

Thermomechanical Damage Modeling of F114 Carbon Steel

A. El Amri, M. El Yakhoulfi Haddou, A. Khamlichi

Abstract—The numerical simulation based on the Finite Element Method (FEM) is widely used in academic institutes and in the industry. It is a useful tool to predict many phenomena present in the classical manufacturing forming processes such as fracture. But, the results of such numerical model depend strongly on the parameters of the constitutive behavior model. The influences of thermal and mechanical loads cause damage. The temperature and strain rate dependent materials' properties and their modelling are discussed. A Johnson-Cook Model of damage has been selected for the numerical simulations. Virtual software called the ABAQUS 6.11 is used for finite element analysis. This model was introduced in order to give information concerning crack initiation during thermal and mechanical loads.

Keywords—Thermomechanical fatigue, failure, numerical simulation, fracture, damages.

I. INTRODUCTION

THE effect of high temperature on the physical and mechanical properties of F114 carbon steel has always been an important study, the micro-cracks can be produced; on the other hand, the high temperature can lead the thermal damage of various physical and chemical changes in the internal structures [1], and cause internal worse changes of steel properties. Dougill et al. [2] introduced damage mechanics into the field of rock mass for the first time. Wang et al. [3] carried out experimental research on the thermal damage of concrete, analyzed the effect of thermal damage caused by load and temperature on the structure of concrete and explained the mechanism of thermal damage of concrete by using electric and ultrasonic wave measurements. Xu [4] and Xie et al. [5] showed that high temperature can greatly damage the internal structure of rocks.

Zhang et al. [6] and Zhang et al. [7] studied a simulation in uniaxial compression of F114 carbon steel at high temperatures and in our study, a statistical thermal damage constitutive model of F114 carbon steel is considered. The properties of thermal damage to steel were studied on the basis of resulting damage, by considering the effect of various temperatures on mechanical properties.

FEM has been widely introduced into the design of manufacturing products because of its high efficiency in predicting several problems and major defects occurring in sheet metal forming manufacturing process like necking, wrinkling, buckling and surface deflections. The damage

evolution depends directly on the state of deformation. Modeling of inelastic behavior and fracture of materials employed in various engineering applications is an important topic in solid mechanics or in optimization of structural design. Therefore, to be able to develop a realistic, accurate and efficient phenomenological mode, it is important to analyze and to understand the complex stress-state-dependent processes of damage and fracture as well as its respective mechanisms acting on different scales. In this context, in the last years, various damage models have been published based on experimental observations as well as on multi-scale approaches [8]-[11]. The heterogeneity of material and stochasticity of microfracture and damage formation have a pronounced effect on the strength and fracture of materials, but can be hardly modeled with the use of the traditional methods, like the fracture mechanics or damage mechanics [12]. Some scholars used extended FEM (XFEM) to study on fracture damage behavior of concrete [13], [14]. Jin Feng [15] imported the subroutine named User Defined Element (UEL) to implement XFEM to simulate the fracture of concrete, based on FEM software ABAQUS. However, only few numerical works can be found in the literature [16]-[18], considering the incompetence of FLD, a reliable numerical method for failure prediction in the stretch-bending case is still under high demand from the forming community. Recently [19] obtained a novel weighting function by transforming the classical stress-based Mohr-Coulomb failure criterion into the space of stress triaxiality, lode parameter and equivalent plastic strain.

II. MATERIALS AND METHODS

Various numerical methods have been used to derive SIF such as Finite Difference Method (FDM), FEM, and Boundary Element Method (BEM). Among them, FEM has been widely employed for the solution of linear elastic and elasto-plastic fracture problems. A typical and practical point matching technique, called Displacement Extrapolation Method (DEM) is chosen for the numerical analysis method.

For the FEM analysis, ABAQUS commercial software was used. One quarter of the steel was modeled because of the symmetry of the geometry, loading and boundary conditions.

The element (S8R) was used which is an 8-node element and has the capability of distributing stress in thickness direction. The arrangement of elements was changed several times to achieve precise results. In addition, finite element mesh was refined near the cutouts.

In all the simulations, points along the x axis were constrained in the y direction and points along the y axis are

A. El Amri*, M. El Yakhoulfi Haddou, and A. Khamlichi are with the Faculty of Sciences, Morocco (*Corresponding author; e-mail: Abdelouahid26@gmail.com).

constrained along x direction. Moreover, in the edge which specimens are subjected to loading, all degrees of freedom were removed from them, except displacement in x direction.

An incremental load-displacement analysis is performed by using the arc-length RIKS method in the ABAQUS software. Moreover, Von-Mises yield criterion and non-linear analysis were performed. The RIKS method uses in geometrically nonlinear static problems, where the load-displacement response shows a negative stiffness and the structural must release strain energy to remain in equilibrium. The RIKS method uses the load magnitude as an additional unknown; it solves simultaneously for loads and displacement [20].

