LIGHTWEIGHT DESIGN OF Ti-6Al-4V FORGINGS

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ABSTRACT
Forged parts made of titanium are generally used in aerospace industry, e.g. for engine mounts, pylon fitting and frame parts. To achieve damage tolerant together with lightweight design of such components the local microstructure resulting from thermomechanical treatment has to be considered. Further influences (e.g. multiaxial loading, notches and impressed mean stress) play also a major role with respect to the fatigue behavior. Therefore a new approach is introduced in this paper containing methodologies for the determination of local S/N-curves for Ti-6Al-4V. They can be embedded in a lifetime prediction based on local stresses.

INTRODUCTION
In the aerospace industry, the realization of lightweight structural components is a top priority. Reducing the weight of structural components increases the potential payload of the aircraft and decreases the fuel consumption. Lightweight design is thereby based on three principal points:
- Material
- Processing
- Design

Material
Titanium alloys have become very important materials in the aircraft industry, due to their excellent properties (such as high fatigue strength and good corrosion resistance) and low density; ideal for lightweight design. Titanium components (particularly Ti-6Al-4V) are used in place of heavy steel components (e.g. airfoils, pylon fitting, undercarriage components, and other structural parts).

Processing
Manufacturing parts according to customer specifications by using forming techniques has both cost and quality advantages, compared to cutting and machining parts out of feedstock plates or bars. Because of this, components are increasingly manufactured by forging. Forging results in better utilization of material through near net shape manufacturing, and also reduces manufacturing costs and provides better mechanical properties, such as high fatigue strengths. Therefore forging is suitable for the processing of lightweight titanium components.

Design
Depending on the thermomechanical treatment of a titanium alloy, in this case Ti-6Al-4V, the microstructure and thus also the mechanical properties can vary in a wide range. Such influences have been documented in numerous reports in the literature, see, for example, Refs [1-12], with the problem that a holistic optimization of the whole product development chain (design, thermomechanical processing) is still lacking. Therefore it is currently not possible to optimize Ti-6Al-4V components with respect to thermomechanical processing and design.

The objective of this study was to determine the fatigue behavior of Ti-6Al-4V in the finite and in the high cycle fatigue region as well as the fatigue crack growth properties in respect of microstructure, mean stress, notches and multiaxial loading. These results were then embedded in a new approach for determination of local S/N-curves to provide a basis for the lifetime prediction and optimization of forged Ti-6Al-4V lightweight structural components. The verification will be done on a purpose designed engine mount.
APPROACH

With the aid of forming simulation using finite element analysis it will be possible to predict the local microstructure in Ti-6Al-4V forgings in respect of the thermomechanical processing. A link between this local microstructure and the fatigue life is necessary to enable an accurate lifetime prediction for forged Ti-6Al-4V components and to optimize their processing. Therefore a new approach (Fig. 1) has been developed where local microstructure results in local microstructural-based S/N-curves and stress intensity factor thresholds. The local microstructural-based S/N-curves can be combined with additional important influences regarding fatigue, e.g. mean stress, notches and multiaxial loading, to local S/N-curves. They provide the basis for computation of the local lifetime of forged components. In combination with the local (microstructural-based) stress intensity factor threshold it is furthermore possible to predict the local damage tolerance (cf. e.g. [13]) by application of the Kitagawa-Takahashi relationship [14] between flaw size and fatigue strength. In addition this new approach provides a direct link of forging simulation and local lifetime or damage tolerance. With these closed optimization loops (forging simulation ⇒ local lifetime / damage tolerance) the thermomechanical processing can be optimized for forgings where the fatigue lifetime or the damage tolerance is the main criterion.

