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EXPLICIT MICROSCOPIC FATIGUE ANALYSIS OF FORGED COMPONENTS

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Abstract

Numerical modelling of fatigue behavior for anisotropic structures has become critical for design applications. This is particularly true for forged components due to the intrinsic anisotropy of the material resulting from the process. The aim of this study is to relate the microstructure features to the process scale, i.e. the engineering scale. Anisotropy is induced by the forming process and the most relevant feature which results from forging, is the preferential orientation of structural defects and grains in the direction of the deformation. Grain flow is modelled using a fiber tensor at the level of the representative elementary volume. It can then be used to improve and refine the Papadopoulos fatigue criterion by taking into account fatigue limits for each direction of anisotropy. In practice, it is very tedious to determine precisely these fatigue limits and impossible to experimentally obtain all of them for each direction of uniaxial loading. To circumvent this difficulty, we simulate the problem at the microstructure scale by considering fiber tensor as the result of the inclusion and grain orientation. Microstructures are then precisely modelled using *DIGIMICRO* software. A representative elementary volume with several inclusions is meshed and high cycle fatigue simulation is performed.

Key words: high cycle fatigue, multiaxial criterion, anisotropy, critical plane approach, fiber tensor, digital material, multiscale approach

1. INTRODUCTION

Among all forming processes, forging gives raise to the most resistant components withstanding a large number of loading modes. Actually, forging induces a strongly heterogeneous microstructure in the material, resulting in a grain flow anisotropy that can explain such high mechanical properties. The problem is the numerical representation of this anisotropy, in particular for finite element software using isotropic laws and associated resolution schemes. Therefore, it is necessary to adapt traditional high cycle fatigue criteria which were developed assuming isotropy to anisotropic material behavior configurations. Moreover, fatigue is a phenomenon which leads to scattered experimental results due to the inherent variability of the microstructure state of the material (Morel & Flaceliere, 2005). Thus, the ANR (French National Research Agency) Optiforge project was launched. Its goal is to account for the forming process and its effect on the microstructure to perform high-cycle fatigue studies. A virtual simulation chain is created between the forming process and the microstructure history. The Papadopoulos criterion (Papadopoulos, 1993) was finally chosen to develop a microstructure scale approach based on forging characteristics. A representative elementary volume is meant to describe explicitly the shape and orientation of both inclusions and grains. This microstructure study is

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performed using the *DIGIMICRO* software (Bernacki et al., 2007)

2. COMPUTATION OF GRAIN FLOW ORIENTATION FOR FORGED COMPONENTS

The software used is a 3D finite element software dedicated to forming processes which provides computations of stress and strain fields throughout a forming process. However, several features of the anisotropy induced by the microstructure are not taken into account for very large strain. This is necessary for an accurate prediction of fatigue properties of the final part. It is well known that grain flow orientation is one of the main causes of higher fatigue capabilities of forged components. A fiber tensor can be defined for grain flow orientation. The fiber tensor is calculated using the polar decomposition of the gradient tensor $\underline{\underline{F}}$ into a rotational part and an orthogonal part. $\underline{\underline{F}}$ given by (1)

$$\underline{\underline{F}} = \underline{\underline{I}} + \underline{\underline{\mathrm{Grad}}}\,\underline{\mathrm{X}} = \underline{\underline{R}}\,\underline{\underline{U}} = \underline{\underline{V}}\,\underline{\underline{R}} \ , \qquad (1)$$

where $\underline{\underline{I}}$ is the unit tensor, $\underline{X}$ is the displacement vector, $\underline{\underline{R}}$ is an orthogonal orientation tensor, $\underline{\underline{V}}$ and $\underline{\underline{U}}$ are symmetric positive tensors named respectively left distortion and right distortion. This is the polar decomposition of $\underline{\underline{F}}$.

The fiber tensor corresponds to the eigenvectors of the distorsion tensor $\underline{\underline{U}}$ normalized by its eigenvalues. Three values are obtained. They correspond to the elongation undergone by the nodes of the mesh in the corresponding eigenspaces.

