



Mechanical properties and hot forming potential of micro-perforated titanium sheets for laminar flow control structures

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ARTICLE INFO

Keywords:

Titanium grade 2
Microstructure
Tensile test
Micro-perforation
Hybrid laminar flow control
Hot forming

ABSTRACT

This study investigates the tensile behavior and microstructural evolution along manufacturing stages of commercially pure titanium grade 2 sheets with laser-induced micro-perforations, developed for application in hybrid laminar flow control (HLFC) aerospace structures. Micro-perforated specimens with two different pitch configurations were tested in multiple directions relative to the rolling direction to evaluate the influence of hole density and crystallographic texture on mechanical properties. Microstructural analysis via EBSD revealed a typical recrystallized α -phase structure with marked crystallographic texture leading to orientation-dependent deformation behavior. The presence of micro-perforations resulted in a moderate decrease in ductility, with strength largely retained across directions, particularly for micro-perforation pattern with 1.0 mm pitch. Fractographic analysis confirmed ductile transcrystalline fracture mechanisms, with dimple structures evident in ligament regions between hole lines. Additionally, the hot forming of micro-perforated sheets into a complex HLFC demonstrator geometry at 715 °C caused noticeable grain coarsening and changes in micro-texture. Mechanical testing post-forming revealed a reduction in both strength and fracture strain, attributed to thermal oxidation and microstructural evolution. Nevertheless, the mechanical properties after hot forming could be approximated using proportional reductions from room temperature data, with deviations within 5%. These findings demonstrate that micro-perforated titanium grade 2 retains favorable mechanical properties under HLFC-relevant manufacturing conditions, supporting its use in next-generation aircraft structures.

1. Introduction

In 1990, an experimental trial was conducted to assess the feasibility of the hybrid laminar flow control (HLFC) technique in a modified Boeing 757 [1]. HLFC is a drag reduction technique that enables extended laminar flow on an aircraft surface at chord Reynolds numbers that would otherwise be associated with turbulent flow. Recent studies have demonstrated that integrating HLFC systems into wing structures can improve aerodynamic efficiency and reduce fuel consumption while maintaining economic viability [2]. Additionally, advances in surface treatment and adhesive bonding have enabled more effective laminar flow control through optimized porous materials and micro-perforations [3]. Applications for HLFC technology are being considered for wings,

horizontal and vertical stabilizers, and nacelles of commercial aircraft. Moreover, the use of computational modeling and experimental validation has refined the design of HLFC systems, allowing precise control of the boundary layer and improved performance under varying flight conditions [4]. Among other things, Young et al. [5] reported different approaches to laminar flow control using porous materials, micro-slotted surfaces and discrete holes.

One of the possible ways of implementing HLFC technology on aircraft fuselage surfaces is based on the use of thin-walled micro-perforated titanium structures [6]. It is fair to say that the production of large scale micro-perforated titanium panels on an industrial scale is a significant challenge. However, it should be noted that the use of micro-perforated panels in the aerospace sector is limited if the degradation of

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<https://doi.org/10.1016/j.matdes.2026.115953>

Received 4 December 2025; Received in revised form 24 March 2026; Accepted 31 March 2026

Available online 1 April 2026

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mechanical and corrosion properties resulting from the presence of micro-holes is not adequately addressed [6]. The static mechanical properties are primarily influenced by the remaining mesh area, which is defined by the hole dimensions and the spacing between the holes [7].

Discrete holes in thin sheet material can be produced using an electron or laser beam, with drilling using Nd-YAG or excimer lasers being the preferred technique since the mid-1980s [5]. In particular, the use of pulsed lasers is the most suitable manufacturing technique to meet the requirements for the production of large titanium plates for HLFC in the aerospace industry [8,9]. To economically produce micro-perforated titanium sheets for HLFC applications, drilling rates of at least 200 holes per second are required, which can be achieved by percussion micro drilling or single-pulse micro drilling [9]. Holes must be uniform in size and shape. Otherwise, non-uniformity will lead to inhomogeneities in suction velocities, which will affect the stability of the local boundary layer [5].

HLFC skins integrated into wing structures must have the required strength, stiffness and fatigue properties. In addition, HLFC skins must not fail or become detached from the wing structure [5]. The most likely causes of in-flight impact damage are hail or bird strike, ground handling impacts and foreign object damage during take-off and landing. From a damage tolerance point of view, the integrity of components must be maintained after impact [5]. Suction surfaces with discrete holes cannot be painted because paint would clog the holes. For this reason, HLFC structures must have good corrosion resistance, which favors titanium over aluminum as material choice [5].

In conjunction with CFRP designs (Airbus A350, Boeing B787), titanium and titanium alloys are preferred metallic materials due to their very good corrosion resistance and compatible coefficient of thermal expansion [10,11]. Good corrosion resistance of HLFC structures ensures long-term surface quality in terms of geometrical tolerances, surface finish and porosity [5]. Young et al. [5] reported that pure titanium and titanium alloys have been the material of choice for many HLFC projects because they can be slotted or drilled and still retain sufficient strength [5]. Titanium has demonstrated durability in harsh rain erosion tests and is considered as a benchmark for other materials [12]. If in contrary to CFRP aircraft structures, titanium parts are introduced in conventional aluminum aircraft structures, it has to be respected that titanium has a higher modulus of elasticity than aluminum, so fitting a stiffer titanium sheet into a conventional aluminum sash will result in high strain-related stresses [13,14].

Commercially pure titanium grade 2 was selected as the primary material for this study, as it represents the most cost-effective choice from both commercial and production perspectives. In general, commercially pure titanium grades 1–4 are preferred over titanium alloys due to their lower cost [15,16]. Among titanium alloys, Ti-6Al-4V remains the most readily available and widely used option. Other potential titanium-based alloys include TA10 (equivalent to Ti grade 12, Ti-0.3Mo-0.8Ni) and Ti-15V-3Cr-3Sn-3Al. The latter alloy offers a key advantage over Ti-6Al-4V, namely a lower modulus of elasticity (82 GPa vs. 110 GPa), which helps to reduce strain-induced stresses at the interface between the perforated skin and the primary wing structure [5].

The mechanical properties of commercial titanium alloys have been extensively studied over the past decades [17]. It has been found that the mechanical properties of titanium alloys are directionally dependent due to the hexagonal lattice structure [15]. In addition, titanium alloys have a high notch sensitivity, which means that the presence of micro-perforations as many stress concentrations can significantly affect the mechanical behaviour. As the mechanical behaviour of structural components in aircraft is of high importance [18], a fundamental understanding of the mechanical behaviour of micro-perforated titanium structures is required before they can be approved for potential applications. For instance, Daandels et al. [7] investigated the fatigue behavior of micro-perforated titanium structures and reported that the presence of micro-perforations reduces the fatigue strength, however,

without mentioning exact values. To date, there is a clear lack of studies that have investigated mechanical properties of micro-perforated titanium alloys in detail.

As understanding mechanical behavior at the coupon level is a fundamental first step in developing new technologies for the aircraft industry [19], the current study investigates the quasi-static tensile behavior of microperforated grade 2 titanium sheets to understand how varying hole spacing and thus hole density influences mechanical properties. The research was motivated by the need to support material and process development for HLFC system within the European project MICROFORM [20], which aimed to enhance aircraft efficiency through advanced structural components.

2. Experimental

2.1. Material and micro-perforation

The material was commercially pure titanium (CP-Ti, ASTM grade 2, AMS4902M [21]). The material was delivered in the form of $1000 \times 2000 \text{ mm}^2$ sheets with a thickness of 0.8 mm. The micro-perforation was introduced by a laser micro-drilling process, which is described, for example, in the work of Stephen et al. [8]. The holes were arranged in a rectangular pattern on the sheet surface. As this study did not focus on the laser micro-drilling process itself, further details of this technology are not provided here, as they form part of the supplier's proprietary know-how for the aerospace industry. Laser micro-drilling of titanium grade 2 sheets was conducted in accordance with the current state of technology and research.

Micro-perforations were introduced into the designated areas of the initial sheet material, and then specimens for tensile testing were extracted from the sheets. Two types of micro-perforations were investigated, where the shortest distances between the neighboring holes were 0.6 mm (designated as pitch 1, P1) and 1.0 mm (designated as pitch 2, P2), respectively. Fig. 1a-d shows the hole patterns for pitch 1 and pitch 2 in the titanium grade 2 sheets, along with a schematic illustration of how tensile specimens were extracted relative to the sheet rolling direction (RD): L (longitudinal, i.e. along the rolling direction), T (transverse) direction, and D (diagonal) direction.

2.2. Microstructural characterization

The structure of a grade 2 titanium sheet and the ligaments around the drilled holes were investigated by scanning electron microscopy (SEM, Jeol JSM-6490LV) combined with electron backscatter diffraction (EBSD, EDAX TSL OIM 7, OIMDC 7.3.1). Micro texture and structural morphology were analyzed. The EBSD analyses were performed with an acceleration voltage of 25 kV, an emission current of 73 μA , a beam current of 5.7 nA, a working distance of 13 mm and an aperture of 120 μm . The magnification was set at $200\times$. The micro area of the prepared specimens examined was $469 \mu\text{m} \times 469 \mu\text{m}$. With a step size of 1.00 μm , this resulted in a number of 254,469 measuring points. The pole numbers were calculated using the GSHE (Generalized Spherical Harmonic Expansion) method.

For the EBSD analysis, specimens were taken from titanium grade 2 sheet in both rolled and laser-drilled conditions, embedded in plastic compounds for fixation, fine ground in several steps (SiC sandpaper) and polished in the final step (OPS suspension). The plane of the polished specimens was defined by the T direction and the thickness or normal (S) direction of the titanium grade 2 sheet. The L direction was therefore perpendicular to the grinding plane aligned by T and S directions.

2.3. Mechanical testing

Flat tensile specimens were cut from the 0.8 mm thick micro-perforated titanium grade 2 sheets by water jet cutting. The flat tensile specimens were then milled to obtain a good edge quality and to

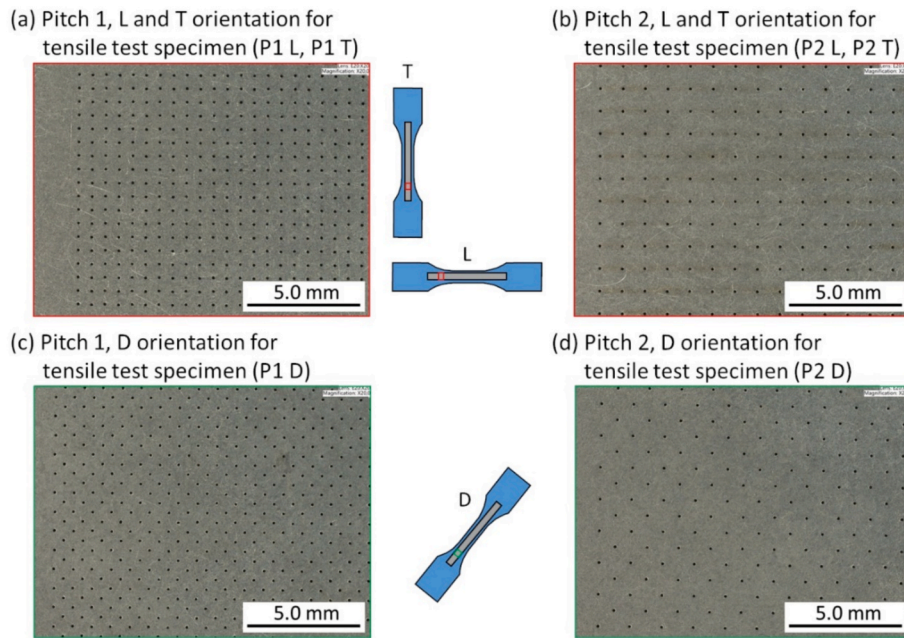


Fig. 1. Appearance of micro-perforation produced by laser drilling; rolling direction (L), transverse direction (T), diagonal direction (D); a), c) pitch 1 (P1, 0.6 mm $\times$ 0.6 mm); b), d) pitch 2 (P2, 1.0 mm $\times$ 1.0 mm).

ensure that the hole pattern was positioned in the center of the flat tensile specimens. The dimensions and orientation of the flat tensile specimens in relation to RD are shown in Fig. 2.

A 200 kN electromechanical testing machine (Zwick 1484) was used for the room temperature tensile tests. The strain of the tensile specimens was measured using a non-contact video extensometer (VideoXtens 1–120). Software (TestXpert) from the manufacturer of the testing machine was used to control the tensile tests and record the data.