The material considered in this study is F114 carbon steel. The main mechanical and thermal properties of tested specimen are summarized in Table I. The specimen geometry is shown in Fig. 1.

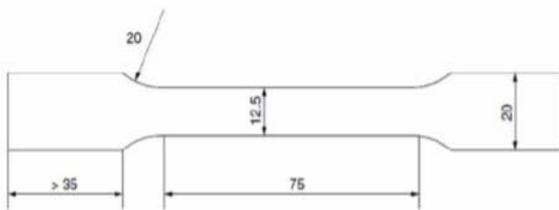


Fig. 1 Dimensions of the F114 Carbon Steel

TABLE I
GLOBAL MECHANICAL PROPERTIES OF F114 CARBON STEEL

F114 Carbon Steel Properties	Value
Tensile modulus MPa	7850
Tensile strength (Nmm ⁻²)	600-750
Yield stress (MPa)	315
Mass thermal capacity (Jkg ⁻¹ K ⁻¹)	460
Thermal conductivity (Wm ⁻¹ K ⁻¹)	47-58

III. THEORETICAL BACKGROUND

When F114 Carbon steel under mechanical load, the evolution of micro-defects inside F114 carbon steel is a stochastic variable, the systemic evolution of micro-defects can be regarded as a non-equilibrium statistical process, in which the failure distribution of micro-units obeys a Weibull distribution [21] and its distribution is a density function shown as (1) [22]:

$$\phi(\varepsilon) = \frac{m}{\alpha} \left(\frac{\varepsilon}{\alpha} \right)^{m-1} \exp \left[- \left(\frac{\varepsilon}{\alpha} \right)^m \right] \quad (1)$$

where ε the steel strain, m is the scale of the Weibull distribution and α the morphological parameter in the form of strain, the two parameters reflect the mechanical properties of the F114 Carbon Steel mass. $\phi(\varepsilon)$ is the probability density of damage of micro-units, measuring the damage probability of micro-units when the steel is loaded.

The damage variable $D(\varepsilon)$ is a measure of material injury, while the degree of injury is related to micro-unit deficiencies, which directly affect the strength of micro-units. Therefore,

between the damage variable $D(\varepsilon)$ and the infinitesimal probability density of damage, the following relationship exists:

$$\phi(\varepsilon) = \frac{dD(\varepsilon)}{d\varepsilon} \quad (2)$$

From (2), we obtain:

$$D(\varepsilon) = \int_0^\varepsilon \phi(x) dx = 1 - \exp \left[- \left(\frac{\varepsilon}{\alpha} \right)^m \right] \quad (3)$$

Equation (3) is the statistical damage evolution equation for steel under a load. It means no-damage to the material when $D(\varepsilon) = 0$, while all the micro-units are destroyed when $D(\varepsilon) = 1$. It is known that, on the one hand, the damage factors are expected to be taken into consideration and on the other hand, conditions should not become more complicated by the physical equation which is considered the damage. Based on this idea we proposed a strain equivalent assumption: if the stress σ were replaced by the effective stress σ_{eff} . Then, we

can obtain the following equations: $\varepsilon_0 = \frac{\sigma_{eff}}{E_{T0}}$, $\varepsilon = \frac{\sigma}{E}$, because

the effective stress σ_{eff} has the following properties:

$$\sigma_{eff} = \frac{\sigma}{1 - D(\varepsilon)} \quad (4)$$

$$\frac{\sigma}{E} = \varepsilon = \frac{\sigma}{(1 - D(\varepsilon)) E_{T0}} \quad (5)$$

Equation (5) can also be expressed as:

$$\sigma = E_{T0} (1 - D(\varepsilon)) \varepsilon \quad (6)$$

where E_{T0} is the Young's modulus of steel without damage due to mechanical loading at given temperature. Substituting (3) into (6), we obtain:

$$\sigma = E_{T0} \times \exp \left[- \left(\frac{\varepsilon}{\alpha} \right)^m \right] \times \varepsilon \quad (7)$$

Equation (7) is the constitutive equation of steel damage under uniaxial compression. The parameters α and m can be obtained based on the peak intensity point $C (\sigma_c, \varepsilon_c)$ of the full stress-strain curve under uniaxial compression.