Moreover, to follow the fiber tensor at all stages of the process, a transformation of the gradient tensor is carried out from the initial position (Milesi et al., 2007). This transformation is a bijective transformation. By noting t_0 the initial time of the process, *t*, the current time of the calculus, and *t*', the time corresponding to the previous increment of the simulation, we can associate an initial continuum domain position Ω_{t_0} for t_0, Ω_t for *t* and $\Omega_{t'}$ for *t*' and, respectively a point with the position m_{t0}, m_t and $m_{t'}$ (figure 1). Equation (1) becomes:

$$\underline{\underline{F}}_{t_0,t} = \underline{\underline{F}}_{t',t} \circ \underline{\underline{F}}_{t_0,t'} \, , \qquad (2)$$

where $\underline{\underline{F}}_{t_0,t'}$ is the gradient tensor calculated between

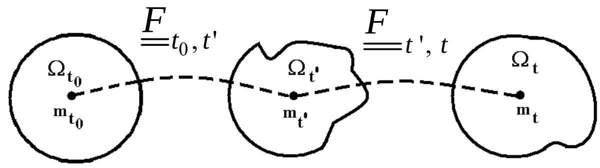

Fig. 1. *Transformation of a continuum domain.*

t_0 and *t*', $\underline{\underline{F}}_{t',t}$, the gradient tensor between *t*' and *t* and $\underline{\underline{F}}_{t_0,t}$ gradient tensor between t_0 and *t*.

Thus, this allows to use the initial orientation of the material and follows it during the simulation. For instance, figure 2 shows a cambering process with no initial grain flow orientation. The eigenvector of the fiber tensor corresponding to the first eigenvalue of the orthogonal tensor is represented. These vectors are oriented towards the preferential direction of the flow. For example, in area B, the extremity of the component is compressed. The flow is clearly in the transverse direction as predicted in figure 2. However, this is only one eigenvector and it is important to consider also the other two and the respective eigenvalues to describe the grain flow.

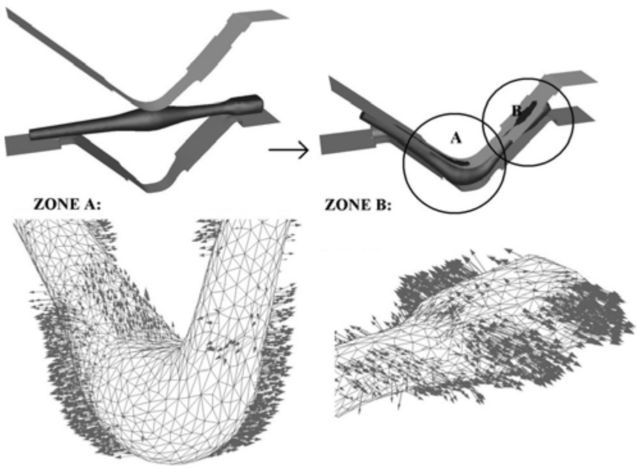

Fig. 2. *Flow orientation for a cambering process.*

3. THE CRITICAL PLANE APPROACH FOR FATIGUE CRITERIA

Classical high cycle fatigue criteria are determinist criteria, which means that for a calculated stress field and intrinsic parameters of the material, they provide a unique domain of validity. For most criteria, this domain is defined using a critical line in a specific space. This is the case of the Papadopoulos criterion (Papadopoulos, 1993). The main idea consists in splitting a given structure into many subvolumes which could be considered as representative elementary volumes (figure 3).

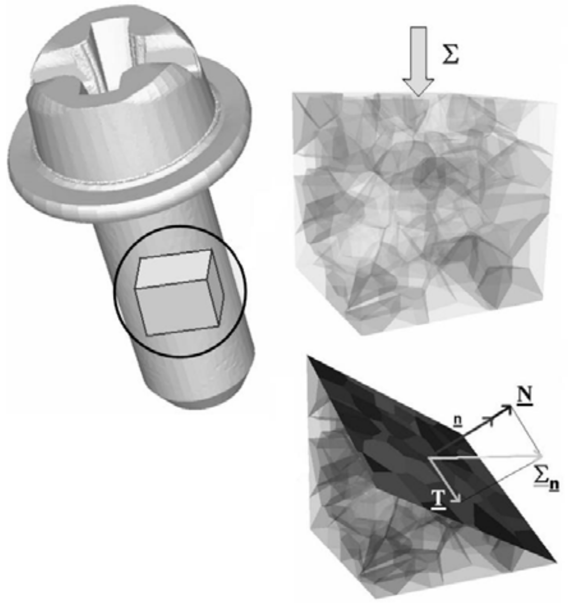

Fig. 3. Schematics of a Representative Elementary Volume (R.E.V.).

Then, the maximum stress over a complete loading cycle is computed to determine when the structure breaks up.