2.4. Description of the experimental approach

The overall experimental workflow, summarized in Fig. 3, provides a structured overview of the study. The experimental program integrates material processing, mechanical characterization, microstructural analysis, and post-forming evaluation to establish clear relationships between microstructure and mechanical properties of micro-perforated Ti grade 2 sheets. Mechanical characterization begins with room-temperature tensile testing and fractographic analysis of both as-received base material (BM) and micro-perforated sheets. The microstructure of BM and perforated sheets is characterized using SEM combined with EBSD to evaluate the influence of micro-perforation on directional anisotropy during tensile loading.

In the final stage, a hot-forming process is implemented to manufacture HLFC demonstrator components from the micro-perforated Ti sheets. Hot forming is performed at 715 °C, simulating industrial

processing conditions. From the formed HLFC demonstrators, tensile specimens are extracted for post-forming mechanical evaluation. This procedure enables assessment of how micro-perforations and forming conditions affect structural performance. Fractured specimens are further examined to identify the underlying fracture mechanisms and their correlation with the micro-perforation patterns. Overall, the workflow combines micro-perforation, microstructural characterization, specimen preparation, mechanical testing, hot forming, post-forming evaluation, and fractographic analysis into a coherent experimental program that systematically links material processing to mechanical behavior.

3. Results and discussions

3.1. Microstructure of grade 2 titanium sheet and around drilled holes

Fig. 4a shows the microstructure of the grade 2 titanium sheet in the section plane aligned by T and S directions in the crystal orientation image. The crystal directions are color coded, i.e. red represents crystal direction $\langle 0001 \rangle$, blue represents $\langle 10\bar{1}0 \rangle$ and green represents $\langle 2\bar{1}1\bar{1}0 \rangle$. The respective crystal directions are parallel to the L direction. The crystal orientation image is dominated by grains with orientations between $\langle 2\bar{1}1\bar{1}0 \rangle$ and $\langle 10\bar{1}0 \rangle$. Rotating the measured individual orientations by 90° around T direction gives the usual (0001), (10 $\bar{1}0$) and (11 $\bar{2}0$) pole figures shown in Fig. 4b, which reveal an

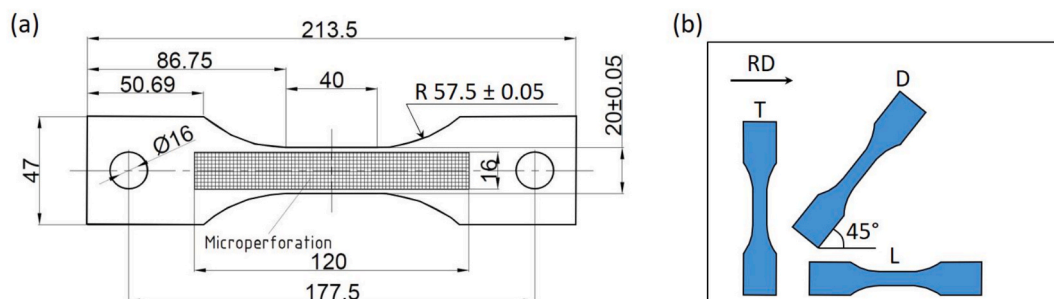


Fig. 2. (a) Geometry and (b) orientation of the specimens used for the tensile test with respect to the rolling direction of the sheet material. All dimensions are in mm.

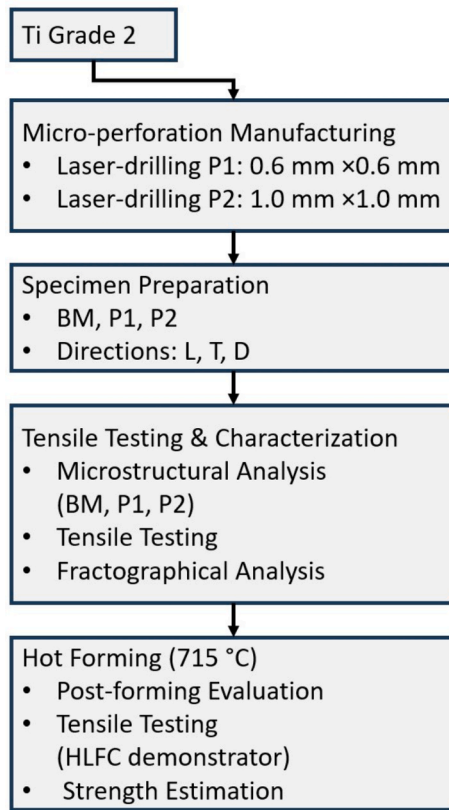


Fig. 3. Schematic overview of the experimental program, showing the main steps of the study.

orthorhombic sample symmetry in the examined section of the Ti grade 2 sheet. The maximum of the basal (00-01) pole densities lies on the T axis, corresponding to the T direction and is inclined at an angle between 30° and 35° to the S direction, while the (11-20) prismatic planes are oriented perpendicular to the L direction. The present micro texture can thus be specified as (0001) at $\pm 30^\circ \rightarrow T$, (11-20) $\perp L$ (corresponds to texture component (01-13)[2-1-10] in (hkl)[uvw] notation).

Ultimate tensile strength (UTS) and yield strength (YS) are direction dependent due to the crystallographic texture of rolled sheets and the hexagonal crystal structure of titanium [15]. The present micro texture is typical of rolled low-alloy titanium sheets [15]; the inclination of the basal planes in the T direction is also typical of rolled sheets with a hexagonal crystal structure and a c/a ratio of less than 1.633 (for pure Ti the c/a ratio is 1.588) [22]. The (0001) pole figure determined by EBSD, as shown in Fig. 4b, is consistent with the textural representations of grade 2 titanium in [15,23–26]. Commercially pure (CP) titanium is produced as a flat rolled product in the form of plates or sheets [15]. The process includes the steps of homogenization, rolling and recrystallisation annealing below the β -transus temperature [15,27]. CP titanium, such as grade 2 titanium, is predominantly rolled unidirectionally into a coil, which results in the basal poles being inclined approximately 30° from normal in the transverse direction (TD) [15].

The c/a ratio of 1.588 is the reason why deformation of titanium is possible through the interaction of basal, prismatic and pyramidal conduction. This means that basal and prismatic $\langle a \rangle$ -slip ($\{0001\} \langle 1100 \rangle$, $\{10-10\} \langle 11-20 \rangle$) as well as pyramidal $\langle c + a \rangle$ -slip of 1st and 2nd order ($\{10-11\} \langle 11-23 \rangle$, $\{10-22\} \langle 11-23 \rangle$) were combined for the calculation of the Taylor factors, because otherwise a homogeneous deformation would not be possible, for which at least 5 independent slip systems are required [22,28,29]. The EBSD software provides a tool (EBSD, EDAX TSL OIM 7, OIMDC 7.3.1) with which grain-specific Taylor factors can be calculated for each measured grain orientation. The averaging of all local Taylor factors with respect to the

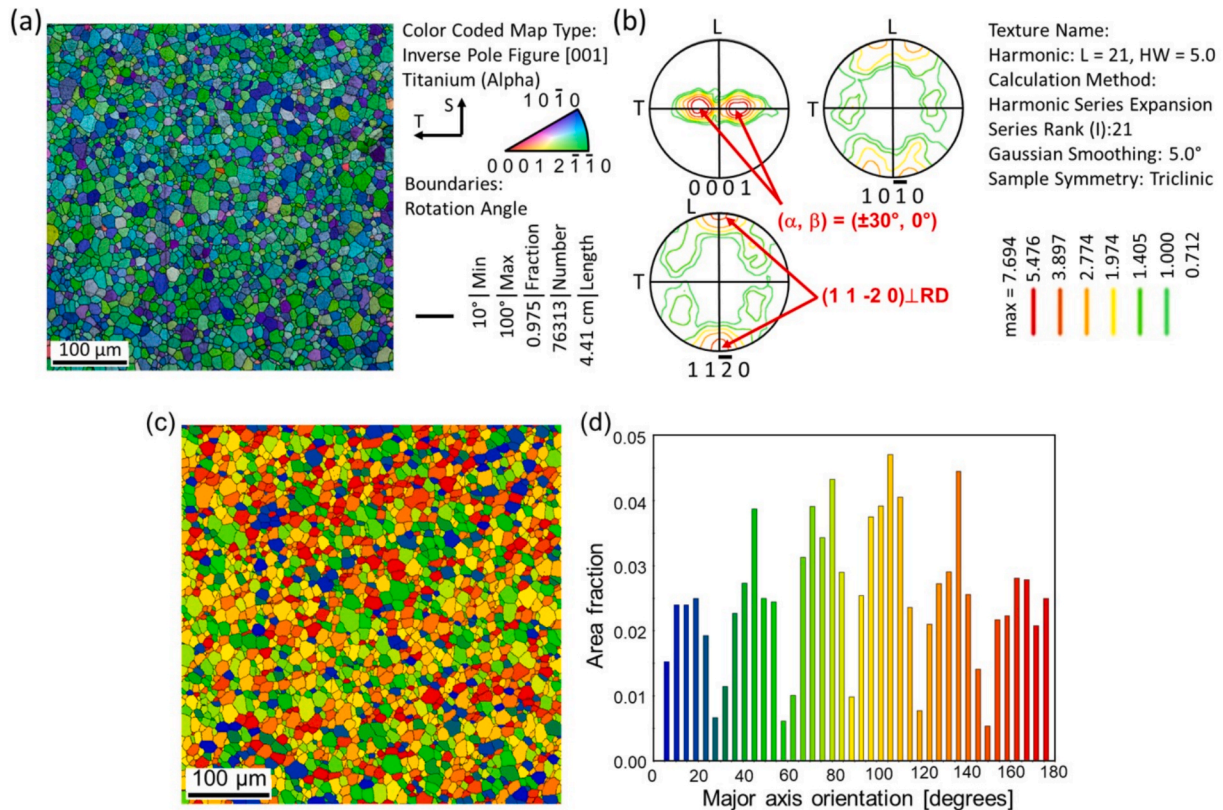


Fig. 4. Microstructure of Ti grade 2 BM: (a) crystal orientation map, (b) pole figures, (c) angular grain orientation map and (d) grain orientation angle with respect to the major axis orientation. The image horizontal in (c)-(d) corresponds to the T direction of the titanium grade 2 sheet.

grain orientation distribution results in the (global) Taylor factor. The yield strength is linked to critical shear stress via the Taylor factor. Based on the present micro texture, the Taylor factors $M_{RD} = 2.30$ and $M_{TD} = 2.50$ were obtained.

The microstructure of the grade 2 titanium sheet analyzed here had a mean grain length of $8.44 \mu\text{m} \pm 3.04 \mu\text{m}$ (d_{max}) and a mean grain width of $4.98 \mu\text{m} \pm 1.94 \mu\text{m}$ (d_{min}) with elongated grains and an elongation ratio of 0.59 ± 0.09 (d_{min} / d_{max}), see Fig. 4c. No preferred orientation of the grains was observed, i.e. the angle between the long axis of the grains (d_{max}) and the T direction parallel to the image horizontal was within the full range of 0° to 180° , Fig. 4d. Thus, the microstructure of the grade 2 titanium sheet was in the recrystallized state. According to Lütjering and Williams [15], the microstructure of CP titanium grades, including titanium grade 2, consists of recrystallized α -grains with Fe-stabilized dispersed β -phase at the grain boundaries. The β -phase inhibits the growth of the α -grains during heat treatments such as recrystallization annealing [15]. In the case of cold-rolled grade 2 titanium sheet, an angular distribution with respect to the long grain axis and the horizontal would have been set at 0° and 180° . In the T-S microsection plane of a laser-drilled grade 2 titanium sheet, the grains in the vicinity of a drilled hole predominantly have crystal directions between $\langle 2\bar{1}10 \rangle // L$ and $\langle 10\bar{1}0 \rangle // L$, see Fig. 5a-b.

To the left and right of the drilled hole, the grain length, grain width and aspect ratio were found to be almost the same as for grade 2 titanium sheet in its original state. Laser drilling did not cause any noticeable change in microstructure (coarsening, distortion) in the vicinity of a drilled hole. On the laser radiation side, the hole diameter of $114 \mu\text{m}$ is larger than the diameter of $74 \mu\text{m}$ on the laser exit side, resulting in a conicity of approximately 0.12 (Fig. 5c).