The material used for this research work was provided by Böhler Schmiedetechnik GmbH & Co KG (Kapfenberg, Austria) in the form of Ti-6Al-4V open-die V-shape and closed-die side-pressed pancake forgings, respectively. Additionally the feedstock billet (FB, diameter 230 mm) for the V-shape forgings was investigated in as-received condition (AR). Different heat treatments (HT) were performed on the forgings: mill-annealing (MA), solution treating with air cooling (ST), solution treating with polymer quenching (STPQ), recryst.-annealing (RA) and beta-annealing (BA). These different heat treatments led to a high diversity of equiaxed and bimodal microstructures, respectively (Fig. 2). Due to the chosen forging temperature of 930°C no crystallographic texture occurs. Mill-annealing does not cause complete recrystallization, and therefore leads to a distinct texture of the primary α-grain shapes, representative of the forging process. A detailed characterization of the different forgings can be found in [15]. The microstructures were characterized with respect to several microstructural parameters (Tab. 1). These are the average primary α-grain size $a_{p}$, the (α+β)-content $C_{α+β}$, the connectivity $Con$ of the primary α-grains, the colony size $Col$ of the lamellae-packets and the mean α-lamellae width $Lam$.

![Fig. 2 – Micrographs of analyzed materials](image)

![Fig. 1 – Approach for damage tolerant lightweight design of Ti-6Al-4V forgings](image)
<table>
<thead>
<tr>
<th>HT</th>
<th>( \alpha_p ) [( \mu m )]</th>
<th>( C_{\text{av}} ) [( % )]</th>
<th>( C_{\text{ol}} ) [( % )]</th>
<th>( C_{\text{ol}} ) [( \mu m )]</th>
<th>Lam [( \mu m )]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>20.3</td>
<td>28.7</td>
<td>9.2</td>
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<td>39.5</td>
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<td>78.9</td>
<td>32.4</td>
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<tr>
<td>ST(_p)</td>
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<td>50.9</td>
<td>33.7</td>
<td>16.1</td>
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<td>0</td>
<td>99.0</td>
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<td>-</td>
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<tr>
<td>AR(_{FB})</td>
<td>9.8</td>
<td>0</td>
<td>0</td>
<td>-</td>
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</tr>
</tbody>
</table>

Tab. 1 – Microstructural characterization

**EXPERIMENTAL PROCEDURE**

The test program consisted of rotating bending, tension/compression, torsional and multiaxial fatigue tests and long crack propagation tests. In addition the crack initiation and short crack growth was studied for two microstructures. All tests were performed at ambient air and at room temperature. Specimens from V-shapes were sampled in transverse direction. This led – in consideration of a constant effective strain in longitudinal direction – to specimens with identical effective strain in the highest loaded cross section. The specimens from pancakes and feedstock bars were taken in longitudinal direction. The sampling was done by water jet cutting or sawing with a band saw, followed by milling and fine turning, respectively. The roughness was measured with a confocal laser scanning microscope (LEXT). The fine turning of the round fatigue specimens led to an average roughness height of 0.6 \( \mu m \).

**Influence of microstructure**

Rotating bending (RB) fatigue tests (stress ratio \( R = -1 \)) were performed on round hourglass specimens with a frequency of 63 Hz. All S/N-curves (cf. Fig. 3) correspond with a survival probability of 50 \%. The results show that the fatigue strength varies in a wide spectrum in respect of the microstructure. The fatigue limit of the equiaxed materials is much lower than those of the bimodal and mill-annealed microstructures.

The fatigue strength in the finite life region shows also strong interdependencies with the microstructure, whereas the slope of the S/N-curves in the finite life region is almost unaffected.

The characterization of the long crack growth behavior (Fig. 4) was done with V-notched single edge bending (SEB) specimens under four point bending loading at a resonant testing rig with a frequency of approximately 140 Hz. Thereby the crack length was measured with the potential drop method. The measurements were performed for four different stress ratios \( R \) (ratio of minimum and maximum stress or stress intensity factor respectively). The stress intensity factor range \( \Delta K \) was derived according to linear elastic fracture mechanics for all stress ratios, cf. [15].

**Fig. 3** – Fatigue behavior in respect of microstructure

**Fig. 4** – Fatigue crack growth behavior in respect of microstructure
Distinct differences were found in the near-threshold region in respect of the stress ratio owing to crack closure effects. This was confirmed by roughness measurements of the fracture surface. A linear relationship between average roughness height $R_a$ and stress intensity factor threshold $\Delta K_{th}$ was found (Fig. 5). Especially the forged materials with the equiaxed and bimodal microstructures exhibit a good accordance with the linear fit. This is caused by a linear correlation of primary α-grain size and fracture surface roughness. The ranking of the different microstructures regarding fatigue crack propagation is not affected by the stress ratio.

