could be the most sensitive to fatigue crack initiation and growth.

Table 2 Explosive welding parameters

Case	Interlayer	Detonation velocity, v_D , mm	Stand-off distance δ , mm
1	Ti Gr. 1	2500	10
2	Ti Gr. 1	2500	15
3	Zr 700	3000	6 + 25

Fig. 3 Profiles of the interfacial bonds with mean height H

2.4 Fatigue tests

Fatigue tests have been conducted under uniaxial force-controlled loading at an ambient temperature of about 20 °C. The constant-amplitude fully reversed uniaxial cyclic loading has been applied in a direction parallel to the plate composite interfaces, with the frequency of loading in the range of 1–10 Hz, adjusted to the force amplitude. As is specified in Fig. 6, the specimen geometry includes three

layers. Detailed sizes of the specimens and loading data are presented in Appendix. Layer thickness ratio in the tested specimens was modified comparing to the as-welded layer thickness ratio due to the limited loading range of the fatigue strength machine. This modification changes the stress distribution (see next chapter). However, it does not influence the main aim of the research. Figure 2 shows the specimen location and orientation, with respect to the welded composite plates. The fatigue failure is here defined when the

Fig. 4 Microstructure with grain deformation and microcracks observed in melted areas **a** Case 1, **b** Case 2, **c** Case 3

Fig. 5 Vickers microhardness distribution across the composite plates with horizontal lines representing the hardness of materials in as-delivered conditions

Fig. 6 Specimen geometry for fatigue test

complete separation of the specimen occurs. During the test, the force signals, elongation, and strain have been measured and recorded. The strain has been measured using an extensometer with a gauge length of 25 mm. For selected specimens, the test has been periodically paused for microscopic observation and crack measurements. The received data allow the thorough analysis of fatigue damage development discussed in the following section.

3 Calculation, results, and discussion

3.1 Stress calculation

Adequate comparison of fatigue results requires the calculation of the stress states in composite layers for all the tested plates. The force applied to the specimen through grips allows assuming a uniform distribution of the strain along the specimen cross-section, as was observed in [46]. Therefore, the material in each layer is considered to be continuum and homogenous. Furthermore, the connection between layers constitutes a continuous flat plane. Moreover, a uniaxial stress state and a linear elastic strain range are assumed.

Based on these assumptions, the following force balance equation is:

$$\sum_{i=1}^3 \varepsilon_a E^{(i)} A^{(i)} - F_a = \varepsilon_a E^{(1)} A^{(1)} + \varepsilon_a E^{(2)} A^{(2)} + \varepsilon_a E^{(3)} A^{(3)} - F_a = 0 \quad (1)$$

where ε_a is the strain amplitude; $E^{(i)}, A^{(i)}$ are the Young's modulus and cross-sectional area of the i th layer, respectively; F_a is the applied force amplitude. Thus, the products $\varepsilon_a E^{(i)}$ are the stress amplitudes $\sigma_a^{(i)}$ for the i -th layer. The strain amplitude ε_a is derived from Eq. (1) and multiplied by the Young's modulus, thereby defining the stress amplitude for each layer as follows:

$$\sigma_a^{(i)} = \frac{F_a E^{(i)}}{\sum_{i=1}^3 E^{(i)} A^{(i)}} \quad (2)$$

3.2 Fatigue lives

Table 3 lists the stress amplitudes for each layer, along with the number of cycles to failure, N_{exp} . Additionally, such a Table includes the location of the fatigue crack initiation that

Table 3 Fatigue test results

	Label	σ_a^{Zr} , MPa	σ_a^{Ti} , MPa	σ_a^{St} , MPa	N_{exp} , cycle	Primary crack
Case 1	F09	192	207	366	15,700	I
	F02	177	190	337	16,800	S
	F01	176	190	336	35,504	S
	F03	164	177	313	46,059	S
	F04	163	175	310	64,000	S
	F05	152	164	290	84,946	S
	F06	145	156	276	169,000	S
	F07	136	146	259	202,500	S
Case 2	F08	128	138	245	921,717	S
	F02	175	188	333	14,979	S
	F03*	160	173	305	15,641	S
	F07	180	194	342	15,896	S
	F01	188	202	358	15,932	S
	F05	154	166	294	78,505	S
	F06	149	160	283	87,260	S
	F08	131	142	251	195,000	S
Case 3	F04	134	144	254	270,687	S
	F02	184	—	351	8702	I
	F01	183	—	349	8963	I
	F04	155	—	298	16,288	I
	F03	156	—	298	17,901	I
	F05	127	—	242	105,000	I
	F06	112	—	214	220,000	I

Not included in the analysis owing to the exceptionally short fatigue life

developed and led to the total separation of the specimen—the primary crack. The primary fatigue cracks were initiated either at the interface with the steel (“I” letter in Table 3) or in the steel surface (“S” letter in Table 3). No crack initiations were observed in the Zr 700 or Ti Gr 1 layers.