3.2. Quasi-static tensile test

The results of the quasi-static tensile tests are summarized in Fig. 6 and Table 1. The yield strength $R_{p0.2}$, ultimate tensile strength R_m and fracture strain A_f are higher in the T and D directions than in the L direction, regardless of the condition. The condition refers to whether the tensile specimens were solid BM, or micro-perforated (P1: $0.6 \text{ mm} \times 0.6$

mm, P2: $1.0 \text{ mm} \times 1.0 \text{ mm}$; distance P2 $\approx 1.7 \times$ distance P1). The behavior of the BM specimens as well as the microperforated specimens depends on the test direction due to the anisotropy of the hcp α -phase and the $(01\bar{1}3)[2\bar{1}10]$ micro texture. As mentioned above, the texture of rolled and recrystallized grade 2 titanium sheet fundamentally influences the mechanical behavior of the specimen. Calculation of Taylor factors, assuming that basal, prismatic and pyramidal slip can occur [[22], [28]-[29]], resulted in $M_{RD} = 2.30$ for loading parallel to L direction and $M_{TD} = 2.50$ for loading transverse to the RD, as previously mentioned. This indicates that the yield strength in the T direction must be higher than in the L direction of the grade 2 titanium sheet. This is confirmed by tensile tests on both BM and laser-perforated flat tensile specimens. Considering the results of the microstructural analysis in Section 3.1, the highest yield strength values for BM are found in the specimens taken and tested in the T direction, see Table 1 and Fig. 6, with an average yield strength of 408 MPa. The highest fracture strain values were obtained for the specimens tested in the D direction (average fracture strain of 46.0%). The highest tensile strength (average tensile strength of 480 MPa) was found in the BM specimens taken in the L direction. The presence of micro perforations shows similar trends.

Laser perforation generally results in a reduction in strength and fracture strain (Table 1). Young et al. [5] considered laser perforation as a surface porosity estimated by:

$$\text{Porosity} = \frac{\pi}{4} \left(\frac{d_{\max \text{ holes}}}{\Delta_{\text{holes}}} \right)^2, \quad (1)$$

where $d_{\max \text{ holes}}$ represents the maximum hole diameter and Δ_{holes} the distance between the holes. With an average hole diameter on the laser radiation side of $114 \mu\text{m}$ (see Fig. 5c), the porosity for laser perforation P1 is 2.82% and for P2 it is 1.02%. Correspondingly, the decrease in yield strength $R_{p0.2}$ and fracture strain A_f of titanium grade 2 sheets with laser perforation P1 is higher than for grade 2 sheets with laser perforation P2, as expected.

All the tensile specimens tested exhibited oblique fracture surfaces. This macroscopic appearance is independent of the direction in which the specimens were extracted from the titanium grade 2 sheet material. It can be seen that the angle between the fracture direction and the

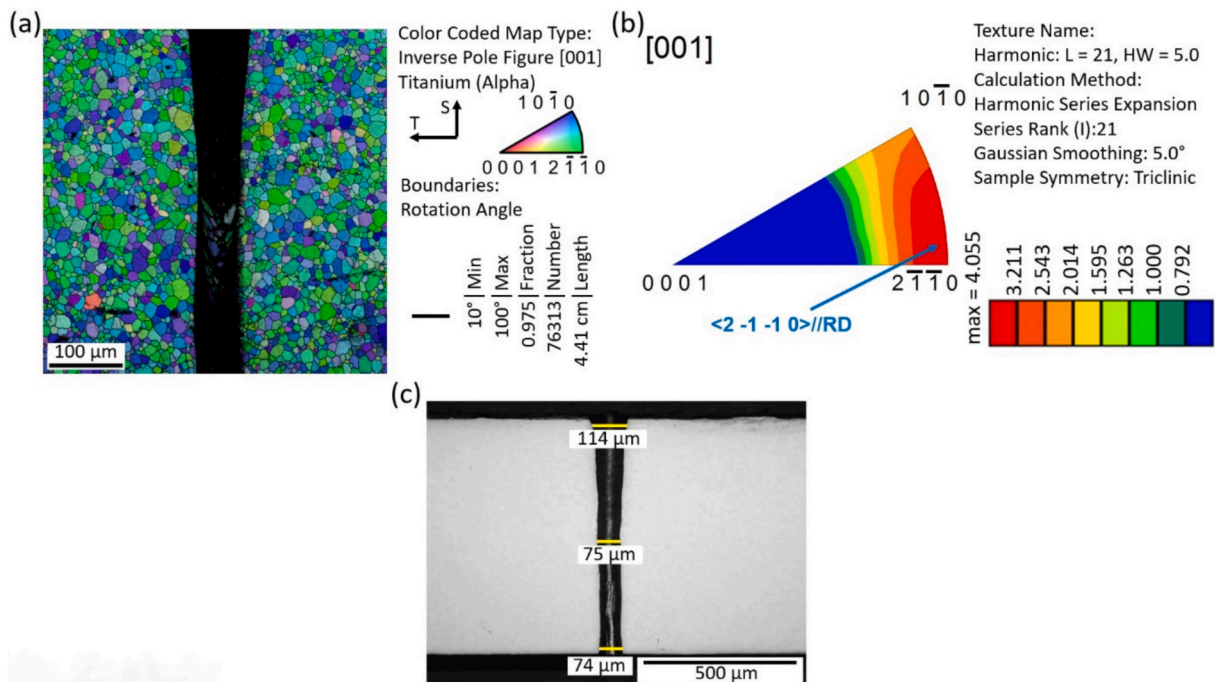


Fig. 5. Microstructure of titanium grade 2 in the vicinity of a laser-drilled hole: (a) crystal orientation map, (b) inverse [001] pole figure ([001] is parallel to the L direction) and (c) conical hole with a conicity of approx. 0.12.

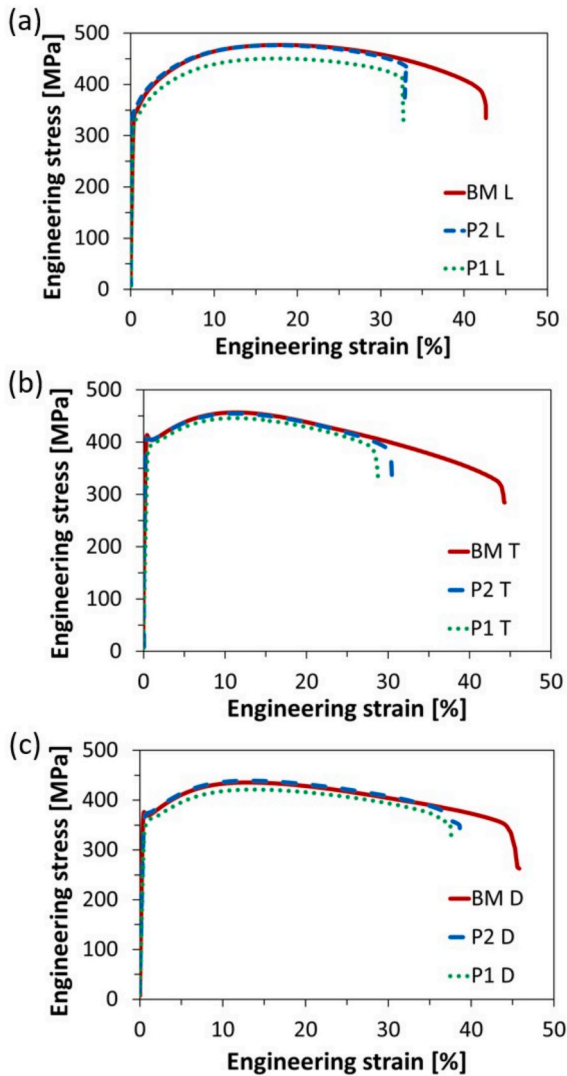


Fig. 6. Tensile test results obtained for specimens extracted (a) in L, (b) T and (c) D directions with regard to the RD of the sheet material, see also Fig. 2. One representative curve for each specimen type/direction is shown.

loading direction is between 48° and 60° , Fig. 7a-c. A sliding fracture under tensile, compressive or bending load occurs macroscopically at an angle of 45° to the applied tensile force and is caused by continued sliding along favorably oriented sliding planes under the effect of critical shear stresses, whereby the fracture position relative to the applied force can be different [30]. A sliding fracture can also be assumed for the flat tensile specimens analyzed here. As previously mentioned, due to the c/a ratio of 1.588, plastic deformation of titanium grade 2 is possible by

combining prismatic $\langle a \rangle$ -sliding and pyramidal $\langle c + a \rangle$ -sliding.

The laser perforation of grade 2 titanium sheets forces the formation of fracture layers in the ligaments between the holes in both L and T directions that are perpendicular to the maximum tensile stress. In contrast, the stressing of laser-perforated grade 2 titanium sheet parallel to the diagonal direction led to the formation of an oblique fracture, similar to the BM behavior. The comparison between the respective laser perforations P1 and P2 shows that different hole densities have no influence on the macroscopic fracture position, see Fig. 7d-i. Increasing the hole spacing by reducing the hole density or by rotating the laser-perforated titanium grade 2 sheet tends to lead to the formation of a more oblique fracture position in the flat tensile specimens, which reduces the number of cracks. This effectively makes the load-bearing ligaments larger, so that the processes leading to sliding fracture are less likely to be hindered by the drilled walls. It should be noted that both the solid BM and the laser-perforated flat tensile specimens exhibited clearly visible necking.

The macroscopic fracture behavior of the specimens after tensile test is shown in Fig. 7. As can be seen in the photos of the BM specimens (Fig. 7a-c), the lower the angle between the fracture direction and the loading direction, the higher the deformation. This results in a higher level of ductility. Thus, the values for the angle of 60° , 54° and 48° correlate with the values for the fracture strain of 43.8%, 45.2% and 46%, which were determined for the directions L, T and D, respectively. The presence of micro-perforations brings the additional fracture locations into the load-bearing cross-section, so that the fracture direction is inclined transverse to the load direction. This happens because the fracture predominantly runs through the nearest holes in a direction transverse to the load direction. This results in a reduction in the angle between the load direction and the predominant fracture direction. This reduction is more pronounced in the case of P1 because there are more holes compared to P2. There is also a clear reduction in the level of necking in tensile specimens with micro-perforation compared to BM specimens.

The characteristic values of laser-perforated grade 2 titanium sheets are slightly lower in the laser-perforated state than in the BM, but higher than the values for yield strength, tensile strength and fracture strain given in [15]. Titanium grade 2 contains a maximum of 0.03 wt-% nitrogen, 0.25 wt-% oxygen and 0.30 wt-% iron and has a tensile strength of 345 MPa, a yield strength of 275 MPa (also up to 450 MPa [17]) and a fracture strain of 20% according to [15].

The variation of yield strength, ultimate tensile strength, and fracture strain as a function of relative density (defined as 100% minus porosity level in %) is presented in Fig. 8. The results indicate that micro-perforation leads to a reduction in both yield strength (Fig. 8a) and fracture strain (Fig. 8c). Specifically, as the relative density decreases or the hole density increases, both the fracture strain and the yield strength decline.

The differences in ultimate tensile strength between the reference condition (BM) and micro-perforation P2 are minor (Fig. 8b). However, reducing the hole spacing from P2 to P1 leads to a clearly noticeable

Table 1

Tensile test results (average values from three specimens). The table also shows the percentage reduction relative to the BM properties for each loading direction.