To calculate this critical stress level for each R.E.V., it is assumed that an adapted state (or shakedown state) with a purely elastic behavior at the grain level, has been reached. Indeed, at the macroscopic level, the structure might be seen as undergoing an elastic loading but, locally, at the microscopic level, it may be possible that one or several grains are unfavorably oriented, thus leading to a local plastic behavior. This adapted state is reached after few cycles (typically about 1000 cycles). Figure 4 shows the progressive stabilization at the microstructure level; Σ is the macroscopic stress, σ is the microscopic stress (for each grain), E is the macroscopic and ε, the microscopic strain obtained from a Lin-Taylor approach (Papadopoulos, 1993).

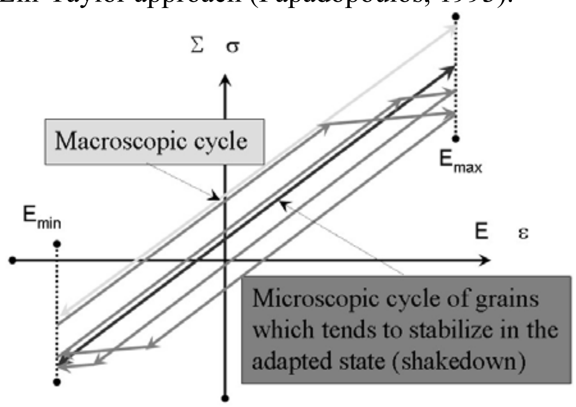

Fig. 4. *Macroscopic behavior of the structure and Microscopic behavior of a grain misoriented which undergoes a plastic deformation*

If no shakedown state can be reached, a crack is initiated at the microscopic level; it will lead to a macroscopic crack after some cycles. If $\underline{\Sigma}_n$ is the stress applied onto a cross section (plane of normal $\underline{n}$) of the representative elementary volume (figure 3), its projection onto the plane is the shear stress $\underline{T}$. The goal of these criteria is to investigate iteratively many different plane orientations in order to find the maximum value of the shear stress. Moreover, the effect of the hydrostatic stress has to be added since it has a high influence on the fatigue behavior (Dang Van et al., 1989). The safe domain is defined by the following relationship:

$$T_\Sigma + \alpha\Sigma_{H,\max} \le \beta\,, \qquad (3)$$

which defines a linear domain as seen in figure 5.

If the curve described by the shear stress projected onto the critical plane is below a so-called threshold line, there is no initiation of macroscopic crack.

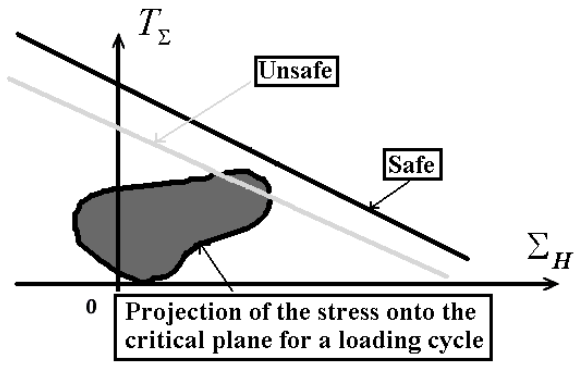

Fig. 5. *Threshold domain for a determinist fatigue criterion.*

Generally, T_Σ is the $\max\limits_{\underline{n}} \max\limits_{t\in[0,P]} \underline{T}$ value on the critical plane (where P is the loading period) and $\Sigma_{H,\max}$ is the maximum hydrostatic stress over the loading cycle (Morel & Flaceliere, 2005). Coefficients α and β are deduced from two reference fatigue limits (with a stress load ratio $R=-1$) from tension and torsion data (Papadopoulos, 1993).

Figure 6 shows the contour values calculated with the Papadopoulos criterion for a tension - compression and torsion simulations of standardized test specimens. As expected, the critical zone is located at the surface near the restricted neck in the case of a torsion simulation whereas for traction – compression, it is located in the transverse section. If the value of the normalized criterion is greater or equal to 1, a macroscopic crack initiation is expected.

