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Vrednotenje termomehansko obremenjenih izdelkov z deformacijskim pristopom

Evaluating Thermo-Mechanically Loaded Components Using a Strain-Life Approach

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Deformacijski pristop sodi med najbolj uveljavljene metode vrednotenja izdelkov, izpostavljenih utrujanju. Za njegovo uporabo pri termomehanskih obremenilnih stanjih in modeliranje lokalnih temperaturno-napetostno-deformacijskih stanj je uporabljen napetostno nadzorovan reološki model vzmet - drsnik s Prandtlovim operatorjem, ki omogoča modeliranje elastoplastičnih materialnih lastnosti. Postopek je razširjen za uporabo na zahtevnih izdelkih v kombinaciji z metodo končnih elementov (MKE). Predstavljeni postopek vrednotenja se uvršča med deljene postopke, pri katerih se ločeno določi napetostno-deformacijska stanja in ločeno izračuna poškodba. Za izračun je bil razvit program za izračun poškodbe (PIP), ki ima možnost uvoza rezultatov, pridobljenih z linearno ali nelinearno MKE analizo. Kritična mesta so določena z uporabo deformacijskih zdržljivostnih krivulj in Skeltonovega energijskega postopka. Materialni podatki so za neizmerjene temperature interpolirani z linearno ali odsekoma kubično Hermit-ovo metodo. Uporaba razvitega modela je prikazana na primeru dveh standardiziranih oblik preizkušancev za deformacijsko nadzorovane preizkuse pri nespremenljivem temperaturnem polju in za kombinacijo naključnega poteka temperaturne in mehanske obremenitve. Raziskana je tudi temperaturna odvisnost parametra Kp, ki je uporabljen v Neuberjevi formuli za oceno elastoplastičnih napetostno-deformacijskih stanj iz rezultatov linearne MKE analize. Predstavljen postopek omogoča računsko hitro vrednotenje izdelkov, obremenjenih z naključno kombinacijo temperaturne in mehanske obremenitve.

(Ključne besede: termomehansko utrujanje, poškodba, deformacijski postopki vrednotenja, metode končnih elementov)

The strain-life approach is one of the most commonly used methods for evaluating component fatigue. In its application for thermo-mechanically load states and for modelling local temperature stress-strain states, we use a stress-controlled rheological spring-slider model with an operator of the Prandtl type, which makes it possible to model the elasto-plastic material properties. The approach is used to evaluate complex components in combination with the finite-element method (FEM). The described evaluation approach is classified as one of the non-unified procedures, where we can determine separately the stress-strain states and separately calculate the damage. For the damage calculation a Damage Calculation Program (DCP) was developed. It has the possibility to import the results acquired by linear or nonlinear FEM analysis. The critical areas are determined by using a deformation endurance curve and the Skelton approach. The material data on non-measured temperatures is interpolated with the linear or cubic Hermite method. The application of the developed model is shown on two standard-shaped test specimens for deformation control tests in a constant temperature field and for a combination of the random temperature history and the mechanical load. The temperature dependence of the Kp parameter used in the Neuber formula for estimating the elasto-plastic stress-strain states from the results of the linear FEM analysis is also included in the research. The described procedure enables a fast numerical validation with a random combination of temperature and mechanical load.

(Keywords: thermo-mechanical fatigue, damages, strain-life approach, finite element methods)

0 UVOD

V avtomobilu je vrsta termomehansko obremenjenih delov, to so glava in blok motorja, nosilci motorja, zavore ter celotni izpušni sistem. Vedno večje zahteve po zdržljivosti izdelkov in krajših razvojnih časih so privedle do velikega napredka metod napovedovanja zdržljivosti termomehansko obremenjenih izdelkov.

Za uspešno napoved dobe trajanja je treba upoštevati ustrezen materialni model s parametri, pridobljenimi s testiranji, modeliranje napetostno-deformacijskih stanj med cikličnim obremenjevanjem, večosnost, model kopičenja poškodb ter preizkušanje izdelkov za ovrednotenje soodvisnost med simulacijami in meritvami.

Za obratovalne razmere, kjer so prisotna zapletena napetostno-deformacijska stanja je v prvi vrsti pomembna izbira pravilnega kriterija za vrednotenje večosnega utrujanja. Trenutno so najbolj razširjeni naslednji postopki:

- izračun primerjalne napetosti ali deformacije ([1] do [3]) v vsakem vozlišču modela končnih elementov,
- uporaba napetostnih ali deformacijskih invariant [3],
- metoda kritične prerezne ravnine (prva sta jo predlagala Brown in Miller ter kasneje dodelali mnogi raziskovalci (Socie, Fatemi – Socie, Papadopoulous, … – [4], [1] in [3])), ki upošteva v vsakem vozlišču najbolj kritično ravnino za ocenitev dobe trajanja in
- energijski postopek ([5] in [14]), ki upošteva sproščeno energijo med cikličnim obremenjevanjem.

Poleg zgornje delitve se lahko postopki delijo tudi glede na področje uporabe in zahteve analize. Zgodovinsko je bila prva delitev med "visokocikličnim" (VCU) in "malocikličnim" (MCU) utrujanjem. Na področju VCU je bilo najodmevnejše pionirsko delo Wöhlerja z razvojem napetostnega pristopa. Na področju MCU pa v šestdesetih letih dvajsetega stoletja prispevek Mansona in Coffina z uveljavitvijo deformacijskega pristopa. Tovrstna delitev je pogosta tudi dandanes zaradi pretežnih elastičnih deformacij pri utrujanju VCU ter plastičnih deformacij pri utrujanju MCU, kar je opazno pri metodi kritične prerezne ravnine [3] ali energijski metodi [5]. Pomembno raziskovalno področje je tudi razvoj enotnega modela za utrujanje VCU in MCU, kar je na primeru energijskih metod prikazano v [5] in [21].

Namen prispevka je pokazati razviti postopek, ki je kot razširitev metod podanih v [9],

1 INTRODUCTION

In a car there are several thermo-mechanically loaded components, e.g., the engine block and head, the engine supports, the brakes and the whole exhaust system. The growing demands for longer lives and shorter development times have led to great advances in the methods for predicting the life of thermo-mechanically loaded components.

For an efficient life prediction several requirements have to be fulfilled: a proper material model with material parameters derived from testing, modelling of the stress-strain response during cycle loading, multi-axiality, a damage accumulation model, and component testing to evaluate the correlation between the life prediction models and the experiments.

In operating conditions where complex stress-strain fields are present, the first challenge is to properly select the multi-axial fatigue criterion. At present the following criteria are the most widely used:

- Calculation of the equivalent stress or strain ([1] to [3]) in each node of the finite-element model.
- The use of stress or strain invariants [3].
- The critical plane approach (initially suggested by Brown and Miller and later modified by several researchers, e.g., Socie, Fatemi – Socie and Papadopoulous – [4], [1] and [3]) that considers the critical plane in each selected node for the life estimation.
- The energy criterion ([5] and [14]) that takes into account the dissipated energy during cycle loading.

Besides the upper division, approaches can be divided according to their field of usage or analyses requirements. Historically, the first division was between high-cycle (HCF) and low-cycle fatigue (LCF). Wöhler pioneered the field of HCF and the development of the stress-life approach. In the field of LCF Manson and Coffin made substantial developments with the establishment of the strain-life approach. This differentiation is still present today, mainly due to the tendencies for elastic deformation in HCF and inelastic deformation in LCF, as can be seen in the critical plane approach in [3] or the energy method [5]. An important field of research concerns the development of a unified approach to LCF and HCF, as can be seen in the example of the energy methods in [5] and [21].