Specimen type/ direction	$R_{p0.2}$ [MPa]	Reduction in $R_{p0.2}$ relative to BM [%]	R_m [MPa]	Reduction in R_m relative to BM [%]	A_f [%]	Reduction in A_f relative to BM [%]
BM L	349		480		43.8	
BM T	408		453		45.2	
BM D	376		433		46.0	
P1 L	329	-5.7	456	-5.0	31.9	-27.2
P1 T	391	-4.2	447	-1.3	28.7	-36.5
P1 D	358	-4.8	428	-1.2	36.7	-20.2
P2 L	345	-1.1	476	-0.1	33.8	-22.8
P2 T	405	-0.1	455	0.0	30.7	-32.1
P2 D	373	-0.1	439	+1.4	37.2	-19.1

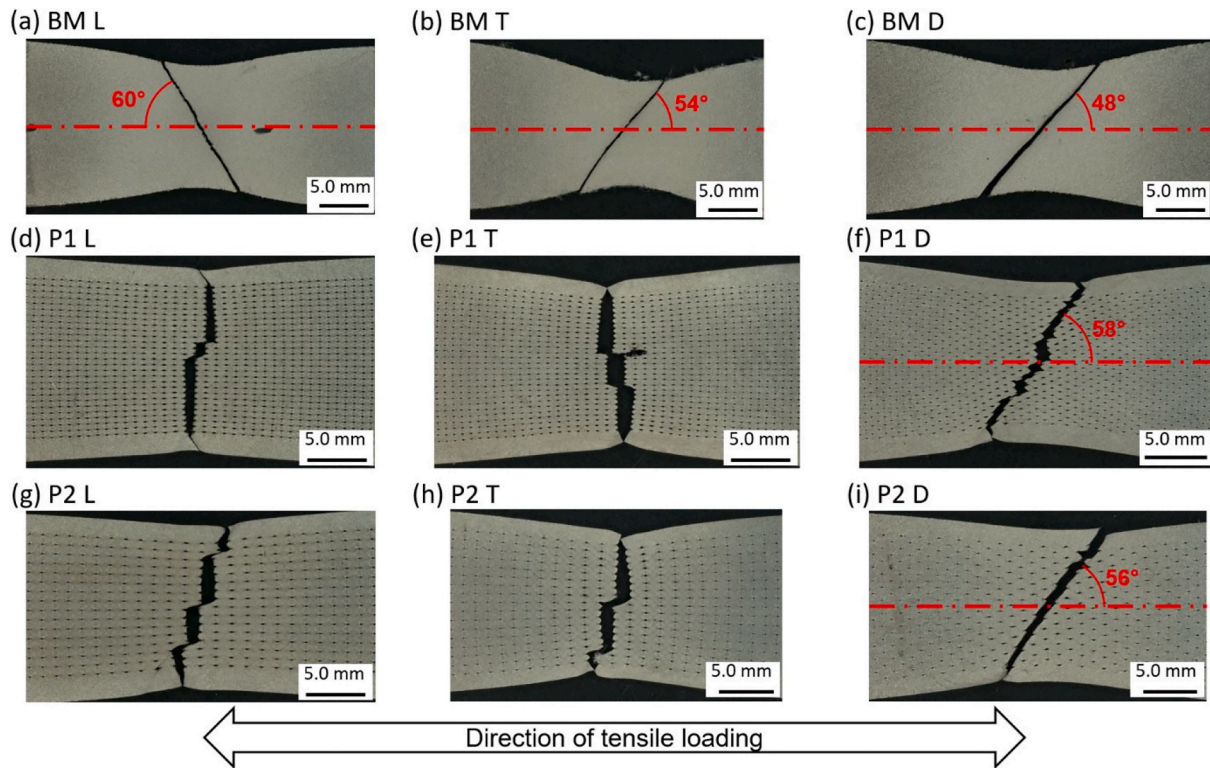


Fig. 7. Macrographs of failed flat tensile specimens after the tensile test.

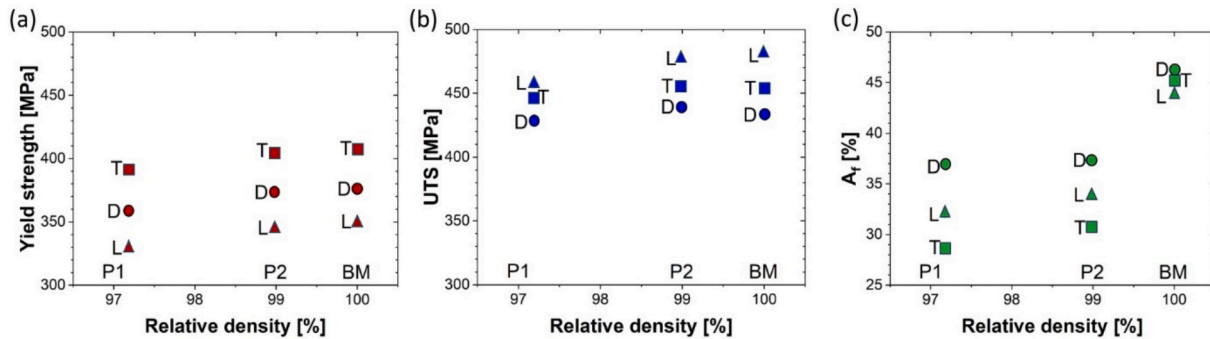


Fig. 8. Comparison of the effects of directional dependence (L, T, D) and micro-perforation on (a) yield strength, (b) ultimate tensile strength, and (c) fracture strain.

decrease in ultimate tensile strength. In the respective conditions P1, P2, and BM, the microtexture of commercially pure titanium grade 2 determines the yield strength, ultimate tensile strength, and fracture strain. However, as shown in Fig. 8, the mechanical behavior of micro-perforated 0.8 mm thick titanium grade 2 sheet is governed by the combined effect of hole density and microtexture.

Regardless of the relative density, the fracture strain in the T direction is lower than in the L direction, which in turn is lower than in the D direction (Fig. 8c). The highest elongations at fracture were observed in the D direction for all conditions (P1, P2, and BM). This observation suggests that the slip paths for mobile dislocations are likely more favorable in the D direction than in the L or T directions, which would explain the higher elongations at fracture measured. Based on this assumption, the laser-drilled holes can be considered as obstacles that interrupt the slip planes within the hexagonal α grains. The greater the number of laser-drilled holes, the more pronounced their effect as barriers to dislocation motion, potentially leading to strengthening. This strengthening effect likely explains why the reduction in strength due to laser perforation was relatively moderate.

The anisotropy caused by the texture of the grade 2 titanium sheet is not affected by micro-perforations P1 and P2. The crystal orientation images in Fig. 4a and Fig. 5a show that the crystal orientations in both the ligament (material between the laser-drilled holes) and the drilled hole environment are between $\langle 2-1-10 \rangle$ and $\langle 10-10 \rangle$. Furthermore, no differences between the drilled hole environment and the ligament were found in terms of average grain size. This means that the heat input during laser drilling had no influence on the surrounding structure. It can therefore be assumed that the same deformation and failure mechanisms occur in the ligaments of the P1 and P2 perforated Ti grade 2 sheets as in the reference state (BM) of the titanium grade 2 sheet. This is indicated by a comparison of the fracture surfaces of the flat tensile specimens in the BM, P2, and P1 states (Figs. 10, 11, 12).

Fig. 9 illustrates the deformation of laser-drilled holes using the example of a P2 micro-perforated titanium grade 2 sheet. Prior to mechanical loading, the laser-drilled holes are nearly circular. Under tensile loading, the ligaments between the holes deform, causing the originally circular holes to elongate in the direction of the applied tensile force and take an elliptical shape. Simultaneously, the ligaments

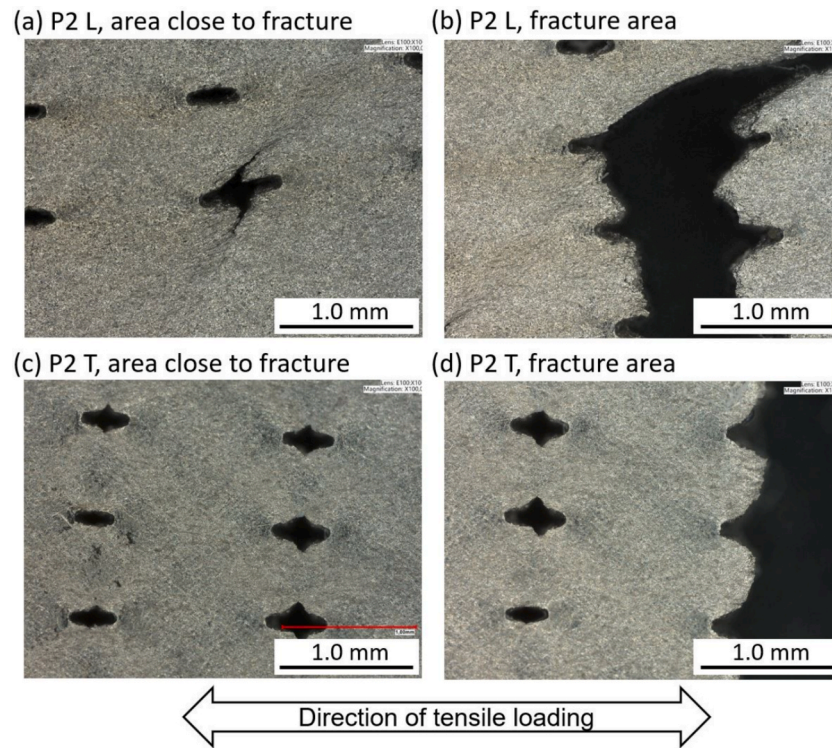


Fig. 9. Detailed view of the fracture in the case of the failed tensile specimens with micro-perforation P2. During plastic deformation, the initially circular laser-drilled holes elongated into ellipses along the tensile stress direction (a, c) and constricted near the fracture surface, where cracks originated at the narrowed regions (b, d).

between adjacent holes undergo localized necking. The elliptically deformed holes, together with the necked ligament regions, act as notches that promote stress concentration. Once the deformation capacity of the ligaments is exhausted, cracks initiate in the necked regions on both sides along the walls of the elliptically elongated holes. Except for the necked regions, the width of the elliptically deformed holes corresponds approx. to the original diameter of the undeformed laser-drilled holes (about 110–120 μm). It should be noted that in the L direction, the elliptically deformed holes (Fig. 9a, b) are more elongated than in the T direction (Fig. 9c, d), which correlates with the texture-dependent fracture strain.

Under quasi-static tensile loading, damage evolution occurred on both sides through the ligaments between the laser-drilled holes. Fig. 9a illustrates the formation of damage at a necked region, accompanied by a surrounding plastic zone. At the macroscopic level, ductile fracture progressed in a discontinuous manner, which is attributed to the perforation pattern of the laser-drilled holes. The discontinuity in fracture behavior arises because damage accumulation ceases locally once a critical deformation at a ligament adjacent to a hole is reached.

3.3. Fracture surface analysis after the tensile test

Figs. 10, 11 and 12 show micro fractographic images of the flat tensile specimens in the reference condition BM and with micro-perforations P2 and P1, respectively. The fracture surfaces of the flat tensile specimens of laser-drilled grade 2 titanium sheet tested show that, irrespective of the direction of relative to the specimen orientation (Fig. 2b), the respective holes between the fracture ligaments have a conical shape and the fracture ligaments are characterized by a dimple structure. The dimple structure is the result of void coalescence during plastic deformation until final transcrystalline-ductile fracture. The present figures do not show visible grain boundaries with a dimple structure, so intergranular fracture failure can be ruled out. In [30] it was reported that in α titanium alloys voids are formed at sites of stress

concentration due to dislocation accumulation at grain boundaries, and void growth continues along the grain boundaries and leads to the formation of larger voids. Transcrystalline dimple fracture [30] is the result of this deformation process.

However, the appearance of the characteristic features of the respective fracture surface differs depending on the respective test direction, which is essentially due to the micro texture, which was previously specified as (0001) at $\pm 30^\circ \rightarrow \text{T}$, (11–20) $\perp \text{L}$ ((01–13) [2–1–10]). For this micro texture (equivalent notation: (01–13) [2–1–10]), the Taylor factor estimated in the L direction is lower than in the T direction, which led to the expectation of a correspondingly lower value for the yield strength in the rolling direction L than in the transverse direction T and was confirmed by tensile tests (see Table 1, Fig. 6). Dimples and outgoing slip lines can be recognized at the fracture edges of the drilled holes. This appearance is rougher on the flat tensile specimens tested in the L direction (Fig. 11b–d) than on the flat tensile specimens tested parallel to the T direction (Fig. 11f–h). This is also consistent with the fact that the dimples on the fracture surface of the tensile specimen tested in L direction (Fig. 11d) are deeper than those on the fracture surface of the tensile specimen tested in T direction (Fig. 11f). The dimple flanks on the L-tensile specimen also exhibited slip lines, flow lines and shear traces (Fig. 11d), which were not visible on the fracture surface of the T-specimens.

In the reference condition (BM), the dimples on the fracture surface of the flat tensile specimen tested in L direction (Fig. 10b–c) are deeper than those on the specimen tested in T direction (Fig. 10e–f). In the T- and D direction specimens (Fig. 10e–f and Fig. 10h–i), the dimples are distorted. According to [30], this distortion can be attributed to shear stresses, which deform the dimples in the shear direction, resulting in so-called slip dimples.