**Influence of impressed mean stress**

Tension/compression (TC) tests were performed on round hourglass specimens with different stress ratios $R$. The results show that impressed mean stress significantly reduces the fatigue strength of Ti-6Al-4V (Fig. 6). Furthermore it was observed that the transition point shifts beyond $10^7$ load cycles for stress ratios greater-than-or-equal 0. This is important because literature data ([2], [11], [16], [17]) was only found for $10^7$ load cycles resulting in a non-conservative fatigue limit for stress ratios greater-than-or-equal 0.

The slope of the S/N-curves in the finite life region is not affected by the stress ratio.

**Influence of multiaxial loading**

Alternating torsion and multiaxial (combined rotating bending and alternating torsion with $\tau/\sigma = 0.5$) fatigue tests were performed on round hourglass specimens in ambient air (room temperature) with a frequency of 30 Hz. In addition tension/compression tests were done on mild notched round specimens (same relative stress gradient as unnotched specimens under torsional or multiaxial loading). It was observed that the fatigue limit for tension/compression load $\sigma_f$ is 560 MPa. The endurance limit under alternating torsion load $\tau_f$ is approximately 315 MPa. This leads to a ratio $\tau_f/\sigma_f$ of 0.56; typical for ductile materials. Therefore the Mises equivalent stress (for plane stress state cf. Eq. 1) was used for comparison of the S/N-curves for tension/compression, torsional and multiaxial loading, respectively.

$$\sigma_{Es} = \sqrt{\frac{\sigma_x^2 + \sigma_y^2 - \sigma_x \sigma_y + 3\tau_{xy}^2}{2}} \quad (1)$$

The experimental results (Fig. 7) show that the Mises equivalent stress leads to a good accordance of fatigue limits in respect of type of loading. In the finite life region differences can be found; caused by an overestimation of shear stresses with respect to crack propagation. Therefore the Mises equivalent stress is valid for high cycle fatigue region and conservative for finite life.
Influence of notches

Notches cause stress concentration in combination with high relative stress gradients. The relative stress gradient, $\chi^*$ [1/mm], is defined as the slope of the stress distribution at the point of maximum stress and is related to the maximum stress (Equ. 2).

$$\chi^* = \frac{d\sigma}{dx} \frac{1}{\sigma_{\text{max}}}$$  (2)

In a lifetime estimation based on local stresses the so-called supporting effect of notches is included by consideration of the local relative stress gradient (e.g. [18]).

Fatigue tests were hence done on unnotched and notched round specimens (mill-annealed microstructure) under tension/compression or rotating bending loading (ambient air, room temperature). The experimental results are shown in Fig. 8. The plotted stress amplitudes are Mises equivalent stresses due to the multiaxial stress state in the notch roots. All S/N-curves correspond to a survival probability of 50%.

The experimental results show that the mill-annealed microstructure exhibits for $\chi^*<0.4$ and $\chi^*>0.5$ no supporting effect in the high cycle fatigue region. Only stress gradients between 0.4 and 0.5 led to higher fatigue limits. Due to additional fatigue tests on STPQ Ti-6Al-4V it can be suggested that this (currently unclear) behavior is limited on MA microstructures.

Fig. 7 – Fatigue behavior in respect of type of loading

Fig. 8 – Fatigue behavior in respect of notches

**FATIGUE MODELS**

The experimental results show that the fatigue behavior of Ti-6Al-4V is influenced by microstructure, mean stress and notches. Models were hence developed for consideration of these influences in a lifetime prediction based on local stresses.

Linking microstructure and fatigue

The microstructure was related to fatigue using several microstructural parameters. The fatigue limit was thereby linked with mean primary $\alpha$-grain size (via Hall-Petch relationship) or $(\alpha+\beta)$-colony size (via linear relation), depending on the $(\alpha+\beta)$-content, cf. Fig. 9. The fatigue limit of microstructures with low $(\alpha+\beta)$-content depends on the primary $\alpha$-grain size, those of microstructures with higher $(\alpha+\beta)$-content depends on the $(\alpha+\beta)$-colony size.