The purpose of this paper is to show a developed procedure that is an extension of the

[11] in [12], uporaben v kombinaciji z metodo končnih elementov (MKE) na izdelkih zahtevnih oblik. Metoda uporablja elastoplastičen materialni model vzmet - drsnik, ki omogoča modeliranje napetostno-deformacijskih stanj pri spremenljivih obremenitvah in temperaturah. V nadaljevanju je prikazan celotni postopek ter njegova overitev na dveh primerih.

1 PREDLAGANI POSTOPEK VREDNOTENJA TERMOMEHANSKEGA UTRUJANJA

1.1 Deljenje analiz

V primeru termomehanskega utrujanja (TMU) na izdelek hkrati delujejo spreminjajoče se mehanske obremenitve (sile, tlak itn.) in temperaturne obremenitve zaradi segrevanja izdelka. Za pridobitev temperaturnih polj v izdelku, ki se uporabijo v trdnostnih analizah, je treba opraviti delitev med termičnimi oz. analizami CFD in trdnostnimi preračuni. Pri prvi skupini analiz se pridobi temperaturna polja v izdelku za celoten obremenitveni potek, ki se nato skupaj z mehanskimi obremenitvami uporabijo v trdnostni MKE analizi.

V našem primeru za izračun poškodbe izvedemo delitev med trdnostno in poškodbeno analizo. Pridobljena napetostno-deformacijska in temperaturna polja se izvozijo v razviti program za izračun poškodbe (PIP), kjer se izvedejo končni preračuni. Uporabljena delitev analiz je uspešno uporabljena skupaj s Skeltonovim energijskim kriterijem v avtomobilski industriji ([1],[7] in [8]).

Predlagan postopek vrednotenja poteka v naslednjem vrstnem redu:

1. Izračun temperaturnih polj za celotni potek obremenitev s prehodno termično ali CFD analizo MKE.
2. Izračun napetostno-deformacijskega odziva za obračalne točke obremenitvenega poteka z MKE. Analiza je lahko linearna ali nelinearna.
3. Iz MKE je izvoženi potek napetosti in temperature za vsa vozlišča v razviti program za izračun poškodbe (PIP).
4. Če so napetosti pridobljene z linearno analizo, so v PIP-u napetosti v plastičnem področju ocenjene z Neuberjevo formulo.
5. V PIP-u se izvede modeliranje celotnih histereznih zank z reološkim modelom vzmet - drsnik [9].

methods given in [9], [11] and [12]. It is used in combination with the finite-element method (FEM) and can be applied to components with a complex shape. The procedure uses an elastoplastic spring-slider material model, which enables the modelling of stress-strain states under variable loads and temperatures. In the sections that follow the entire process and its validation on two examples are shown.

1 THE PROPOSED PROCEDURE FOR TMF EVALUATION

1.1 Uncoupling of analysis

In the case of thermo-mechanical fatigue (TMF) the variable mechanical loading (force, pressure, etc.) and the temperature loading are acting simultaneously on the component. In order to obtain the temperature fields that are used in stress-strain analyses the thermal or CFD analyses and the structural analyses are uncoupled. With the first group of analyses the temperature fields for the entire load history are obtained, which are later applied in combination with the mechanical loadings in the structural finite-element analyses (FEA).

For the damage calculation the uncoupling between the structural and the damage analyses is performed too. The obtained stress-strain and temperature fields are exported to the developed Damage Calculation Program (DCP), where the final calculation is performed. This kind of uncoupling is successfully applied in combination with Skelton's energy criterion in the automotive industry ([1],[7] and [8]).

The proposed evaluation procedure is performed in the next steps:

1. Calculation of the temperature fields for the load history with the transient thermal FEA or CFD analyses.
2. Calculation of the stress-strain response for the turning points in the given load history with the FEA. The analysis can be either linear or non-linear.
3. From the FEA the stress and temperature histories for all the nodes are exported to the specifically developed Damage Calculation Program (DCP).
4. If the stresses have been computed with the linear FEA the DCP estimates the elastoplastic stresses at the turning points with the Neuber approximate formula.
5. In the DCP a stress-strain modelling of the complete hysteresis loops is performed using the stress-controlled spring-slider model [9].

6. Štetje obremenitvenih ciklov z rainflow metodo z upoštevanjem metode zapiranja ciklov, predstavljene v [9], in ekvivalentne temperature cikla[9].
7. Izvedena je ocena poškodbe s Smith-Watson-Topper-jevim parametrom [10] in ocena sproščene energije.

1.2 Napetostno nadzorovan model elastoplastičnosti

Modeliranje napetostno-deformacijskega odziva v PIP-u se izvaja s serijsko vezanim modelom vzmet - drsnik, ki je zmožen modeliranja kinematičnega utrjevanja za izotermne in neizotermne primere. Ker je bil model že obširno predstavljen v [9], so v nadaljevanju podane le končne enačbe. Ob neupoštevanju izotropnega utrjevanja je za vrednotenje utrujanja pogosto v uporabi stabilizirana ciklična napetostno-deformacijska Ramberg-Osgoodova krivulja [9]:

6. After the stress-strain modelling the rainflow cycle counting is performed, by utilizing the cycle closure method used in [9] and the calculation of the equivalent cycle temperature [9].
7. Damage estimation using the Smith-Watson-Topper parameter [10] and the estimation of the dissipated energy is performed.

1.2 Stress-controlled model of elastoplasticity

Modelling of the stress-strain response in the DCP is performed with the stress-controlled serially connected spring-slider model, which is capable of modelling elastoplastic hardening solids and nonlinear kinematic hardening for isothermal or non-isothermal cases. The model was thoroughly presented in [9], which is why only the final set of equations is listed below:

$$\varepsilon = g(\sigma, T) = \frac{\sigma}{E(T)} + \left(\frac{\sigma}{K'(T)}\right)^{1/n'(T)} \quad (1),$$

kjer so: T temperatura, $E(T)$ modul elastičnosti, $K'(T)$ koeficient cikličnega utrjevanja in $n'(T)$ eksponent cikličnega utrjevanja. Poleg zgornje enačbe se lahko uporabi katerokoli elastoplastično razmerje s kinematičnim utrjevanjem.

Ob predpostavki, da so na voljo stabilizirane ciklične napetostno-deformacijske krivulje, je lahko elastoplastična deformacija modelirana s Prandtlovim operatorjem. Celotna elastoplastična deformacija je lahko izražena v obliki Prandtlovega operatorja:

T, $E(T)$, $K'(T)$ and $n'(T)$ are the temperature, the Young modulus, the cyclic hardening coefficient, and the cyclic hardening exponent, respectively. There is no limitation, however, on using any other stress-strain relation that exhibits elastoplastic behaviour with nonlinear kinematic hardening.