A comparison between the BM and the micro-perforated conditions P1 and P2 shows that the overall failure mechanism is the same in all cases. However, differences exist that can be traced back to the hole pattern in the titanium grade 2 tensile specimens. Measurements of the

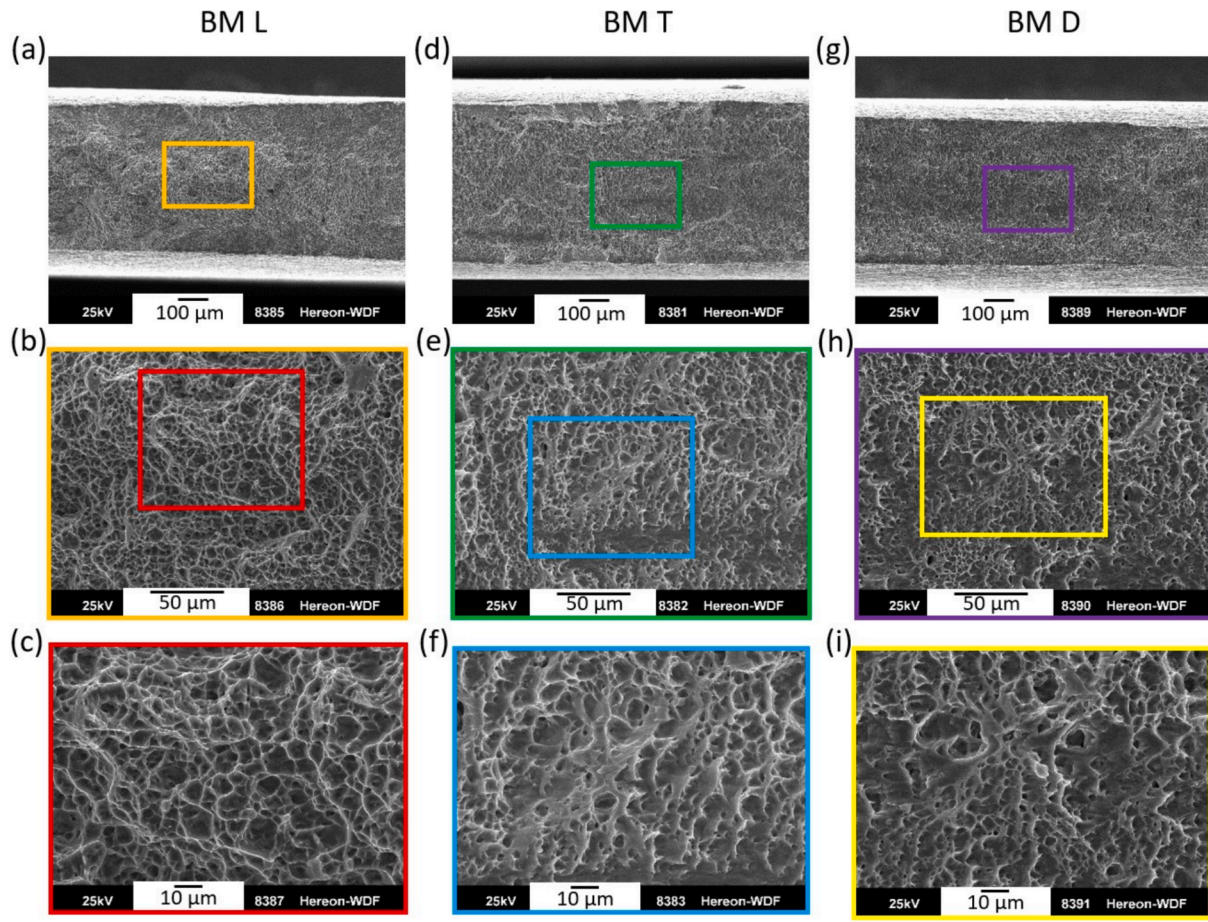


Fig. 10. Fracture surfaces of flat tensile specimens in the reference condition (BM), tested in the (a)–(c) L direction, (d)–(f) T direction, and (g)–(i) D direction.

thickness along the fracture edge at the specimen front revealed a progressive reduction in thickness in the order of P1, P2, and BM.

To quantify the deformation anisotropy, the Lankford factor r was employed. For sheet materials, it is defined as:

$$r = \frac{1}{4}(r_L + 2r_D + r_T) \quad (2)$$

Here, r_L , r_D , and r_T denote the Lankford factors in the L, D, and T directions, respectively, and can be determined using Eq. (3):

$$r_{L,D,T} = \frac{A_{f,L,D,T}}{\left| \frac{S-S_0}{S_0} \right|} \quad (3)$$

$A_{f,L,D,T}$ represents the fracture strain in the corresponding direction, measured at the onset of necking during the tensile test. The parameter S is the average thickness in the necking zone after the tensile test, and S_0 is the initial sheet thickness (0.8 mm).

According to DIN EN ISO 10113 [31], the Lankford factor is formally defined using logarithmic (true) strains. However, for the purpose of this study—aimed at estimating the effect of micro-perforation on directional anisotropy—we applied the equation using engineering strains rather than true strains. The thickness in the necking zone after the tensile test was measured by analyzing the fracture surfaces. For specimens with micro-perforations, local variations in thickness around the laser-drilled holes were not considered; instead, the average thickness was determined.

The results of the directional anisotropy analysis are summarized in Table 2. The data indicate that thickness reduction is governed by both the intrinsic crystallographic texture of commercially pure titanium

grade 2 and the density of the micro-perforation pattern. In general, an increase in hole density reduces the extent of thickness reduction, which is reflected by higher r -values and thus enhanced resistance to localized thinning in the necking zone.

Specifically, specimens with the higher micro-perforation density (P1) exhibited the highest r -value (2.121), corresponding to the lowest thickness reduction in the necking zone. In contrast, specimens with the lower micro-perforation density showed a reduced r -value (1.760), indicating a greater tendency for thickness reduction. The BM displayed the lowest r -value (1.379) and, consequently, the highest thickness reduction.

Overall, the results demonstrate that micro-perforation significantly influences the directional anisotropy of the sheet material. By tailoring the micro-perforation density, it is possible to modify strain distribution and control thickness reduction behavior, thereby providing an effective approach for adjusting anisotropic deformation characteristics.

A comparison of the respective fracture surfaces shows that a tensile load in the L direction causes greater deformation in a laser-drilled titanium grade 2 flat tensile specimen than in the T direction. The cavity volume increases with deformation [32], i.e. the depth of a honeycomb can be regarded as a measure of the plastic deformation. When looking at the fracture surfaces of the laser-drilled flat tensile specimens subjected to tensile stress in the diagonal direction, the picture that emerges (Fig. 11i-l) is that the D direction is slightly 'softer' than the T direction and slightly 'harder' than the L direction.

The fracture segments of the P2 micro-perforation (hole spacing: 1.0 mm × 1.0 mm) are therefore more deformed in the L direction than in the T direction. The most important indications of this are the dimple structure and slip bands, which are more pronounced on the examined fracture surface of the flat tensile specimens subjected to stress in L

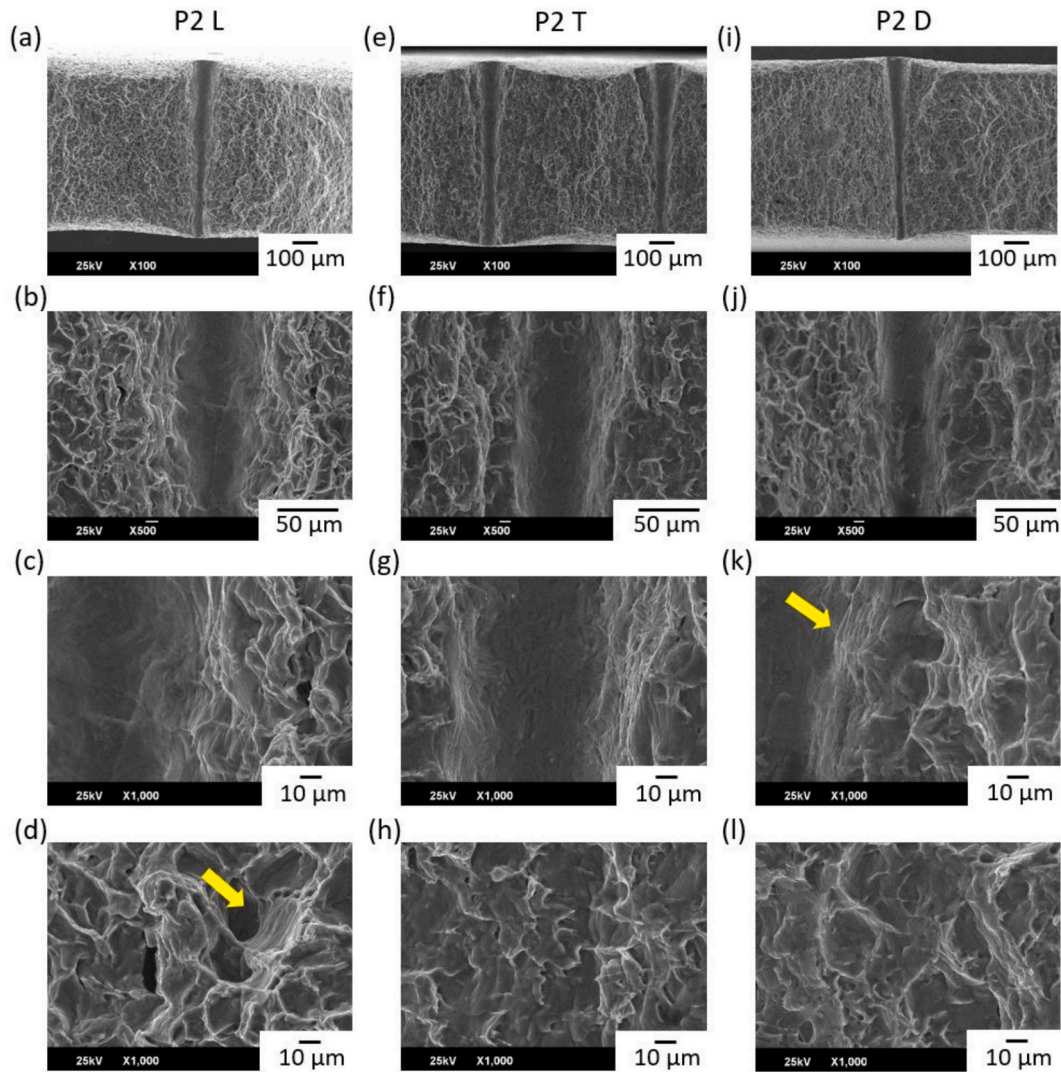


Fig. 11. Fracture surfaces of the flat tensile specimens with the P2 micro-perforation (hole spacing: 1.0 mm x 1.0 mm) tested in (a)-(d) L direction, (e)-(h) T direction and (i)-(l) D direction; slip lines have a wavy appearance (yellow arrows). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2

Lankford factors for states P1, P2, and BM based on thickness measurements and calculations according to Eq. (2).

Condition	S [μm]	S_0 [μm]	A_f	r
P1 D	681	800	0.364	2.121
P1 T	694	800	0.287	
P1 L	611	800	0.319	
P2 D	637	800	0.372	1.762
P2 T	661	800	0.307	
P2 L	632	800	0.338	
BM D	514	800	0.460	1.379
BM T	575	800	0.452	
BM L	536	800	0.438	

direction, than on the fracture surface of the flat tensile specimen subjected to stress in T direction. Examination of the topography of the fracture surfaces on the flat tensile specimens with P1 micro-perforation (hole spacing: 0.6 mm $\times$ 0.6 mm) did not reveal any different picture. However, it was found that the fracture segments in the P1 micro-perforation (Fig. 12a, e, i) were more constricted at the edges of the drilled hole on both the face and the inside than in the P2 micro-perforation (Fig. 11a, e, i). A distortion was observed in one laser-

drilled hole of the P1 micro-perforation (Fig. 12i-k).

4. HLFC-demonstrators

4.1. Hot forming and surface investigation on micro-perforated and hot-formed titanium grade 2 sheets

The hot forming of grade 2 titanium sheet for the production of the HLFC demonstrators (Fig. 13) was carried out by FormTech GmbH. Hot forming of α -titanium alloys such as titanium grade 2 offers the advantage of reducing springback. The reason for this is that at hot forming temperatures the yield strength, and therefore the elastic strain contributing to springback, is significantly reduced [15], resulting in high component accuracy in the end result. Other advantages of hot forming are no residual stresses, no need for springback compensation in the die, high 3D accuracy, very low scrap rate, wall thickness remains constant, perforation holes are not widened by material flow and the influence of wall thickness deviations of $\pm 10\%$ in the delivery state is negligible [15]. On the other hand, there are disadvantages such as the influence of heat on material properties and surface chemistry, the deposition of stop-off products on surfaces, and the need to clean surfaces and holes after hot forming.