Fig. 9 – Linking microstructure and fatigue limit
Eqn. 3 (for \( C_{\alpha+\beta} < 20\% \)) and Eqn. 4 (for \( C_{\alpha+\beta} > 30\% \), cf. Fig. 10) represent the mathematically description for both regions marked in Fig. 9. Thereby \( \alpha_p \) is the mean primary \( \alpha \)-grain size [m] and \( Col \) the \((\alpha+\beta)\)-colony size [\( \mu \m \)].

\[
\sigma_{f,M} = 0.36 \frac{1}{\sqrt{\alpha_p}} + 350 \quad (3)
\]

\[
\sigma_{f,M} = 685 - 6.8 \text{Col} \quad (4)
\]

These measurements confirmed that fatigue cracks initiate even in primary \( \alpha \)-grains or in \((\alpha+\beta)\)-colonies. The size of these microstructural features is hence affecting the fatigue limit. In spite of the low \((\alpha+\beta)\)-content (approximately 20\%) of the mill-annealed microstructure, 58\% of the fatigue cracks initiate in the lamellar \((\alpha+\beta)\)-phase. In the solution treated microstructure with the higher \((\alpha+\beta)\)-content of 51\% almost 80\% of the cracks nucleate in \((\alpha+\beta)\)-phase. Therefore it can be concluded that the cracks initiate easier in \((\alpha+\beta)\)-phase owing to an alloy element partitioning effect, cf. [4].

The initial crack length distributions for both microstructures can be found in Fig. 11. Weibull fits were used for approximation. A comparison of the initial crack length distributions shows that the initial cracks are smaller in the mill-annealed microstructure. The measurement of the microstructurally short crack growth exhibited that the cracks propagate faster in \( \alpha \)-phase than in \((\alpha+\beta)\)-regions. This seems to be the reason for the lower fatigue strength of microstructures with low \((\alpha+\beta)\)-content.

The microstructure also plays a major role regarding long crack growth (cf. Fig. 4). For a quantitative link between microstructure and crack growth the experimental stress intensity factor thresholds were plotted in respect of the stress ratio \( R \), [15]. A linear relationship was chosen to fit the data points. Thereby a fixed point was found at a stress ratio of 0.87 and a stress intensity factor threshold of 1.75 MPaVm.

The slope \( k_{ih} \) of the fitting lines was linked via combination of Hall-Petch-approach and Boltzmann sigmoid with the microstructural parameters connectivity \( \text{Con} \) [%] and primary \( \alpha \)-grain size \( \alpha_p \) [m], cf. Eqn. 5 and Fig. 12.

\[
k_{ih} = 0.0156 \frac{1}{\sqrt{\alpha_p}} - 9.38 - \frac{3.2}{1 + e^{\frac{-\text{Con}}{5}}} \quad (5)
\]

This microstructural-based slope leads in combination with the fixed point mentioned before to a model for the estimation of the stress intensity factor threshold in respect of microstructure and stress ratio.
Additional information and the link of fatigue strength in the finite life region with microstructural parameters can be found in [15].

The mill-annealed microstructure shows some anomalies at low stress gradients (approximately 0.5 mm⁻¹). Higher fatigue strengths were observed; both, under tension/compression and under rotating bending loading. It can be suggested that the “normal” fatigue limit owing to the microstructure is increased if the relative stress gradient \( \chi^* \) is between 0.4 and 0.5 mm⁻¹. For finite life, the tension/compression test result at \( \chi^*=0.5 \) is concordant with the test results at higher and lower stress gradients and also with the microstructural-based fatigue strength (cf. [15]). But the rotating bending test result for \( \chi^*=0.4 \) exhibits anomalous fatigue behavior in finite life region too. It is assumed that these anomalies are limited on mill-annealed microstructures only. Further research will be done on Pancake mill-annealed and V-shape STPQ for clarification of these anomalies.