Supposing that cyclically stable cyclic stress-strain curves are available, the elastoplastic strain can be modelled with an operator of the Prandtl type. The total elastoplastic strain can be expressed in the form known as the operator of the Prandtl type:

$$\varepsilon(t_i) = \sum_{j=0}^{n_r} \alpha_j(T_i)\sigma_{\alpha j}(t_i) \quad (2)$$

za $0 \le t_1 \le t_2 \le \cdots \le t_i \le \cdots$, kjer sta $T_i = T(t_i)$ in $\sigma_{\alpha j}(t_i)$ člena s splošno začetno vrednostjo:

for $0 \le t_1 \le t_2 \le \cdots \le t_i \le \cdots$, where $T_i = T(t_i)$ and $\sigma_{\alpha j}(t_i)$ is the play operator with a general initial value:

$$\sigma_{\alpha j}(t_i) = \max\left\{\sigma(t_i) - r_j, \min\left\{\sigma(t_i) + r_j, \frac{\alpha_j(T_{i-1})}{\alpha_j(T_1)}\sigma_{\alpha j}(t_{i-1})\right\}\right\} \quad (3).$$

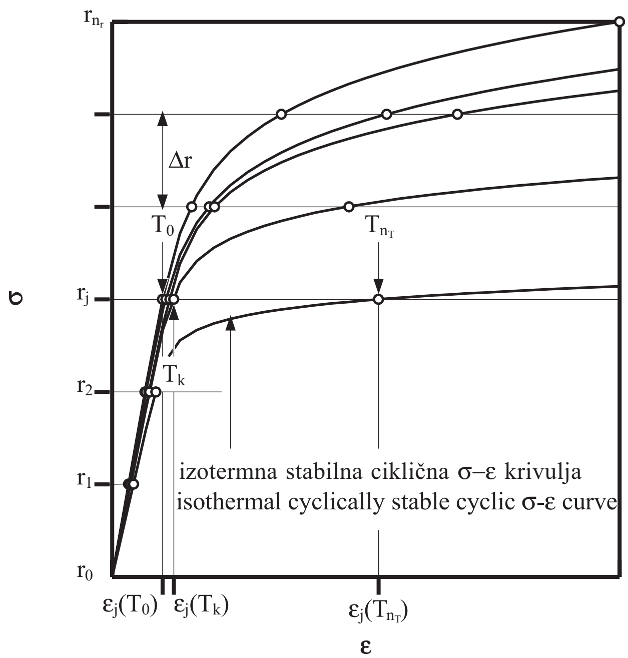
Predpostavimo, da na začetku nimamo zaostalih napetosti, torej velja: $\sigma_{\alpha j}(0) = 0$ in $\varepsilon(0) = 0$. Prandtlove gostote $\alpha_j(T_k)$ v področju $j = 0,...,n_r$ in $k = 0,...,n_T$:

Presumably, there is no residual stress initially, so $\sigma_{\alpha j}(0) = 0$ and $\varepsilon(0) = 0$. The Prandtl densities $\alpha_j(T_k)$ in the range $j = 0,...,n_r$ and $k = 0,...,n_T$:

$$\alpha_j(T_k) = \frac{1}{\Delta r}(\varepsilon_{j+1}(T_k) - 2\varepsilon_j(T_k) + \varepsilon_{j-1}(T_k)) \quad (4)$$

so pridobljeni iz razpoložljivih izotermnih stabiliziranih cikličnih napetostno-deformacijskih krivulj, kjer je $\varepsilon_{-1}(T_k) = \varepsilon_0(T_k) = 0$. Navidezne

are gained from the available isothermal cyclically stable cyclic stress-strain curves, where $\varepsilon_{-1}(T_k) = \varepsilon_0(T_k) = 0$. The fictive yield stresses r_j are usually



Sl. 1. *Določitev Prandtlovih gostot, napetostno nadzirano*
Fig. 1. *Prandtl-density assessment, stress controled*

napetosti r_j so običajno enakomerno razporejene s stalno širino razreda Δr med 0 in največjo pričakovano napetostjo (sl. 1).

Za pospešitev izračuna so vstopni poteki $\sigma(t)$, $T(t)$, materialni parametri in Prandtlove gostote tabelirane s stalnim prirastkom napetosti Δr in prirastkom temperature ΔT. Tabelirani materialni parametri in Prandtlove gostote so izračunane le enkrat ter shranjene pred začetkom σ,ε modeliranja z en. (2).

1.3 Modeliranje napetosti in deformacij

Predznačena primerjalna von Misesova napetost je izvožena iz rezultatov MKE analize v PIP, kjer poteka modeliranje napetostno-deformacijskega odziva z napetostno nadziranim modelom vzmet - drsnik. Napetosti so lahko pridobljene z linearno ali nelinearno MKE analizo. V primeru slednje morata za pridobitev ustreznih rezultatov biti uporabljena enaka materialna modela v programu MKE in PIP-u. Zaradi omejitev modela vzmet - drsnik lahko trenutno uporabljamo le elastoplastične modele s kinematičnim utrjevanjem.

Za dosego računsko hitre metode vrednotenja je velika skrb dana linearno izračunanim napetostim v kombinaciji s aproksimacijskimi enačbami. Med množico

dispersed equidistantly with a constant fictive yield stress class width Δr between the zero stress and the maximum expected stress (Fig. 1).

To speed up the computation, the input histories of $\sigma(t)$, $T(t)$, the material parameters and the Prandtl densities are tabulated by setting the stress increment to Δr and choosing a temperature increment of ΔT. The tabulated material parameters and the Prandtl densities are calculated only once and stored before the σ,ε modelling process beginning at Eq. (2).

1.3 Stress-strain modelling

The signed von Mises stress is exported from the FEA results to the DCP, where the stress-strain modelling with the spring-slider model takes place. Stresses can be computed with a non-linear or linear FEA. In the case of non-linearly computed stresses, the same material model must be applied in both the FEA software and in the DCP program in order to obtain consistent results. Due to the limitations of the spring-slider model elastoplastic kinemetic hardening material models are allowed at the moment.

In order to achieve a computationally fast evaluation method, great care was given to the linearly computed stresses in combination with approximate formulas. There are several aproksimacijskih formul je bila izbrana pogosto uporabljena Neuberjeva aproksimacijska enačba ([9] in [13]):

approximate methods from which the frequently used ([9] and [13]) Neuber approximate formula is applied:

$$\varepsilon = \frac{\sigma}{E(T)}\left(\frac{\sigma_e}{\sigma}\right)^2 \frac{e^*}{S^*/E(T)} \tag{5}$$

kjer sta imenska napetost in deformacija definirana kot $S^* = \sigma_e/K_p$ in $e^* = g(S^*,T)$. K_p je razmerje mejnih obremenitev in $g(S^*,T)$, je stabilizirana ciklična napetostno-deformacijska krivulja, pridobljena v en. (1). K_p je podan kot razmerje [13]:

where the nominal stresses and strains are defined as $S^* = \sigma_e/K_p$ and $e^* = g(S^*,T)$. K_p is the limit load ratio and $g(S^*,T)$ is the cyclic stress-strain curve, as defined in Eq. 1. K_p is calculated using [13]:

$$K_p = \frac{L_P}{L_F} \tag{6}$$

kjer je L_p sila, ki povzroči popolno plastifikacijo prereza in L_F sila, ki povzroči začetek plastifikacije v vozlišču z največjo napetostjo.

V [13] so podane naslednje vrednosti K_p: $K_p = 30$, $K_p = 2{,}5$ (priporočena vrednost) in $K_p = 1$ (ne upošteva Neuberjeve formule, kar pomeni da so vhodne napetosti neposredno uporabljene za modeliranje napetostno-deformacijskih poti). Zaradi temperaturno odvisnih materialnih lastnosti je pričakovana temperaturna odvisnost L_p in L_F. Za boljše ujemanje rezultatov linearne in nelinearne MKE analize je bil uveden temperaturno odvisen K_p:

where L_p is the force that causes the full plastification of the analyzed cross-section and L_F is the force that starts the plastification in the most stressed node.

In [13] the following values of K_p are given: $K_p = 30$, $K_p = 2.5$ (recommended value) and $K_p = 1$ (the Neuber formula is not considered – the input stresses are used directly to model the stress-strain paths). Due to the temperature dependency of the material parameters a temperature dependency is also expected for L_p and L_F. For a better agreement between the linear and non-linear FEA a temperature-dependent K_p is introduced:

$$K_p(T) = \frac{L_P(T)}{L_F(T)} \tag{7}$$

Za primere, prikazane v nadaljevanju, je bil izračunan za najvišjo temperature na površini.