The stress amplitudes in P265GH steel and experimental fatigue lives N_{exp} for all the analysed cases are plotted in Fig. 7. The linear regression lines represented in double logarithmic scales (the Basquin S–N curve) are also estimated and included. The presented error bands for stress amplitudes were calculated using the total differential method. Thus, the total differential of Eq. (2) was calculated with the following declared errors of variables: Young’s modulus $\Delta E = 2\%$ of the nominal value, force $\Delta F_a = 0.5\%$ of the measured value, specimen thickness $\Delta w = 0.05$ mm, width of each layer $\Delta t = 0.05$ mm.

The coefficient of determination R^2 was also calculated and included in the legend of the fatigue plot (Fig. 7). The insufficient number of specimens does not allow to determine whether the data for Cases 1 and 2 belong to the same population. However, the regression lines for Cases 1 and 2 pass through the error bands of both cases. Thus, from

an engineering perspective, Cases 1 and 2 could be merged into one case. This conclusion is supported by the observed significantly similar wave heights and distributions of micro-hardness. The quintuple increase in wave height, observed for Case 3, resulted in a substantial drop in the fatigue lives. For the low-cyclic-fatigue life regime ($\approx 10^4$ cycles), the life was reduced by a factor of two, whereas a life reduction factor equal to three was observed for the high cyclic fatigue regime ($\approx 10^5$ cycles).

3.3 Fatigue crack initiation site and growth

Microscopic observations of regions near the interfaces during the fatigue tests have revealed interesting phenomena. For Cases 1 and 2, initiation of single cracks is observed in the melted area of the Ti Gr 1 – P265GH steel interface under the steel stress amplitudes in the range of 276–294 MPa (Fig. 8).

However, those cracks did not lead to the final fracture. They developed mainly into the steel layer, reaching approximately 60 μm of the total length, when the primary fatigue crack was initiated in the steel site away from the interface

Fig. 7 Stress amplitudes in steel as function of the fatigue life of the composites

Fig. 8 Fatigue cracks initiated at Ti Gr. 1 – P265GH interface **a** Case 1, specimen F06 ($\sigma_a^{\text{St}} = 276$ MPa), **b, c** Case 2, specimen F05 ($\sigma_a^{\text{St}} = 294$ MPa)

and was rapidly developed in several cycles, leading to the complete separation of the specimen. In the steel, for stress amplitudes lower than 276 MPa, initiations of fatigue cracks at the interface were not found. Increasing the stress amplitude resulted in the initiation of multiple cracks in the melted area of the Ti Gr 1 – P265GH interface (Fig. 9). The performed etching process revealed that those cracks propagate transgranularly into the steel layer. For this stress level, the initiated cracks in the melted area propagate additionally into the Ti Gr. 1 layer, perpendicular to the crack direction in the steel. Those cracks propagate along the adiabatic shear bands (Fig. 9). The adiabatic shear bands are localised damages that can occur under the high strain rate as a results of large shear deformation under adiabatic condition [47, 48]. The adiabatic shear bands have approximately 45° inclination to the interface plane [47], and this phenomenon explains orientation of the fatigue cracks in Ti Gr. 1 layer

at the interface. Under the stress amplitude below 360 MPa, those cracks developed even up to 380 μm in length; however, the primary crack initiated in the steel away from the interface.

For the specimen (Case 1, F09) subjected to stress amplitude above 360 MPa, one of the multiple cracks initiated at the interface with steel developed through the entire steel layer leading to the complete separation of the specimen (Fig. 10b). Most of the cracks initiated at the interface with steel inclined by approximately 45°–55° to the applied force direction (Figs. 10a and 11a).

Figure 10 presents photos showing the development of the cracks for Case 1 and specimen F09. The primary crack for this specimen for the final 2000 cycles underwent the Ti Gr. 1 layer (Fig. 10b), causing its partial delamination with the Zr 700 layer. Figure 11 shows photos of the crack growth for Case 2.