### Linking relative stress gradient and fatigue

The supporting effect of a relative stress gradient is often considered in lifetime prediction based on local stresses with an exponential relation [19]. Previous work [10] and the fatigue tests on unnotched and notched specimens show that Ti-6Al-4V exhibits no supporting effect in the high cycle fatigue region, and in the finite life region for \( \chi^*<2 \) too (Fig. 13). Therefore it can be suggested that the fatigue limit in respect of the stress gradient \( \sigma_{f,MG} \) is equal to the fatigue limit of the microstructural-based model \( \sigma_{f,M} \), Eq. 6.

\[
\sigma_{f,MG} = \sigma_{f,M} \quad (6)
\]

### Linking mean stress and fatigue

Several models exist to describe the influence of mean stress on the fatigue strength in the region between \( R=1 \) and \( R=1 \), e.g. Goodman relation or Gerber parable [20]. But the experimental results show that these models are non-conservative for Ti-6Al-4V with respect to the fatigue limit. Therefore a new model was developed where the stress ratio \( R \) is linked with the stress amplitude at \( 10^6 \) load cycles via exponential relation (Equ. 7), cf. Fig. 14.

\[
\sigma_{f,MGM} = \sigma_{f,MG} \cdot e^{-0.834(1+R)} \quad (7)
\]
One possible approach is to include residual stresses in the finite element simulation. These residual stresses acting in a lifetime estimation as mean stresses. The roughness can be included as a separate reduction factor.

Ti-6Al-4V is used up to 350°C but the influence of elevated temperature on the fatigue behavior has very rarely been reported. Tokaji [22] showed that the high cycle fatigue behavior is significantly influenced by temperature. His experimental results are shown in Fig. 17; supplemented by yield strengths of mill-annealed Ti-6Al-4V at different temperatures reported by Boyer et al. [1]. It can be seen that the tensile strength and the fatigue limit exhibit, up to approximately 630 K (the maximum operation temperature of Ti-6Al-4V components), the same decrease with increasing temperature. Therefore a model is suggested using a linear relation between temperature $T$ [K] and fatigue strength (Equ. 8).

$$\sigma_f = 0.9(293 - T) + \sigma_{f,\text{MGM}_R T}$$

Further research work is necessary to verify this model for the present materials.

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**VERIFICATION**

The verification of the presented models has been done on a purpose designed engine mount. First results regarding computational lifetime estimation are presented; component tests will follow.
A first approach was used to link thermomechanical processing and microstructure. Therefore it was possible to get the microstructure-distribution in the component via forging simulation. This distribution was mapped from the forging simulation mesh to a finite element (FE) mesh for stress calculation. The local stress tensor and the local S/N-curve (based on the fatigue models presented above) were hence calculated in every node of the FE mesh. A damage accumulation (according to Miner, cf. [20]) was done to get the damage distribution in the component. The combination of fatigue limit and stress intensity factor threshold (e.g. according to Kitagawa and Takahashi [14]) results in a distribution of the allowable crack size for no-growth (Fig. 18).

Fig. 18 – Colony size (l) and allowable crack size (r)

CONCLUSION

Fatigue tests were done on Ti-6Al-4V specimens. The experimental results were analyzed and used for generation of several fatigue models, cf. (Fig. 19).

With the knowledge of the geometry and load of a component a finite element (FE) analysis can be done to get the stress distribution. An additional forging simulation leads to the microstructure-distribution in the forging. A combination of stresses, microstructural parameters and fatigue models affords a lifetime prediction based on local stresses. This information can then be used for optimization of the thermomechanical processing and/or the geometry for maximum durability and minimum weight. Finally, the forging simulation delivers the optimized process parameters for the forging of an optimized lightweight component.