For the examples that follow it was calculated for the maximum surface temperature.

1.4 Ocena poškodbe

Izbira pravilne metode ocene velikosti poškodbe je ključna za uspešno napoved zdržljivosti izdelka. Prikazana metoda temelji na računsko hitrih in uveljavljenih postopkih. Zato je kot prvi način uporabljen Smith-Watson-Topperjev parameter [10]. Ta je izračunan za vsak obremenitveni cikel iz:

1.4 Damage estimation

An appropriate damage estimation method provides the key to an efficient life-prediction. In the proposed method, the focus is on employing computationally fast and widely accepted approaches. This is the reason why the well-known Smith-Watson-Topper damage parameter [10] was applied as the first damage-estimation method. It is calculated for every load cycle:

$$P_{SWT}{}^2 = (\sigma_a + \sigma_m)\varepsilon_a E(T_e) \tag{8}$$

in število ciklov do začetne razpoke je pridobljeno iz naslednje enačbe:

where the number of cycles to the crack initiation is obtained from:

$$P_{SWT}{}^2 = \sigma'^2_f(T_e)(2N_f)^{2b(T_e)} + \sigma'_f(T_e)E(T_e)\varepsilon'_f(T_e)(2N_f)^{b(T_e)+c(T_e)} \tag{9}$$

kjer je σ'_f napetostni koeficient, b napetostni eksponent, ε'_f deformacijski koeficient in c deformacijski eksponent. Materialni parametri so odvisni od ekvivalentne temperature cikla in so linearno ali odsekoma kubično Hermit-ovo interpolirani. Število ciklov do začetne razpoke je uporabljeno za izračun poškodbe z Minerjevim pravilom o linearnem kopičenju poškodbe.

Kot drugi pokazatelj poškodbe je uporabljena sproščena energija s Skeltonovim energijskim kriterijem ([14] do [16]), ki pridobiva pomembnost na področju TMU ([6] do [8] in [17]). Poglavitna predpostavka je, da material po začetnem utrjevanju ali mehčanju doseže stabilizirano stanje pri katerem izdelek obratuje večino dobe trajanja, ter da je sproščena energija pri stabilizaciji uporabljena kot merilo določitve zdržljivosti izdelka ([6] do [8] in [14]).

Z upoštevanjem zgornje hipoteze je bilo predpostavljeno, da je obremenitveni potek uporabljen v stabiliziranem stanju ter izračunana sproščena energija uporabljena za določitev kritičnih mest konstrukcije. V PIP-u je trenutno v uporabi poenostavljena enačba za izračun energije [17]:

where σ'_f is the fatigue strength coefficient, b is the fatigue strength exponent, ε'_f is the ductility coefficient and c is the ductility exponent. The material parameters depend on the equivalent cycle temperature and can be linearly or piecewise cubic Hermite interpolated. The number of cycles to the crack initiation is used to estimate the damage with the Miner linear damage-accumulation rule.

Skelton's energy criterion is used ([14] to [16]) as the second damage indicator, which is gaining considerable importance in TMF evaluations ([6] to [8] and [17]). It is based on the assumption that after the initial hardening or softening the material reaches a stabilized state, in which the part operates for the majority of the lifetime, and that the cumulated dissipated energy during stabilization can be considered as a material constant used as a crack-initiation criterion ([6] to [8] and [14]).

In accordance with this it was considered that the load history is applied in the stabilized state and the dissipated energy was used for the identification of the most critical area of the component. At the moment in the DCP the simplified equation is used [17]:

$$\Delta W_p \approx \Delta\sigma \cdot \Delta\varepsilon_p \qquad (10).$$

Ta je uporabljena za izračun energije v vsakem obremenitvenem ciklu, ki se nato linearno akumulira skozi celotni potek obremenitve:

It is used for calculating the dissipated energy per counted cycle. Through the calculation of the load history in the stabilized state it is linearly accumulated:

$$W_p = \sum_{cycles} \Delta W_{p,i} \qquad (11).$$

Vrednost W_p je uporabljena za določitev kritičnih mest konstrukcije. Obe uporabljeni metodi sta primerni za naključni potek temperaturnih in mehanskih obremenitev.

The value is used for the identification of the critical areas. Both methods are suitable for a random history of the mechanical and thermal loads.

2 PRIMERI

Namen naslednjega poglavja je pokazati, da je predlagana metoda uporabna za analize zahtevnih izdelkov TMU. Za vrednotenje materialnega modela v PIP-u so rezultati modeliranja napetostno-deformacijskih poti primerjani z rezultati nelinearne analize s priznanim programskim paketom ANSYS. Za dosego kratkih računskih časov je velika pozornost namenjena linearni MKE analizi v kombinaciji z Neuberjevo aproksimacijsko formulo. Vpliv vrednosti K_p na napetostno-deformacijske poti, poškodbo in sproščeno energijo je bil tudi preučen.

2 EXAMPLES

The aim of the following section is to show that the proposed procedure can be successfully used in the TMF analyses of complex components. To enable the DCP validation, the obtained stress-strain paths are compared with non-linear FEA results obtained with the renowned ANSYS software. In order to reduce the computational times, great care has been put on linear FEA in combination with the Neuber approximate formula. The influence of K_p upon the stress-strain trajectory, damage and dissipated energy was studied.

2.1 Preizkušanca in material

Na sliki 2 sta prikazani obliki uporabljenih standardnih preizkušancev ASTM [18], ki sta primerni tudi za preizkuse pri povišanih temperaturah. Preizkušanec z okroglim prerezom premera 9 mm ter spremenjeni 5 mm debeli ploščati preizkušanec. Slednjemu je za lažje spremljanje naraščanja poškodbe in simulacije zahtevnih napetostno-deformacijskih stanj na sredini dodana 3 mm luknja. Oba preizkušanca sta bila v področju pritrditve skrajšana za zmanjšanje velikosti numeričnega modela. Število končnih elementov za okrogli preizkušanec je 6030, za ploščati pa 7700 elementov. Mreža je bila zgoščena v področju segrevanja in na pričakovanih kritičnih mestih. Vsi preizkusi so bili izvedeni na delovni postaji 2,8 GHz Pentium IV, 4 GB RAM, Windows XP.

Za ovrednotenje predlagane metode je bil izbran material: jeklo 10 CrMo 9 10 (toplotna obdelava 930 °C/1,5 h zrak, 710 °C/1,5 h zrak, 680 °C peč), s parametri za Ramberg-Osgoodovo razmerje in Manson-Coffin-Morrowo krivuljo, pridobljenimi iz [19] za 23, 300, 400, 500 in 600 °C.