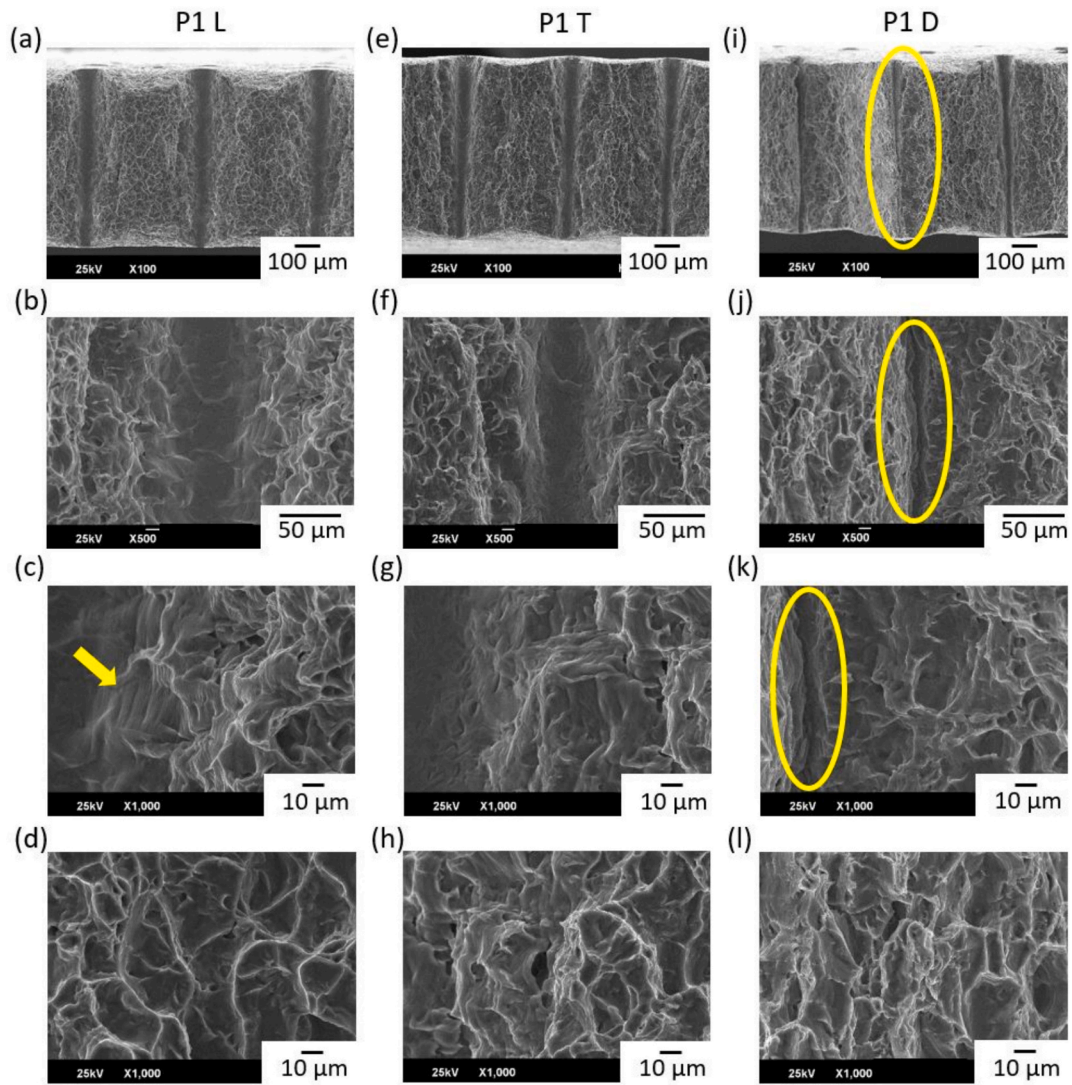


Fig. 12. Fracture surfaces of the flat tensile specimens with the P1 micro-perforation (hole spacing: $0.6 \text{ mm} \times 0.6 \text{ mm}$) tested in (a)–(d) L direction, (e)–(h) T direction and (i)–(l) D direction; slip lines have a wavy appearance (yellow arrow); Figures (i)–(k) show that a laser-drilled hole is distorted (yellow ellipses). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The micro-structure of the HLFC demonstrator with the P1 laser perforation ($600 \mu\text{m} \times 600 \mu\text{m}$, equivalent surface porosity: 2.82%) was analyzed because the initial condition gave the lowest values for tensile strength, yield strength and fracture strain in the tensile test. The 0.8 mm thick laser-perforated grade 2 titanium sheets were supplied by AEROMETALLIC in $1000 \text{ mm} \times 2000 \text{ mm}$ format and cut into $800 \text{ mm} \times 800 \text{ mm}$ blanks by water jet cutting to match the mould size. The hot forming was carried out in such a way that the laser entrance side of the titanium grade 2 sheets was the inside of an HLFC demonstrator and the laser exit side was the outside. The hot forming process consisted of preheating for 5 min, hot forming and hot calibration at 715°C . Details of the hot forming process can be found in the corresponding deliverable of the project report available on CORDIS EU research results [20]. The HLFC demonstrator is characterized by a pronounced convex curvature in the height, width and length directions and a deep concave saddle on the top, see Fig. 13.

The surface and microstructure of the HLFC demonstrator were analyzed at 5 different positions. For this purpose, small samples were taken from the upper part of the demonstrator as shown in Fig. 13a. Fig. 14a–c show the laser entry side of the laser-perforated titanium grade 2 sheet before the hot forming process. It is characterized by the equidistance between the respective drilled holes and their slight ovality

as well as dendrites (Fig. 14c, indicated with white arrow) on the walls of the drilled holes. In the hot-formed state, the drilled holes exhibit a significantly more pronounced ovality on both the laser beam entry side (Fig. 14d–f) and the laser beam exit side (Fig. 14g–i). The pronounced ovalities in the drill holes were observed in all samples taken from the hot-formed HLFC demonstrator (Positions 1–5, see Fig. 13a).

Furthermore, it can be seen that the distances between the drilled holes did not change significantly as a result of hot forming (comparison between Fig. 14b, e and h), which is also confirmed by looking at the microsection images (Fig. 15a–h). The drilled hole diameter on the laser beam entry side varied from $113 \mu\text{m}$ to $162 \mu\text{m}$, on the laser beam exit side from $67.5 \mu\text{m}$ to $91.3 \mu\text{m}$. The conicity thus ranged between 0.12 and 0.15 (Fig. 15a–h). The results obtained suggest that convex curvature and concavity in the saddle area of the HLFC demonstrator have no noticeable influence on the drilled hole diameters. The available investigation results on the macroscopic structure of the HLFC demonstrator show that the borehole size and shape are almost uniform and comparable to the flat micro-perforated sheets (Fig. 5c), which should have a favorable effect on the stability of the local boundary layer [5]. Added to this is the equidistance of the boreholes, which was not affected by the deformation during the hot forming process.

An average grain length of $8.44 \mu\text{m} \pm 3.04 \mu\text{m}$ (d_{max}) and an average

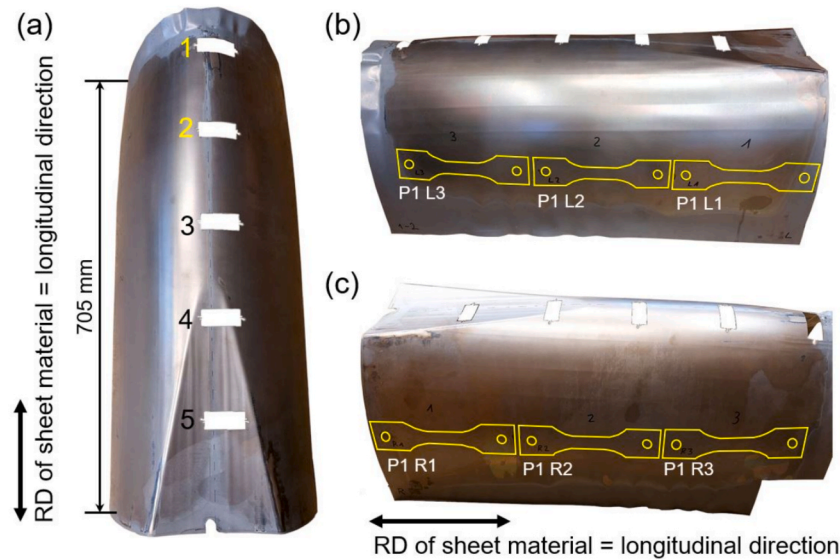


Fig. 13. (a) HLFC demonstrator made of laser-perforated titanium grade 2 sheet hot-formed at 715 °C with positions 1 to 5 where specimens were extracted for surface and microstructural investigations. (b) – (c) Left and right sides of the demonstrator with marked positions for the extraction of tensile test specimens.

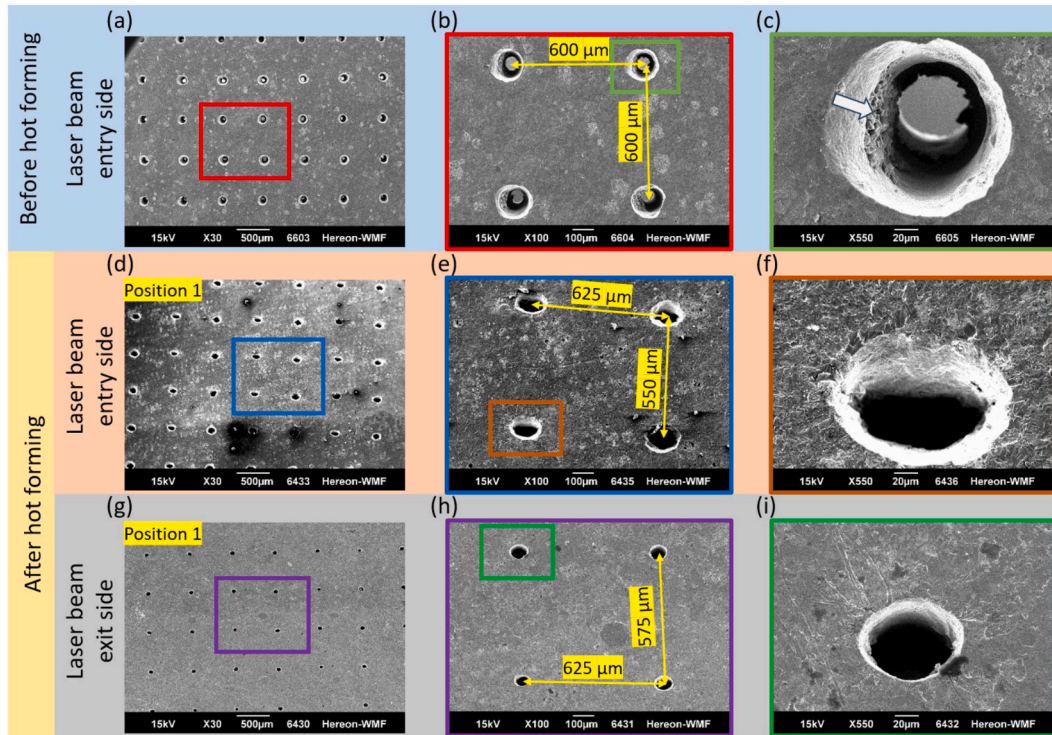


Fig. 14. (a)-(c) Laser-perforated titanium grade 2 sheets on the laser entry side in the initial state before hot forming; surface investigation on specimen extracted from Position 1 shows (d)-(f) laser beam entry side in the hot-formed state and (g)-(i) laser beam exit side in the hot-formed state, respectively.

grain width of $4.98 \mu\text{m} \pm 1.94 \mu\text{m}$ ($d_{\min}$) were determined in the grade 2 titanium sheet, resulting in an elongation ratio of 0.59 ± 0.09 ($d_{\min}/d_{\max}$). Following hot forming at 715 °C, significant coarsening of the microstructure was observed. The mean grain length was found to be $29.78 \mu\text{m} \pm 16.49 \mu\text{m}$ ($d_{\max}$), the mean grain width $15.73 \mu\text{m} \pm 1.94 \mu\text{m}$ ($d_{\min}$), and the aspect ratio 0.54 ± 0.13 . The crystal orientation pattern in Fig. 16a shows that the grain change was uneven. In addition to smaller grains, there are also coarser grains, meaning the microstructure morphology can be described as heterogeneous. The orthorhombic sample symmetry of the titanium grade 2 sheet and its initial texture (01–13) [2–1–10] changed as a result of hot forming. As shown in [15],

cold-formed titanium grade 3, a commercially pure unalloyed titanium with higher mechanical strength than grade 2, has a microstructure with a mean grain diameter of approximately 10 μm after 3.5 h at 600 °C, whereas a grain diameter of approximately 45 μm was determined after 3.5 h at 750 °C. This demonstrates that grain growth is not unusual in this case, assuming that titanium grade 3 tends to exhibit similar temperature-dependent behavior to grade 2. However, an increase in grain size is expected to result in a decrease in yield strength.