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REFERENCES


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Overview

Motivation

Material Characterization

Experimental Results

Verification

Models

Conclusion
Overview

Material Characterization

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Verification

Experimental Results

Motivation

Conclusion
Lightweight Design in Aviation

Reduction of fuel consumption:
~ 30 % of take-off weight is fuel

Increase of payload

Snowball effect:
1 kg reduction of a component save additional
1 kg in airplane (engine, gears, …)

Airframe: 7 wt.-% Ti

Engine: 36 wt.-% Ti
Light Weight Design of Ti-6Al-4V Structural Components

Motivation

Light Weight Design

- Low density
- Corrosion resistance
- Good mechanical properties

Material
- Ti-6Al-4V
- High strength

Processing
- Forging
- Near net shape

Design
Approach for Damage Tolerant Lightweight Design

Motivation

Geometry ➔ Forging Simulation

FE Analysis ➔ Stress Distribution

Local Microstructure

Local Lifetime

Surface, Multiax. Loading

Further Influences

Mean Stress, Notches

Local S/N-Curves

Local Stress Intensity Threshold

Local Lifetime

Local S/N-Curves

Local Damage Tolerance

Mean Stress, Notches

Further Influences

Local Lifetime

Local S/N-Curves

Local Damage Tolerance
Approach for Damage Tolerant Lightweight Design

Motivation

Geometry
Forging Simulation
FE Analysis → Stress Distribution
Local Microstructure
Local Stress Intensity Threshold
Local Lifetime
Local Damage Tolerance
Closed Optimization Loop

Further Influences
Mean Stress, Notches
Surface, Multiax. Loading
Local Lifetime
Local Damage Tolerance
**Material Characterization**

**Feedstock billet**
- Ø230mm
- As-received

**V-Shapes**
- Closed-die forging
- Forged on screw press
- Forging temp. 930°C
- Two heats

**Pancakes**
- Open-die forging
- Forged on hydraulic press
- Forging temp. 930°C
- One heat
Material Characterization

High diversity

AR...As-received
MA...Mill-annealed
BA...Beta-annealed
ST...Solution treated
RA...Recyrst.-annealed
STPQ...ST polymer quenched
Fatigue Behavior in Respect of Microstructure

- Huge variation of fatigue strength and crack propagation rate
Fatigue Behavior in Respect of Microstructure

V-Shape MA
(α+β)-content: 20%
Crack initiates in:
58% (α+β)-phase
42% α-phase

Pancake ST
(α+β)-content: 51%
Crack initiates in:
77% (α+β)-phase
23% α-phase
Experimental Results

High Cycle Fatigue in Respect of Mean Stress and Notches

- Significant influence of impressed mean stress
- High notch sensitivity & no supporting effect due to stress gradient

\[ \chi^* = 0.4 \ldots 0.5 \]
\[ \chi^* < 0.4 \text{ or } > 0.5 \]

\[ N_T > 10^7 \]
Influence of Multiaxial Loading

Mises equivalent stress:

$$\sigma_{a,ES} = \sqrt{\sigma_n^2 + 3\tau^2}$$

- Valid for high cycle fatigue
- Overestimation of shear stress in finite life region
- Conservative for finite life

Differences at finite life region

Accordance at fatigue limit
Overview

- Material Characterization
- Models
- Experimental Results
- Verification
- Motivation
- Conclusion
Influence of Local Microstructure

Stress intensity factor threshold

Fixed point

$f(\alpha_p)$

$f(Col)$

$k_{th}$
Influence of Mean Stress and Notches

\[ \sigma_{\text{max}} = \text{const.} \]

\[ 100\% \]

Maximum stress significant for HCF
Overview

Material Characterization

Models

Experimental Results

Verification

Motivation

Conclusion
Verification

Geometry
Purpose designed engine mount

- Computational lifetime prediction has been done
- Component tests will follow

FE-Analyses
Forging simulation
- Microstructure distribution

Finite-element analysis
- Mises stress distribution

Results
Damage distribution

Allowable crack size distribution
Overview

Material Characterization

Models

Experimental Results

Verification

Conclusion

Motivation
Acknowledgements & Literature

The authors would like to thank the Austrian Federal Ministry for Transport, Innovation and Technology, the Austrian Federal Ministry of Economics and Labor, the federal governments of Vienna, Styria, Tyrol, Upper Austria and Lower Austria and the Austrian Research Promotion Agency for the funding of this work, in the framework of the Austrian Aeronautics Research Program and FFG’s BRIDGE program. The support by Böhler Schmiedetechnik GmbH & Co KG is much valued.

Literature


Thank you for your attention!

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