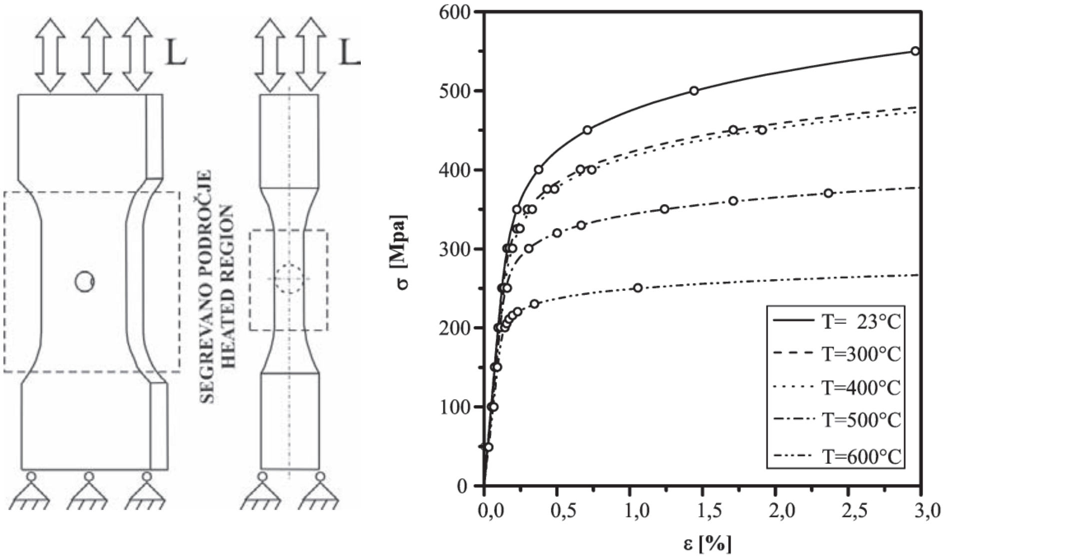
Za nelinearno MKE analizo v programu ANSYS je linearizirana Ramberg-Osgoodova krivulja z uporabo večlinearnega Besselingovega modela [20] s kinematičnim utrjevanjem. Točke uporabljene za linearizacijo, so prikazane na sliki 2 (desno). Za oceno poškodbe so bile izračunane

2.1 Specimens and material

Fig. 2. shows the used ASTM [18] specimens that are also suitable for testing at elevated temperatures. These specimens are the round specimen of diameter 9 mm and the modified 6 mm thick, flat specimen. In the latter a hole of 3 mm was introduced in the centre to facilitate the damage evolution and to simulate complex stress-strain states. Both specimens were shortened for the FEA evaluation in the fixation-gripping area to reduce the size of the model. The round specimen has 6030 elements and the flat one 7700 elements. The mesh was refined in the heating area and at the expected critical areas. All the analyses were performed with a 2.8 GHz Pentium IV, 4 GB RAM, Windows XP-based workstation.

For validation of the proposed approach the following material was chosen: Steel 10 CrMo 9 10 (heat treatment 930 °C/1.5 h air, 710 °C/1.5 h air, 680 °C furnace) with the Ramberg-Osgood and Manson-Coffin-Morrow parameters obtained from [19] for 23, 300, 400, 500 and 600 °C.

For the non-linear analyses in the ANSYS program, the linearization of the Ramber-Osgood curve was made with the multi-linear kinematic hardening Besseling model [20]. The points used for the linearization are shown in Fig. 2 (right). For the damage evaluation, temperature-dependent P_{SWT}



Sl. 2. *Uporabljena preizkušanca (levo) in temperaturno odvisne Ramberg-Osgood-ove krivulje s točkami, uporabljenimi za linearizacijo (desno)*

Fig. 2. *The used specimens (left) and the temperature dependent Ramber-Osgood curves with the points used for the linearization (right)*

temperaturno odvisne krivulje P_{SWT}, pridobljene iz parametrov, podanih v [19].

2.2 Obremenitve

V prispevku sta predstavljena dva nadzorna preizkusa. Prvi je izveden pri nespremenljivih temperaturnih poljih z naslednjimi najvišjimi temperaturami na segreti površini: 20, 300, 400, 500 in 600 °C (sl. 2). V teh primerih je bil upoštevan en obremenitveni cikel z R = -1 in z obremenitvama L_1 = 12 kN in L_2 = 25 kN. Sili sta izbrani tako, da pri L_1 v ploščatem preizkušancu napetosti presegajo ciklično mejo tečenja $R'_{p;0,2}$ le v konicah napetosti okoli dodane luknje, pri sili L_2 pa v večjem delu prereza.

Drugi obremenitveni primer je naključni umetni potek temperaturne in mehanske obremenitve, prikazana na sliki 3. Ta je kombinacija velikih in majhnih hitrosti segrevanja in deformacij z zadrževalnimi časi. Zapleteni potek je izbran za prikaz splošnosti predstavljene metode. Poudariti je treba, da hitrost obremenjevanja ne vpliva na elastoplastični materialni model.

Točke na sliki 3 prikazujejo potrebna mesta trdnostnih analiz, kar znaša 22 analiz za obdobje 30 s.

2.3 Rezultati

Prikazani so rezultati izračunanih poškodb in sproščenih energij ter pridobljene napetostno

curves were calculated using the parameters given in [19].

2.2 Loadings

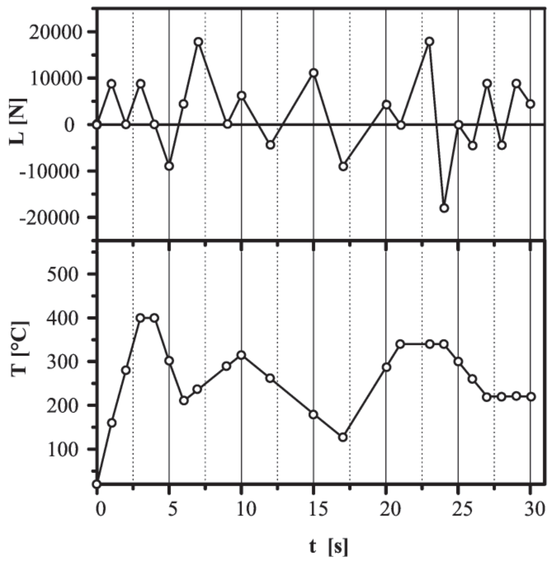
In the paper, two types of validation tests are shown. At first this is done using constant temperature fields with the following maximum surface temperatures in the heated region, 20, 300, 400, 500 and 600 °C (see Fig. 2). In these cases the analyses were performed for one reversed cycle with R = -1 and the force amplitudes L_1 = 12 kN and L_2 = 25 kN. The forces were chosen so that the stresses in the flat specimen exceed the cyclic yield stress $R'_{p;0,2}$ only in stress peaks around the introduced hole and with force L_2 in a larger part of the cross-section.

The second load case is a synthetic random force and temperature history, as shown in Fig. 3. It is a combination of high-low heating rates and hold times. This complex history was chosen to demonstrate the broad applicability of the proposed model. It is important to emphasize that strain rates do not influence the elastoplastic material model at all.

The points in Fig. 3 show the locations of the needed structural analyses, which amounts to a total of 33 analyses for a 30-seconds load history.

2.3 Results

Damages, dissipated energies and stress-strain paths obtained from the linear and non-linear



Sl. 3. *Potek temperature in sile za naključno obremenitev*
Fig. 3. *Random force and temperature histroy*

deformacijske poti za primere nelinearne analize in linearne v kombinacijami z različnimi K_p. Zaradi povezave mehanske in od temperature odvisne specifične deformacije se najbolj poškodovano vozlišče pri različnih temperaturnih poljih spreminja, četudi so sile enake. Zato je za primerjavo rezultatov pri obeh preizkušancih izbrano enako vozlišče za vse primere, to je najbolj poškodovano vozlišče pri linearni analizi in 20 °C. Za okrogli preizkušanec ima izbrano vozlišče številko 7025, za ploščati pa 2288.

Napetostno-deformacijske poti so pridobljene neposredno iz predznačene von Misesove napetosti in skupne predznačene von Misesove specifične deformacije, pridobljene iz nelinearne analize v ANSYS-u. Prikazane so tudi poti izračunane s PIP, iz rezultatov napetosti nelinearne MKE analize pa tudi tiste, pridobljene iz linearno pridobljenih napetosti v kombinaciji z različnimi K_p.