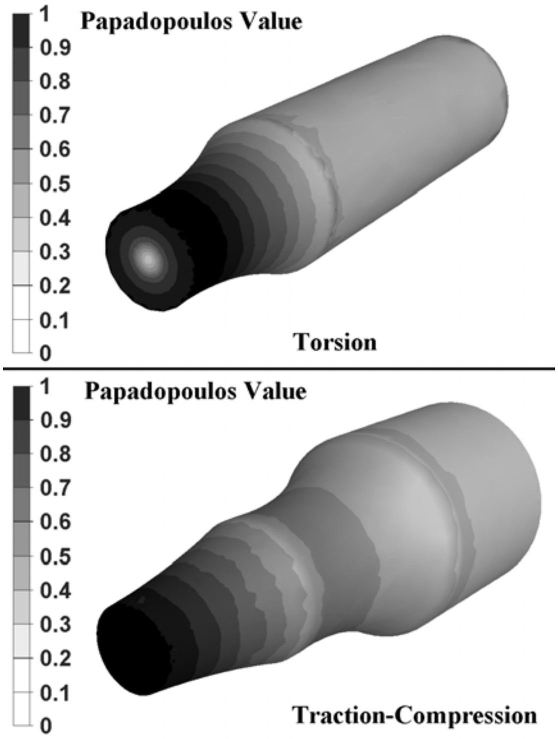

Fig. 6. *Normalized Papadopoulos criterion calculated on standardized traction-compression and torsion test specimens.*

4. ADAPTED PAPADOPOULOS CRITERION FOR ANISOTROPIC STRUCTURE

To account for the grain flow orientation, the fiber tensor is used as an input of the fatigue criterion. This means that the endurance limit is determined with respect to the loading direction. Experimentally, this endurance limit is determined in the direction of anisotropy (longitudinal) and in the transverse direction. A third direction (generally 45°) is however necessary for a better prediction because it is well known that the shear stress is maximum for a certain angle (Schmid law). With these values of the endurance limit for three angles, it is then possible to enhance the Papadopoulos criterion by using the respective endurance coefficients. Three domains of validity can be identified. The most conservative domain, for which the stress cycle onto the critical plane is the nearest to the limit domain, is selected. To improve this criterion, a stochastic analysis should be performed by considering experimental results of the Wöhler curves for each endurance limit.

To use this method, at least fatigue limits for three independent conditions/orientations are needed. However, experimentally, it is very difficult or, sometimes impossible, to extract a sample with the appropriate grain flow orientation from an industrial component, hence the need for microstructure simulations. Indeed, from simple tests (traction and torsion) and by considering that anisotropy can be linked directly to the microstructure, simulations can be performed on an oriented microstructure. The orientation of the microstructure can be predicted from the forming process with the fiber tensor: it then gives the direction of anisotropy. These microstructure-based simulations allow to store several endurance limits by only changing the orientation of the microstructure.

We have been working on a bainitic steel METASCO® MC. Several analyses show that the probability of crack initiation is high near MnSs (Temmel et al., 2006) inclusions (manganese sulphide), very common in modern steels due to their benefic role during machining (figure 7). For that reason, new pre-processor, *DIGIMICRO*, is used to create realistic digital microstructures.

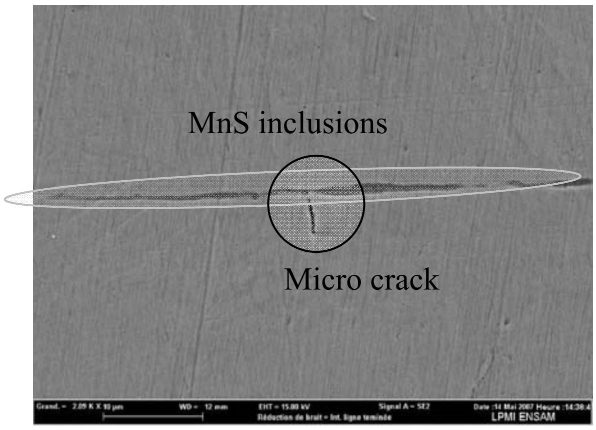

Fig. 7. *Cracks are initiated near MnS inclusions (Pessart et al., 2007).*

5. THE DIGITAL MATERIAL

We will consider a R.E.V. and will investigate different means of representing the heterogeneous microstructure. A first technique to account for inclusions and grains is to generate a mesh and to assign a domain type (e.g. inclusion, grain) to each element of the mesh. The main drawback of this method is the high number of elements required to obtain good results. Indeed, the roughness of the domain description is problematic (figure 8).

Therefore, a new pre-processor in which the microstructure geometry is first generated, including grains and inclusions was developed. Then, the anisotropic 3D mesher MTC is used to mesh the microstructure (Coupez, 1991). This new pre-processor is named *DIGIMICRO* (Bernacki et al., 2007). *DIGIMICRO* was only able to create Voronoï tessellation for granular structures. New features have been added to this software in order to provide also inclusions generation allowing for a new approach for microstructure description. The advantage of such a tool is to provide a final mesh which is refined near the edge of all domains i.e. grains or inclusions (figure 9).