Fig. 9 Fatigue cracks initiated at Ti Gr. 1 – P265GH interface for Case 2, specimen F07 ($\sigma_a^{\text{St}} = 342 \text{ MPa}$)

Fig. 10 Case 1. Development of cracks at the interface in specimen F09 ($\sigma_a^{\text{St}} = 366$ MPa) in two spots (a) and (b)

Fig. 11 Case 2. **a** Development of crack at the interface in specimen F07 ($\sigma_a^{\text{St}} = 342$ MPa), **b** development of crack at the interface in specimen F05 ($\sigma_a^{\text{St}} = 294$ MPa), **c** macro fractures of F07 and specimen F05

Case 3 is characterised by multiple cracks initiated in the melted areas of the interface with steel even under the lowest stress amplitude $\sigma_a^{\text{St}} = 214$ MPa. Furthermore, all primary cracks were initiated at the interface with steel. Exemplary photos of the crack development for Case 3 are shown in Fig. 12. The cracks did not lead to delamination between the two Zr 700 layers (Fig. 12). Adiabatic shear bands were found in Zr 700 layer at the interface with steel, along which fatigue cracks propagated (Fig. 12b).

All three cases of welding systems are characterised by no fatigue cracks initiated at the interfaces of Zr 700 – Ti Gr. 1 or Zr 700 – Zr 700. The non-existence of melted areas and insignificant mechanical property mismatch between these layers led to fatigue resistance higher than that observed at the interfaces with steel.

The evolutions of the observed cracks that initiate at the interface with the steel layer enable them to be named as transfacial cracks—the cracks growing through the interface. Note that a limited number of cracks could be classified as interfacial type, e.g., the crack observed at the Zr – Ti interface (Fig. 10b) and the cracks with partial paths within the Ti – Steel interface (Fig. 9).

4 Conclusion

The main conclusions of the study are summarised as follows:

- In the case of significant mechanical property mismatch between bonded layers, such as the ratio of Young's modulus around two layers (steel/Zr or steel/Ti), the interfacial wave height has a significant effect on the fatigue resistance.
- Fatigue crack may initiate at the interface with steel depending on the applied loading amplitude and the height of the interfacial wave. However, they may not lead to the final fracture for a lower loading amplitude and lower wave height.
- The increase in the interfacial wave height in the steel from approximately 70 μm to approximately 340 μm reduces the fatigue life by two to three times.
- Insight into the evolution of crack initiation at the interface reveals their frequent growth into the adjacent layers along two distinct planes, with the angle between them being equal to 90°.
- The adiabatic shear bands were found in Ti Gr. 1 and Zr 700 layers, promoting fatigue crack growth along these bands.

Fig. 12 Case 3. **a** Development of the crack at the interface in specimen F02 ($\sigma_a^{\text{St}} = 351$ MPa), **b** fatigue crack along the adiabatic shear bands

- The lack of melted areas and insignificant mechanical property mismatch between Zr 700 – Ti Gr. 1 and Zr 700 – Zr 700 layers led to a higher fatigue resistance than that observed at the interfaces with steel. No fatigue cracks were detected at the Zr 700 – Ti Gr. 1 and Zr 700 – Zr 700 interfaces.

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Author contributions AK: conceptualization, writing, original draft, methodology; AC: writing – review and editing; GR: investigation; SD: investigation, data curation; MP: investigation.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Sizes of specimen and fatigue loading data

	Label	t_1 , mm	t_2 , mm	T , mm	w , mm	F_a , kN	f , Hz
Case 1	F09	4.88	1.95	12.08	9.08	28.0	1
	F02	4.70	1.95	11.97	9.02	26.0	2
	F01	4.73	1.94	12.02	8.94	26.0	2
	F03	4.57	1.96	12.02	8.95	24.0	4
	F04	4.66	1.93	12.02	9.01	24.0	4
	F05	4.57	1.94	12.02	8.88	22.0	8
	F06	4.52	1.93	11.97	8.94	21.0	8
	F07	4.59	1.93	12.05	9.00	20.0	8
	F08	4.75	1.94	11.99	9.00	19.0	10

	Label	t_1 , mm	t_2 , mm	T , mm	w , mm	F_a , kN	f , Hz
Case 2	F02	4.70	1.95	12.00	9.08	26.0	2
	F03	4.75	1.95	12.05	9.02	24.0	2
	F07	4.87	1.95	12.07	9.01	26.0	1
	F01	4.88	1.95	12.08	9.00	28.0	2
	F05	4.90	1.95	11.96	9.01	23.0	4
	F06	4.79	1.95	11.99	8.98	22.0	5
	F08	4.79	1.95	11.99	8.78	14.0	10
	F04	4.53	1.95	11.79	6.64	20.0	7
Case 3	F02	4.11	3.10	12.06	8.99	26.0	2
	F01	4.15	3.10	12.04	8.93	26.0	2
	F04	4.06	3.10	12.01	8.97	22.0	4
	F03	4.27	3.10	12.07	8.90	22.0	4
	F05	4.18	3.10	12.07	8.93	18.0	8
	F06	4.19	3.10	12.06	8.98	16.0	10

Sizes were measured using an optical microscope at several points (mean values are presented in the above table).

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