V naslednjih slikah so uporabljene naslednje oznake:

A. Napetosti in deformacije so pridobljene iz nelinearne MKE analize.
B. Napetosti v obračalnih točkah so pridobljene iz nelinearne MKE analize, ki so nato uporabljene v PIP-u za izračun celotne napetostno-deformacijske poti za K_p = 1.
C. Napetosti v obračalnih točkah so pridobljene iz linearne MKE analize, ki so nato uporabljene v PIP-u za izračun celotne napetostno-deformacijske poti za K_p = 30.
D. Napetosti v obračalnih točkah so pridobljene iz linearne MKE analize, ki so nato uporabljene v PIP-u za izračun celotne napetostno-deformacijske poti za K_p = 2,5.
E. Napetosti v obračalnih točkah so pridobljene iz linearne MKE analize, ki so nato uporabljene v PIP-u za izračun celotne napetostno-deformacijske poti za $K_p(T)$ (en. (8)).

2.3.1 Nelinearna MKE analiza

S primerjavo rezultatov nelinearne analize v ANSYS-u in izračunanih poti v PIP-u je ugotovljeno, da je dobro ujemanje doseženo v obračalnih točkah (sl. 4 in 5). Kljub temu so razlike opazne iz naslednjih razlogov: poti, izvožene iz ANSYS-a, so izpostavljene linearizaciji Ramberg-Osgoodove krivulje in primerjalne napetosti ter specifične deformacije so v MKE programu izračunane iz celotnega

FEA in combination with different K_p's are presented in this section. Due to the different interactions between the mechanical and thermal strains, the location of the most damaged node can move if the temperature field changes, even if the mechanical force remains unchanged. That is why when comparing the results the same node is chosen for all the load cases. This is the most damaged node in the linear analysis at 20 °C. For the round specimen it is numbered 7025 and for the flat specimen, 2288.

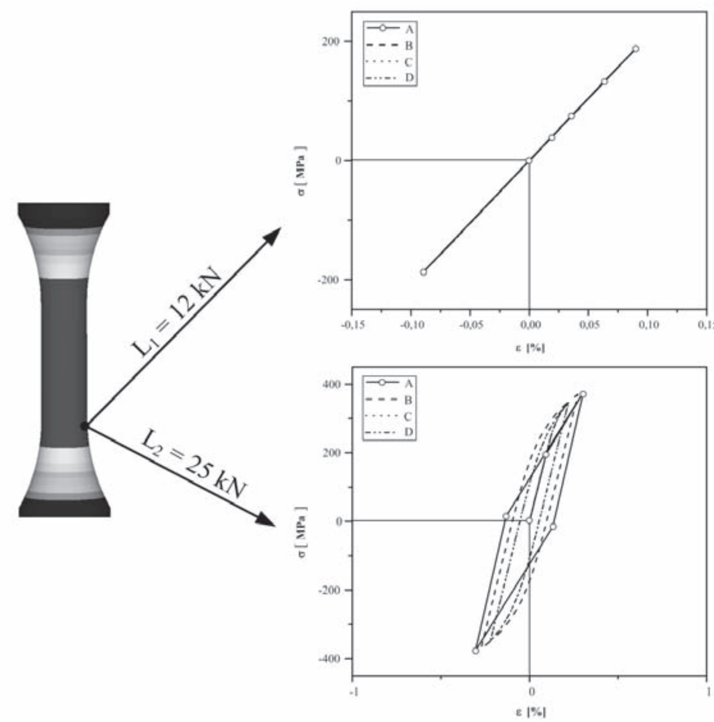
Stress-strain trajectories were obtained directly from the exported signed von Mises stresses and the signed total mechanical von Mises strains as provided by the non-linear solutions in the ANSYS software. Stress-strain paths obtained by DCP from the non-linear FEA stress results, as well as those from linear FEA stresses for two distinct K_p's, are also presented.

In the figures below, the following notation is used:

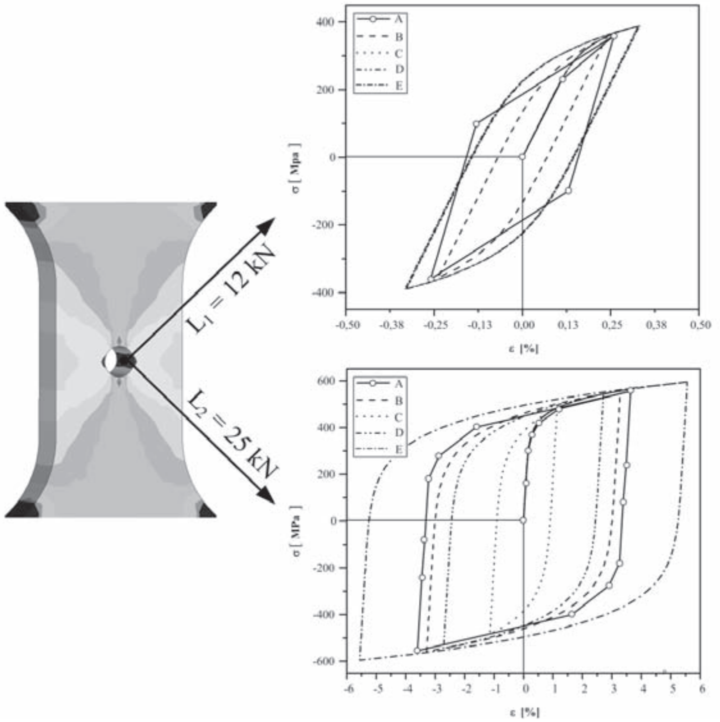
A. Stresses and strains that were gained from the non-linear FEA.
B. Stresses at the turning points were taken from the non-linear FEA, and these values were then processed by DCP to produce complete stress-strain trajectories for K_p = 1.
C. Stresses at the turning points were taken from the linear FEA, and these values were then processed by DCP to produce complete stress-strain trajectories for K_p = 30.
D. Stresses at the turning points were taken from the linear FEA, and these values were then processed by DCP to produce complete stress-strain trajectories for K_p = 2.5.
E. Stresses at the turning points were taken from the linear FEA, and these values were then processed by DCP to produce complete stress-strain trajectories for $K_p(T)$ (see Eq. 8).

2.3.1 Non-linear FEA

By comparing the non-linear FEA results from ANSYS with the stress-strain paths obtained from DCP it is clear that good agreement was reached at the turning points (Fig. 4 and 5). However, there are differences for the following reasons: Firstly, the trajectories drawn from the stress and strain values exported from ANSYS are influenced by the linearization of the Ramberg-Osgood curves and secondly, in the FEA software, the equivalent stresses and strains are computed from the



Sl. 4. *Prikaz histereznih zank v vozlišču 7025 za okrogli preizkušanec pri 20 °C*
Fig. 4. *Hysteresis loops in node 7025 of the round specimen at 20°C*



Sl. 5. *Prikaz histereznih zank v vozlišču 2288 za ploščati preizkušanec pri 20 °C*
Fig. 5. *Hysteresis loops in node 2288 of the flat specimen at 20°C*

tenzorja napetosti, medtem ko so v PIP-u izračunane z enoosnim modelom na temelju predznačene primerjalne napetosti, uvožene iz ANSYS-a.

2.3.2 Linearna MKE analiza

S primerjavo poti, pridobljenih z linearno analizo v kombinaciji z Neuberjevo formulo, lahko preučimo vpliv parametra K_p. V primeru okroglega preizkušanca pri L_1 ne pride do plastifikacije, v primeru L_2 je tečenje materiala opazno. Za vse vrednosti K_p je ujemanje s histereznimi zankami iz nelinearne analize dobro. Izrazitejše razlike so opazne v ploščatem preizkušancu. V primeru L_1, vrednosti $K_p(T)$ in K_p = 2,5 dasta podobne rezultate, najboljše ujemanje je doseženo s K_p = 30. V primeru L_2, pri katerem je tečenje materiala izrazitejše, vrednost K_p = 30 da izrazito nekonzervativne rezultate, izračunan $K_p(T)$ pa konzervativne. V tem primeru je najboljše ujemanje doseženo s priporočenim K_p = 2,5.