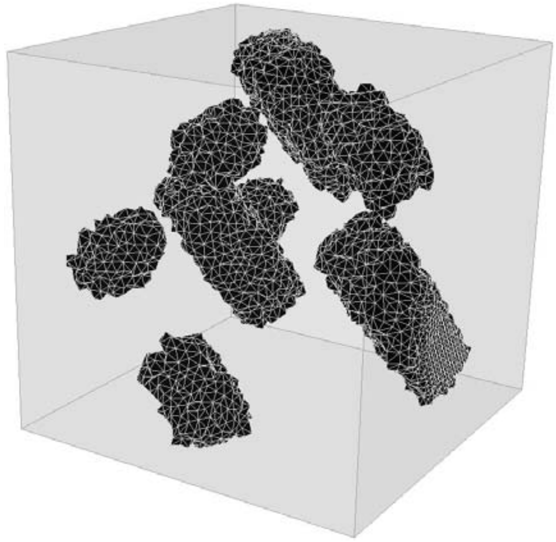

Fig. 8. Inclusions shape selected on the basis of an initial mesh.

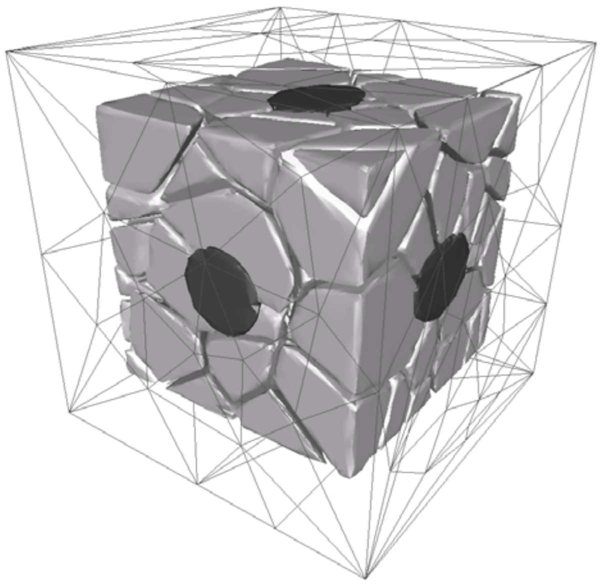

Fig. 9. Mesh of a microstructure composed of 100 grains and 6 inclusions.

A realistic microstructure can be reconstructed from experimental data by considering, on the one hand, the granular tessellation, and, on the other hand, the inclusions and porosities.

First, geometric data are gathered and the structure is meshed with a 3D mesher to create an anisotropic mesh near the interface of all constituents. Inclusion shapes and locations can be either given by the user or obtained using a random algorithm. Security distances between each pair of inclusions can be used in order to avoid interpenetration between them. This security distance allows to build R.E.V. with high inclusion density. The granular tessellation can be also oriented and depends on the level of deformation (figure 10).

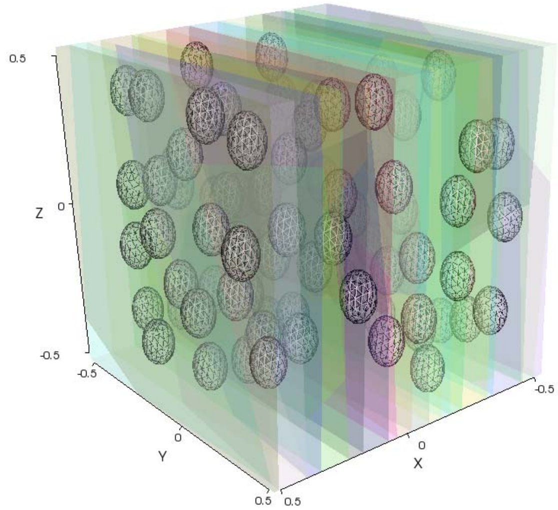

Fig. 10. Oriented granular structure with 100 inclusions.

It is possible to split each part of the mesh thanks to a linear function associated to each domain (level-set function: Sethian, 1996). This function equals 0 at the interface, is positive within the respective domain and negative outside the domain. It is used to associate rheological laws to each subdomain. One should stress however that such interfaces between domains cannot be a divisible part of the global mesh and no friction law can be applied.

Finally, the R.E.V. is coated by a surrounding domain. This domain is meshed and its role is to transmit boundary conditions to the R.E.V. and avoid edge effects for the microstructure computation.