The uneven coarsening of the structure was accompanied by an increase in pole density from 7.7 mrd, Fig. 4b, to 25.2 mrd, Fig. 16(b), which can be attributed to the decrease in the number of grains in the

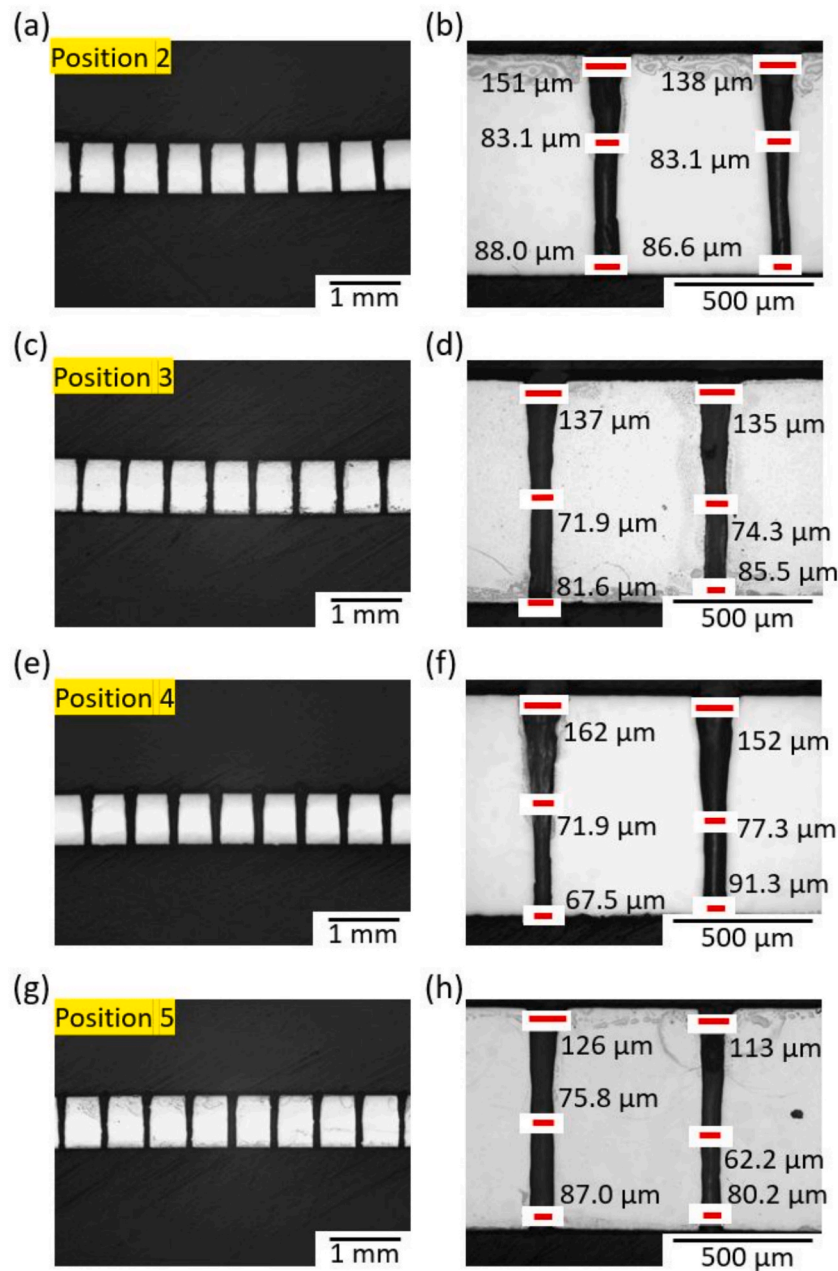


Fig. 15. Representation of the drilled holes in cross section (for the indication of positions on the HLFC demonstrator see Fig. 13a; (a)-(b) Position 2, (c)-(d) Position 3, (e)-(f) Position 4, (g)-(h) Position 5.

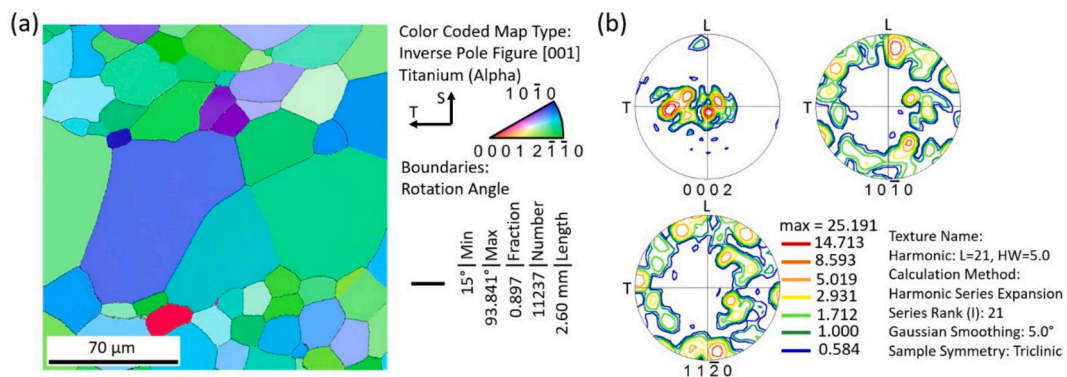


Fig. 16. Microstructure of hot-formed and laser-perforated titanium grade 2 sheet: (a) Crystal orientation map and (b) pole figures.

micro area examined. Furthermore, hot forming and grain coarsening led to a distribution of basal planes with different pole densities around the S direction (see (0001) pole figure in Fig. 4b), and in the circumferential direction of the (10–10) and (11–20) pole figures (see (10–10) and (11–21) pole figures in Fig. 16b). The initial texture tended to develop into an $\langle 0001 \rangle // S$ rotation texture with a large spread of the polar angles (α , β) around S direction.

4.2. Mechanical properties of hot-formed HLFC demonstrator

According to Lütjering and Williams [15], commercial pure titanium alloys such as grade 3 are expected to exhibit grain coarsening when subjected to heat treatment at temperatures above 600 °C, which typically leads to a reduction in yield strength. Therefore, this phenomenon should be investigated by means of tensile tests using flat specimens extracted from the HLFC demonstrator. For this purpose, flat tensile specimens in as-formed condition and without chemical machining of surfaces, with geometry corresponding to the drawing in Fig. 2a were prepared from the hot-formed HLFC demonstrator, as illustrated in Fig. 13b–c. The original sheet rolling direction (L) aligned with the longitudinal axis of the HLFC demonstrator, from which the specimens were taken (see Fig. 13).

Table 3 presents the tensile test results, comparing the initial state of the P1 laser-perforated grade 2 titanium sheet with that of the hot-formed HLFC demonstrator. Both the yield strength and ultimate tensile strength of the hot-formed P1 laser-perforated sheet are lower than in the initial condition, primarily due to grain coarsening. Fig. 17a shows the corresponding stress–strain curves of the flat tensile specimens extracted from the HLFC demonstrator, as well as the representative stress–strain curves for sheet material with and without micro-perforation in the initial state. It is clearly observed that the fracture strain is significantly reduced after the hot-forming process compared to the initial condition, both with and without micro-perforations. This may be due to changes in the surface morphology of the micro-perforated grade 2 titanium sheet caused by the heat effect during hot forming.

In order to investigate the reason for the reduced fracture strain after hot forming, the surfaces of fractured tensile specimens were compared in the necking region. The investigation focused on specimens extracted from micro-perforated sheets and from hot-formed components.

The tensile specimen extracted in the L direction from the micro-perforated sheet (P1), whose fracture surfaces are shown in Fig. 12a–d, reveals that the initially nearly circular perforations became elliptically elongated as a result of ligament deformation during tensile loading (Fig. 18a–b). The ligament surface between the upper and lower rows of perforations appears smoother than the regions adjacent to the sides of

Table 3

Tensile test results obtained from HLFC flat tensile specimens L1, L2, L3, R1, R2 and R3 in comparison to the initial state at room temperature. The values for fracture strain refer to the strain values at which unstable fracture of the specimen during the tensile test occurs, with the values in brackets referring to the final stage of unstable fracture.

Specimen type and direction	YS, R_p 0.2 [MPa]	UTS, R_m [MPa]	Fracture strain, A_f [%]
Initial state (average values)			
P1 L	329	456	31.9
P1 T	391	447	28.7
P1 D	358	428	36.7
HLFC demonstrator, hot-formed at 715 °C			
P1 L1	255	385	17 (19.9)
P1 L2	261	368	15 (18.3)
P1 L3	267	392	19 (23.8)
P1 R1	265	392	18 (24.6)
P1 R2	268	386	19 (23.2)
P1 R3	268	391	21 (24.3)
Average values	264	386	18 (22.3)

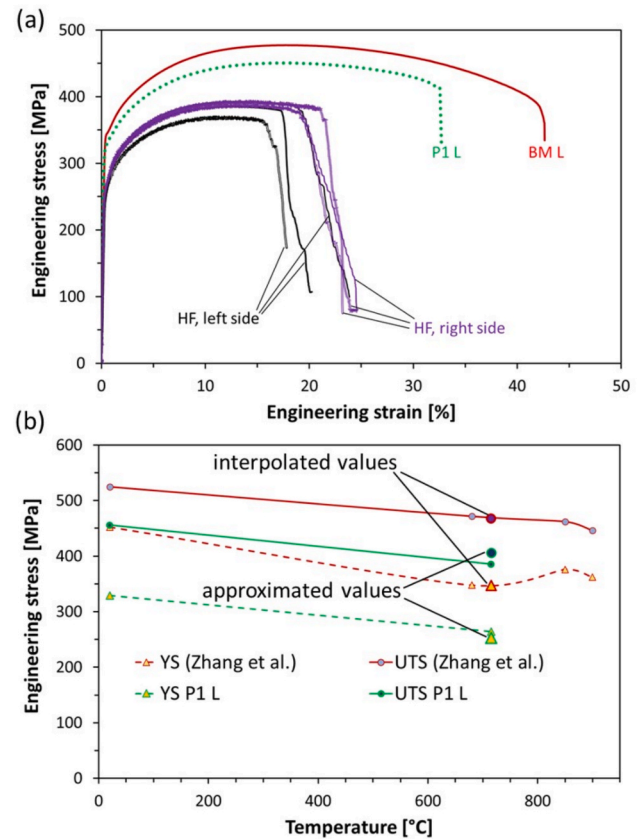


Fig. 17. (a) Engineering stress–strain curves obtained using flat tensile specimens extracted from the hot-formed (HF) HLFC demonstrator with two representative stress–strain curves extracted from sheet material (BM and micro-perforated with pitch P1). (b) Temperature dependence of yield and tensile strength for BM and microperforated with pitch P1. The data for the grade 2 BM were taken from [34]. Estimated values at a temperature of 715 °C were calculated considering the proportional reduction of strength values with regard to room temperature obtained using the data for BM.

the perforations, where the surface exhibits overall higher roughness (Fig. 18b–c). The observed surface roughness can therefore be attributed to plastic deformation occurring during the tensile test. As illustrated in Fig. 18d, the surface surrounding the deformed laser-drilled hole exhibits not only the characteristic scale-like morphology but also distinct sliding lines that promote additional surface roughening.

The flat tensile specimen extracted from an HLFC demonstrator in the L direction (micro-perforation with pitch P1; see Fig. 18e–f) exhibits essentially the same appearance with regard to hole geometry. However, the surface shows numerous microcracks (see Fig. 18g). As previously noted, hot forming is associated with several drawbacks, including the thermal effects on the material's properties and surface chemistry, the deposition of process by-products on surfaces and the requirement for cleaning surfaces and holes after forming. While an oxygen-enriched surface layer (commonly referred to as the 'alpha-case') is not easily detectable in commercially pure α -titanium alloys using metallographic analysis, as it typically is in $\alpha + \beta$ alloys such as Ti-6Al-4V [33], even a slight increase in oxygen content can negatively impact ductility [15]. Therefore, in hot-formed, micro-perforated titanium components, an increased surface area exposed to oxidation resulting from a higher perforation density can be also expected to lead to a more pronounced reduction in fracture strain.