Ugotovimo lahko, da v primeru izrazitejšega tečenja priporočena vrednost K_p oz. izračunani $K_p(T)$ da boljše ujemanje z nelinearno analizo oz. konzervativne rezultate. Vrednost K_p = 30 je uporabna v področju majhne plastifikacije materiala.

Za primer naključne obremenitve so ujemanja v okroglem preizkušancu dobra (sl. 6) v ploščatem preizkušancu pa so v določenih primerih

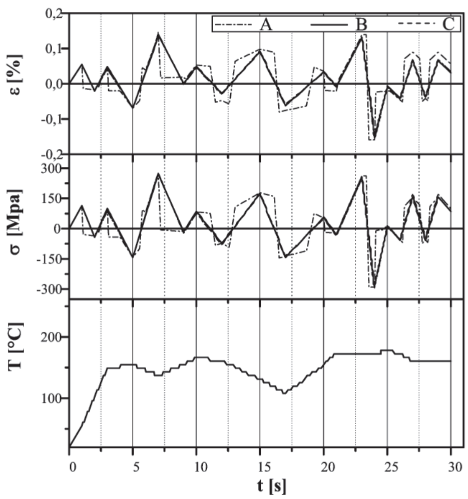
complete stress and strain tensors, whereas in DCP the strain is calculated with the proposed uniaxial model from the signed equivalent von Mises stresses imported from ANSYS.

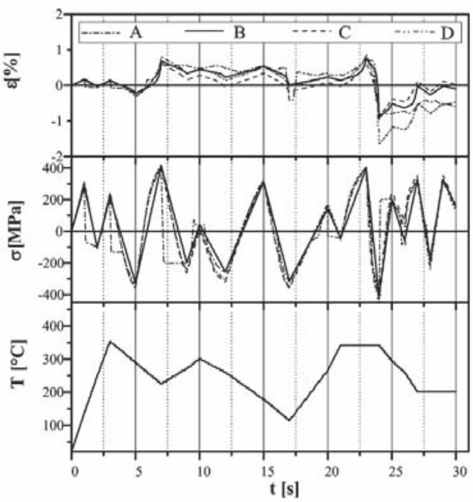
2.3.2 Linear FEA

By comparing the stress-strain trajectories computed with the linear FEA and then transformed with the Neuber approximate formula, the influence of K_p can be studied. For the round specimen plastification is present only for the force L_2. For all constant-temperature load cases and all K_p's the agreement with the non-linear FEA results is good. More pronounced differences are present in the flat specimen. In the case of L_1, $K_p(T)$ and K_p = 2.5 give similar results, where the best agreement is obtained with K_p = 30 . In the case of L_2 (more plastification), K_p = 30 gives strongly non-conservative results. On the other hand, the calculated $K_p(T)$ gives conservative results. In this case the best results are obtained with the recommended K_p = 2.5.

It can be concluded that in the case of pronounced plastification the recommended value of K_p and the calculated $K_p(T)$ give the best agreement with the non-linear FEA and conservative results. K_p = 30 can be used in the case when little plastification is present.

In the case of the random loading the agreements are good for the round specimen, whereas with the flat specimen the stresses and





Sl. 6. *Napetostno, deformacijski in temperaturni odziv pri naključni obremenitvi: levo v vozlišču 7025 okroglega preizkušanca, desno v vozlišču 2288 ploščatega preizkušanca*

Fig. 6. *Stress, strain and temperature response for the random loading: left in node 7025 of the round specimen, right in node 2288 of the flat specimen*

napetosti in deformacije precenjene (sl. 6). V splošnem je ujemanje med rezultati linearnih analiz v kombinaciji z različnimi K_p in nelinearno MKE analizo dobro. Večja odstopanja so opazna v točkah kjer je izrazitejša plastifikacija, kar je v skladu s prejšnjimi ugotovitvami.

2.3.3 Poškodba in sproščena energija

Prejšnje poglavje je osnova za oceno poškodbe in sproščene energije. Predpostavljeno je, da so poškodbe in sproščene energija ocenjene s PIP na osnovi nelinearnih rezultatov MKE "najboljše" in so uporabljene kot primerjalne vrednosti.

Na sliki 7 so prikazane poškodbe v odvisnosti od temperature. Ujemanje rezultatov *C* in *D* z primerjalno *B* je boljše pri okroglem preizkušancu, pri katerem so ocene za oba K_p na nekonzervativni strani. V primeru ploščatega preizkušanca je ugotovljena konzervativna ocena za vse vrednosti K_p pri L_1 ter pri vrednosti L_2 za izračunani $K_p(T)$ (razen pri T_{max} = 600 °C).

Za primerjavo porazdelitve poškodbe in sproščene energije so podane slike za ploščati preizkušanec (sl. 8) ter za okrogli preizkušanec (sl. 9). Pri okroglem preizkušancu so zaradi enoosnega napetostnega stanja v sredinskem prerezu porazdelitve poškodbe in sproščene energije za prikazane primere enake. S slike 8 je za ploščati preizkušanec razvidno, da poškodba in sproščena

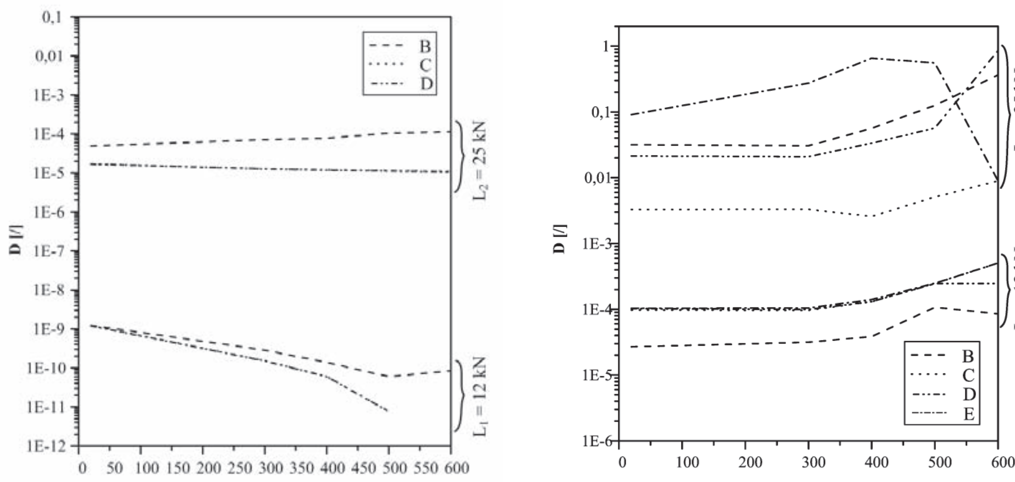
strains are in some cases overestimated (Fig. 6). In general, the agreement of the linear analyses in combination with the different K_p's and the non-linear FEA is good. Major discrepancies are present where plastification is more pronounced, which is in accordance with the previous findings.

2.3.3 Damage and dissipated energy

The previous section is the basis for the damage and dissipated energy estimation. It is assumed that the damage and dissipated energy estimated with DCP based on the non-linear FEA are the "best" and considered as reference values in relation to those obtained from the linear FEA.