This structure can be tested numerically for a fatigue loading simulation in order to calculate the endurance function. Torsion and tension simulation results can be compared to experimental ones to adjust parameters.

6. NUMERICAL SIMULATION OF A MICROSTRUCTURAL R.E.V.

Once the microstructure mesh has been generated, a finite element software is used for the mechanical computations. Rheological laws are attributed to each domain. To obtain a correct probabilistic behavior of a realistic structure, each parameter of the law can be selected randomly by choosing a value in a given interval. The panel of inclusions is then given by realistic and statistically representative parameters. Figure 11 shows the von Mises stress on a cross-section of the microstructure containing two inclusions.

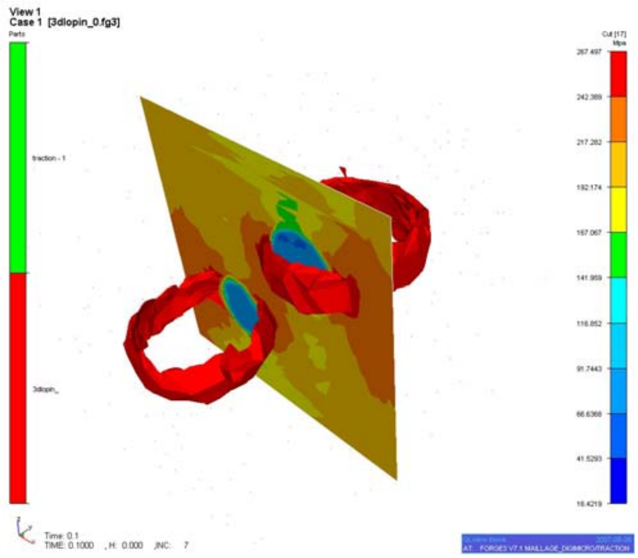

Fig. 11. *Stress concentration around two inclusions.*

The most difficult issue is the correlation between the rheological law used in the forming process and the rheological law of the matrix with embedded inclusions and/or grains.

In a first simulation, it is assumed that the matrix has the same rheological law as the one used for the macroscopic forming process simulation. For the inclusions, the elastic-plastic constitutive law is obtained from literature (Temmel et al., 2006). Simple traction-compression or torsion tests are then simulated and the influence of the shape, the number and the orientation of the inclusions can be studied.

7. CONCLUSIONS AND PERSPECTIVES

This work presents a new approach of fatigue analysis by considering directly the anisotropy of a forged component thanks to the Papadopoulos criterion. A representative microstructure is coupled with a classical fatigue simulation. This link between forming simulation and fatigue analysis at the microstructure scale is promising and will allow to improve fatigue computation predictions.

8. ACKNOWLEDGEMENTS

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ANALIZA MIKROSKOPOWA ZMĘCZENIA W ELEMENTACH KUTYCH

Streszczenie

Numeryczne modelowanie zmęczenia materiału staje się kluczową sprawą dla zastosowań w projektowaniu procesów. Jest to szczególnie istotne dla elementów kutych, ze względu na nieodłączną anizotropię materiału wynikającą z charakteru procesu kucia. Celem niniejszej pracy jest odniesienie cech mikrostruktury materiału do skali procesu, to znaczy do skali analizowanej przez inżynierów. Anizotropia jest wprowadzana do materiału w czasie procesu przeróbki plastycznej i najbardziej odpowiednią cechą strukturalną, która wynika z procesu kucia, jest uprzywilejowana orientacja defektów strukturalnych i ziaren w kierunku odkształcenia. Odkształcenie ziaren jest modelowane za pomocą tensora struktury włóknistej na poziomie reprezentatywnego elementu objętości. Poprzez rozważenie kryterium zmęczeniowego w każdym anizotropowym kierunku, ten tensor może być wykorzystany do poprawy i udoskonalenia kryterium zmęczeniowego Papadopoulosa. Dokładne wyznaczenie tych granic odporności zmęczeniowej jest bardzo żmudne, a określenie ich dla wszystkich kierunków przy jednoosiowym obciążeniu na podstawie badań doświadczalnych jest praktycznie niemożliwe. Aby pokonać te trudności przeprowadzono symulacje tego problemu w skali mikrostruktury poprzez rozważenie tensora struktury włóknistej wynikającego z orientacji wtrąceń i ziaren. Mikrostruktura jest modelowana dokładnie programem DIGIMICRO. Reprezentacyjny element objętości z wtrąceniami pokryto siatką elementów I przeprowadzony symulacje wysoko cyklowego zmęczenia.

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