Fig. 17b presents a comparison of the temperature dependence of the yield strength and tensile strength of titanium grade 2, both with and without micro-perforation (pitch P1). The data for BM without micro-perforation were taken from reference [34]. The strength values for

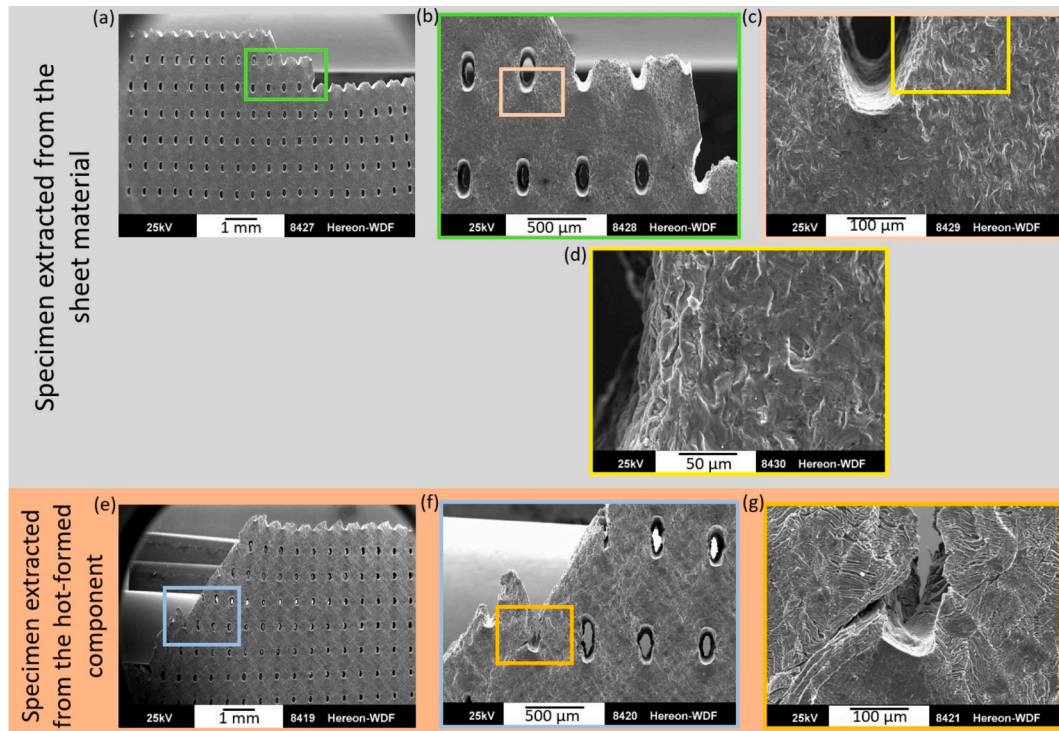


Fig. 18. Surface morphology of the specimens after the tensile test in the necking zone near the drilled holes (pitch P1). (a)–(d) Specimens after tensile testing, extracted from the microperforated sheet material. (e)–(g) Specimens after tensile testing, extracted from the hot-formed HLFC demonstrator.

BM are approximately linearly dependent on temperature up to about 700 °C (Fig. 17b). To estimate the mechanical properties at an elevated temperature of 715 °C, a proportional reduction in strength values relative to room temperature was applied, based on the behavior of the unperforated titanium grade 2 BM. At 715 °C, the interpolated yield strength and tensile strength of the BM are 347 MPa and 468 MPa, corresponding to 77% and 89% of their respective room temperature values. Assuming the same proportional reduction applies to the microperforated material after hot forming, the estimated yield strength and tensile strength are 253 MPa and 406 MPa, respectively. When compared to the experimentally determined average values from tensile testing, the deviation is 4.3% for yield strength and 5.3% for tensile strength. These results indicate that, by considering the known temperature-dependent strength reduction of the BM, the mechanical properties after hot-forming of microperforated titanium grade 2 can be accurately predicted based on room temperature data, with an error margin of approximately 5%.

Fig. 19 shows the fracture surfaces of the two specimens extracted from the HLFC demonstrator after the tensile test. The demonstrator was hot-formed from a micro-perforated titanium sheet with pitch P1. One specimen was extracted from the left side of the demonstrator (P1 L2) and one from the right (P1 R2). In the edge regions of the ligaments, smooth facets are particularly prominent (Fig. 19b and f), indicating that fracture in these areas occurred with minimal plastic deformation. This behavior may be associated with cracking along the laser-drilled hole walls (Fig. 19c and g). Notably, the smooth facets are adjacent to dimple-like structures (Fig. 18d and h).

The tensile specimens extracted from the hot-formed HLFC demonstrator exhibit a noticeable reduction in fracture strain compared to the initial micro-perforated sheet material. Fractographic analysis described above reveals low-deformation fracture regions in the vicinity of the laser-drilled holes, as well as cracks along the laser-drilled hole walls and on the surface. These observations indicate that surface modifications induced by hot forming are a major contributing factor to the reduced fracture strain observed in the tensile specimens extracted from

the HLFC demonstrator.

In particular, the increased surface roughness, the presence of microcracks, and the transition from ductile dimple-like structures to locally smooth fracture facets suggest that crack initiation due to tensile loading occurred prematurely at surface-affected regions. Hot forming at 715 °C promotes thermal oxidation and may lead to subtle oxygen enrichment of the surface layer. Even slight oxygen uptake in commercially pure titanium is known to impair ductility [15]. In micro-perforated components, the high density of laser-drilled holes substantially increases the effective surface area exposed to oxidation and process-related surface alterations. Consequently, crack initiation at the hole edges and along modified surface layers is facilitated, leading to earlier onset of unstable fracture and thus reduced fracture strain.

In contrast, the reduction in yield strength after hot forming follows a different mechanism. The experimentally measured yield strength values agree closely (within approximately 5%) with values estimated from the temperature-dependent strength reduction of the BM. This strong correlation indicates that the decrease in yield strength is primarily governed by intrinsic microstructural changes rather than surface deterioration. The reduction in yield strength is therefore mainly attributed to grain coarsening resulting from thermal exposure during hot forming. Grain growth reduces the resistance to dislocation motion, leading to a lower yield stress in accordance with established strengthening mechanisms.

Thus, while fracture strain is predominantly affected by surface-related deterioration and crack initiation phenomena, the yield strength reduction is controlled by bulk microstructural evolution during high-temperature processing.

5. Summary and Conclusions

The research presented in this work offers a comprehensive assessment of the mechanical behavior of micro-perforated titanium grade 2 sheets used in HLFC applications. The influence of laser-drilled hole spacing, rolling direction, and hot forming was analyzed through

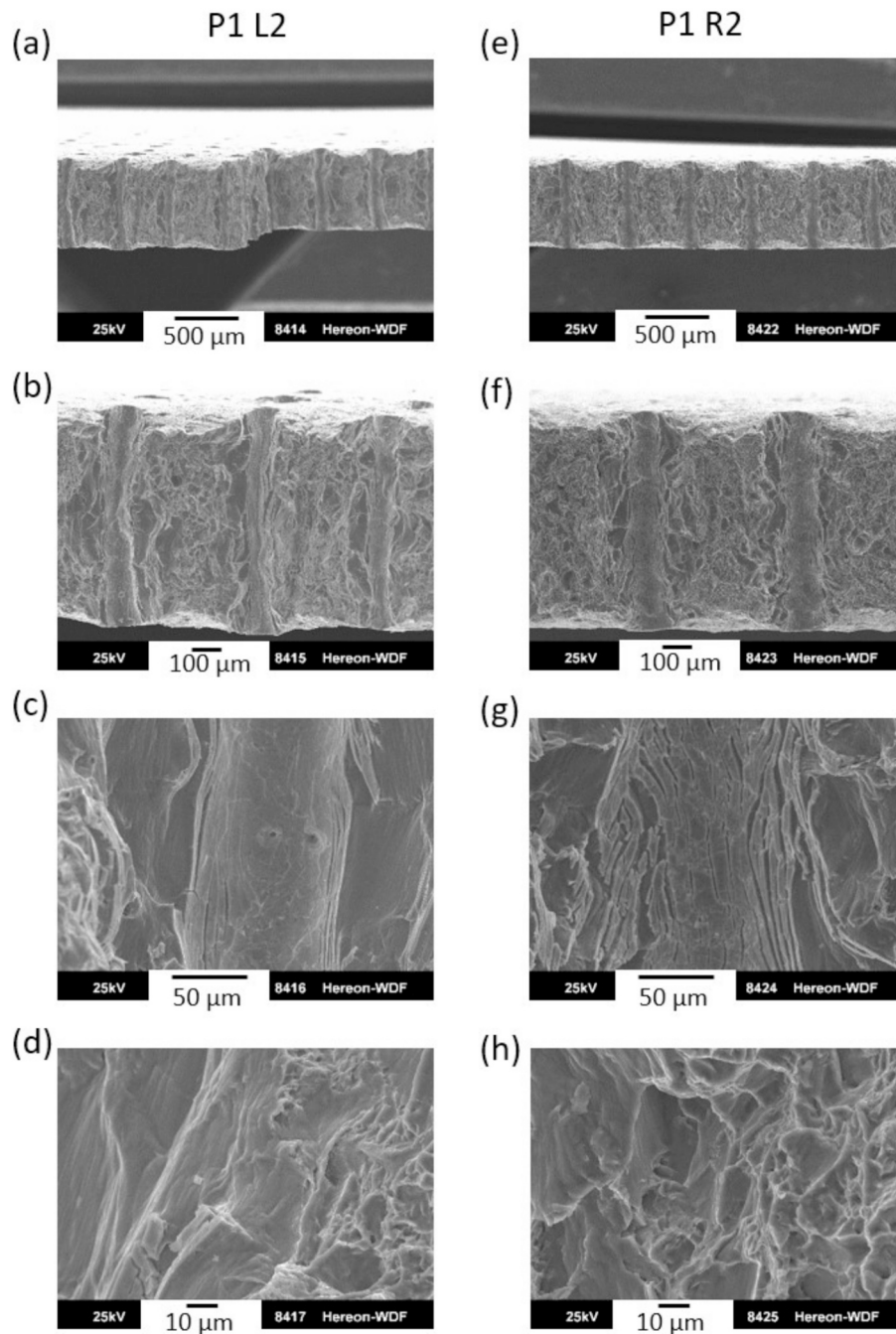


Fig. 19. Fracture surfaces of the specimens extracted from the HLFC demonstrator after the tensile test. (a)–(d) Tensile specimen P1 L2 (Fig. 13b); (e)–(h) Tensile specimen P1 R2 (Fig. 13c).

mechanical testing along different loading directions, EBSD-based microstructural characterization, and fractographic evaluation. The tensile behavior exhibited strong directional dependence due to crystallographic texture and micro-perforation pattern, with the transverse and diagonal directions generally showing improved strength and ductility. Micro-perforation resulted in localized ligament deformation but did not significantly compromise the material's strength.

Hot forming of the micro-perforated titanium grade 2 sheet at 715 °C into a full-scale HLFC demonstrator resulted in measurable changes in mechanical properties. Thermal exposure during forming led to grain coarsening, which is identified as the primary reason for the observed reduction in yield strength. The good agreement between experimentally measured strength values and those predicted from the temperature-dependent behavior of the BM (deviation < 5%) confirms

that the strength reduction is predominantly governed by bulk microstructural evolution and can be reliably estimated from room-temperature data.

In contrast, the decrease in fracture strain is mainly attributed to surface-related effects. Fractographic analyses revealed low-deformation fracture regions near laser-drilled holes, cracks along hole walls, and surface microcracks, indicating premature crack initiation at surface-affected zones. These features are likely associated with surface modifications induced by hot forming, including possible oxidation on both internal (drilled hole) and external surfaces. The increased surface area inherent to the micro-perforated structure further enhances the susceptibility to such effects, thereby promoting earlier onset of unstable fracture.

Despite the combined influence of grain coarsening and surface

modifications, the residual strength and ductility after hot forming remain within an acceptable range for structural application. The present results therefore provide a reliable basis for the design and industrial implementation of laser-perforated titanium sheets in HLFC structures, enabling accurate prediction of post-forming mechanical properties and improved strength assessment at component level.

Funding sources

The investigations were part of the project MICROFORM (Forming of micro-perforated outer skin of HLFC wings assisted by FEM simulation), funded by the European Union within the Horizon 2020/Clean Sky 2 JU programme, Grant Agreement 886409, in which the consortium partners Lortek S Coop (Coordinator), Sofitec Aero SL, FormTech GmbH and Helmholtz-Zentrum Hereon were involved.

CRediT authorship contribution statement

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Declaration of competing 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.

Data availability

Data will be made available on request.

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