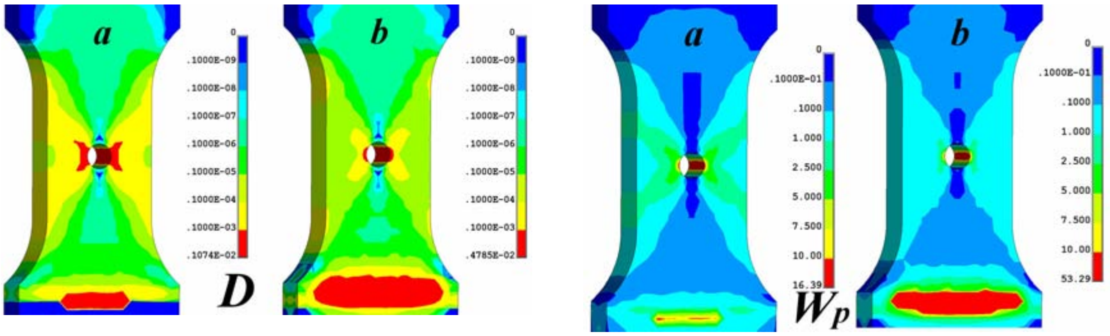
The temperature dependency of the damage is shown in Fig. 7. The agreement between the results C and D with the reference results B is better for the round specimen, where the estimations for both K_p's are on the non-conservative side. For the flat specimen a conservative estimation is observed for all K_p's at K_p and at L_1 for the calculated L_2 (except at T_{max} = 600 °C).

For a comparison of the damage and dissipated energy distribution, Fig. 8 is given for the flat specimen and Fig. 9 is given for the round specimen. Due to the uniaxial stress state in the centre of the round specimen the damage and the dissipated energy distributions are the same for the examples shown. For the flat specimen, Fig. 8 shows the damage and dissipated energy give us



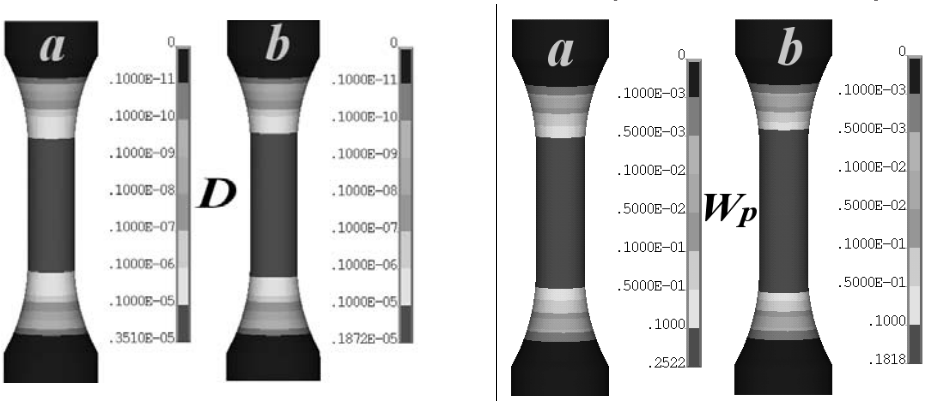
Sl. 7. *Prikaz poškodbe v odvisnosti od temperature: levo za vozlišče 7025 v okroglem preizkušancu, desno za vozlišče 2288 v ploščatem preizkušancu*

Fig. 7. *Temperature dependency of the damage: for node 7025 in round specimen (left) and for node 2288 for the flat specimen (right)*



Sl. 8. *Naključna obremenitev; levo: prikaz porazdelitve poškodbe: a – nelinearna MKE, K_p = 1, b – linearna MKE, K_p = 30; desno: prikaz sproščene energije: a – nelinearna MKE, K_p = 1, b – linearna MKE, K_p = 30*

Fig. 8. *Random loading; left: damage distribution: a – non-linear FEA, K_p = 1, b – linear FEA, K_p = 30; right: dissipated energy distribution: a – non-linear FEA, K_p = 1, b – linear FEA, K_p = 30*



Sl. 9. *Naključna obremenitev; levo: prikaz porazdelitve poškodbe: a – nelinearna MKE, K_p = 1, b – linearna MKE, K_p = 30; desno: prikaz sproščene energije: a – nelinearna MKE, K_p = 1, b – linearna MKE, K_p = 30*

Fig. 9. *Random loading; left: damage distribution: a – non-linear FEA, K_p = 1, b – linear FEA, K_p = 30; right: dissipated energy distribution: a – non-linear FEA, K_p = 1, b – linear FEA, K_p = 30*

energija dajeta enaka kritična mesta, z večjim kritičnim področjem okoli luknje v primeru nelinearne analize ter večjim kritičnim področjem okoli pritrdišča v primeru linearne analize v kombinaciji s K_p.

2.3.4 Računski časi

Pri vrednotenju izdelkov, izpostavljenim utrujanju, je pomemben dejavnik za določitev uporabnosti metode tudi računski čas. Čas računanja je bil izmerjen na ploščatem preizkušancu za naključno obremenitev podano na sliki 3. Linearna MKE analiza je trajala 200 s, nelinearna pa 2260 s. Za izračun poškodbe je bilo potrebno 7 s za oba primera. PIP pred oceno poškodbe izvede izračun Prandtlovih gostot, ki je neodvisen od števila obračalnih točk, zato se čas računanja

the same critical areas with a larger critical region around the hole for the non-linear case and a larger critical region around the constraint for the linear FEA in combination with K_p.

2.3.4 Computation times

In a fatigue evaluation the computational time is also of key importance in assessing the usefulness of the method. The computation time was measured for a random loading (Fig. 3) on the flat specimen. The linear FEA took 200 s, whereas the non-linear FEA lasted 2260 s. The damage estimation took approximately 7 s for both cases. Before the damage estimation the DCP calculates the Prandtl densities, which are independent of the turning points. This is why the damage calculation poškodbe z večanjem števila obračalnih točk ne povečuje linearno.

3 SKLEP

V prispevku je prikazan postopek, ki je razširitev metod podanih v [9], [11] in [12] na večosno napetostno-deformacijsko stanje in ponuja rešitev za vrednotenje termomehansko obremenjenih izdelkov v primeru, ko lahko zanemarimo ciklično utrjevanje oz. mehčanje in lezenje. Postopek deli termične oz. analize CFD, trdnostne analize in oceno poškodbe. Poudarek je bil na računsko hitrih metodah, zato so bile raziskave usmerjene v uporabo linearnih MKE analiz v kombinaciji z aproksimacijskimi enačbami. Ugotovljeno je bilo, da vrednost K_p pomembno vpliva na ujemanje rezultatov linearne in nelinearne MKE analize ter oceno poškodbe. Za ta namen je bil uveden temperaturno odvisni $K_p(T)$. Linearne analize v kombinaciji z aproksimacijskimi enačbami in PIP-om so lahko uporabljene le ob pravilni izbiri K_p in manjšem tečenju materiala. Dodatne raziskave vrednosti K_p bodo izvedne za povečanje uporabnosti približnih enačb, ki občutno znižajo računske čase pri dolgih potekih obremenitev.

time is not increased linearly with the increasing number of turning points.

3 CONCLUSION

This paper describes an extension of the methods given in [9], [11] and [12] to a multiaxial stress-strain state and gives a solution for evaluating thermo-mechanically loaded components in the case when cyclic hardening or softening and creep can be neglected. The approach uncouples thermal calculations, stress-strain calculations and damage or dissipated energy estimations. The main focus was put on fast computational methods, which is why the research was done with the linear FEA in combination with approximate formulas. It has been observed that the K_p value strongly influences the agreement between the linear and non-linear FEA results and the damage estimation. For this reason the temperature dependent $K_p(T)$ was introduced. The linear FEA in combination with approximate formulas and the DCP can only be used with the correct K_p and a small amount of plastification. Further research regarding the K_p value will be carried out in order to broaden the applicability of the approximate formulas, which substantially reduce the computation time for long load histories.

4 LITERATURA
4 REFERENCE

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