At the peak intensity point $C (\sigma_c, \varepsilon_c)$ of the uniaxial compression, the gradient rate is zero, so that

$$\frac{d\sigma}{d\varepsilon}\bigg|_{\varepsilon=\varepsilon_0} = E_{T0} \left[1 - m \left(\frac{\varepsilon_c}{\alpha} \right)^m \right] \exp \left[- \left(\frac{\varepsilon_c}{\alpha} \right)^m \right] = 0 \quad (8)$$

At the same time, at point C $(\sigma_c, \varepsilon_c)$ the following relationship holds:

$$\sigma_c = E_{T0} \times \exp \left[- \left(\frac{\varepsilon_c}{\alpha} \right)^m \right] \times \varepsilon_c \quad (9)$$

From (8) and (9), we can obtain:

$$m = \frac{1}{\ln \left(\frac{\sigma_c}{E_{T0} \varepsilon_c} \right)} = \frac{1}{\ln E_{T0} - \ln E_c} \quad (10)$$

$$\alpha = \varepsilon_c \left(\frac{1}{m} \right)^{-1/m} \quad (11)$$

Substituting (10) into (11), we can obtain α . Equation (10) shows that m is a parameter of material brittleness, which has a relationship with the Young's modulus E_{T0} and the secant Young's modulus at the peak load point E_c . Substituting (10) and (11) into (3), we have

$$D(\varepsilon) = 1 - \exp \left[- \left(\frac{\varepsilon}{\alpha} \right)^m \right] = 1 - \exp \left[- \left(\frac{\varepsilon}{\varepsilon_c} \right)^m \right] \quad (12)$$

IV. RESULT AND DISCUSSION

In the load-displacement figure, Fig. 1, two important points can be observed. First point is relevant to plastic collapse load which is not the necessary load for physical collapse of the structure. In fact, plastic strains take place significantly at this point. Second point is relevant to the maximum load which could be tolerated by the structure, which is named by plastic instability load.

The evolution of the strain during the simulation shows that after an initial compaction, the increase of strain is linear with time. Consequently, the strain rate is constant during the latter, steady state, part of the simulation. Using the steady-state strain rates, linear relationship was found between the calculated strain rate and the applied differential stress ranging from 60 Pa to 140 Pa.

Failure was assumed to correspond to the loss of load carrying capability in the displacement controlled simulation. The steel was assumed to have the following material properties; $E= 7850\text{MPa}$, Yield stress= 315MPa , $\nu = 0.3$ with a hardening modulus of 7850MPa . The conventional plasticity yield surface is also shown to be larger, with a higher strain to failure, than the porous material, a result confirmed by experimental results. For this, simulation, the final void fraction was 0.70. A calculation was also performed to check the sensitivity of the solution to mesh size.

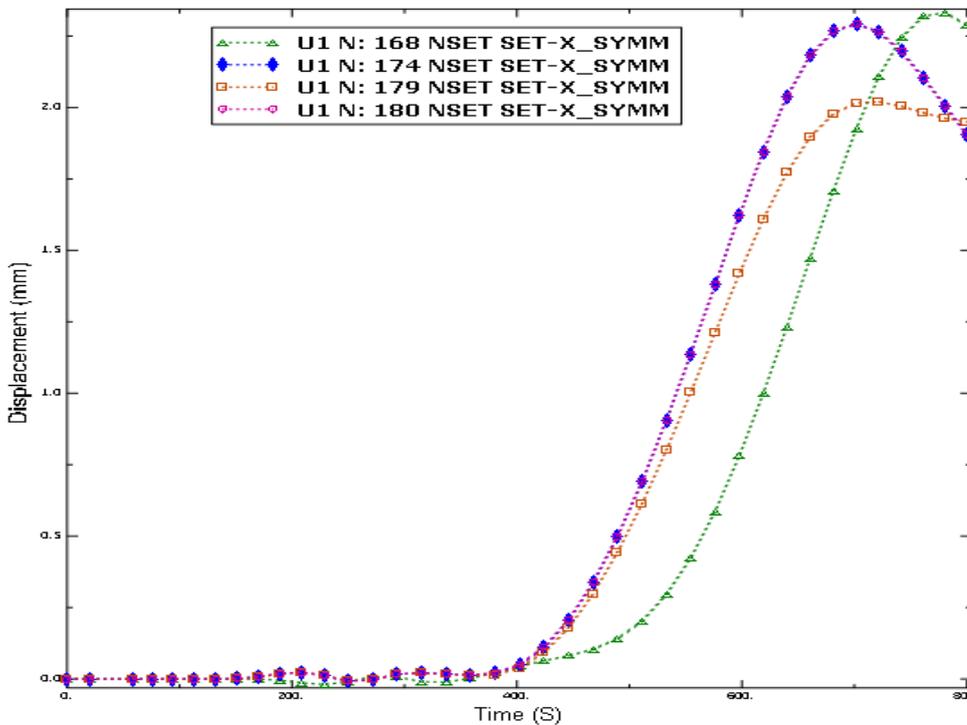


Fig. 2 Evolution of displacement with the time test

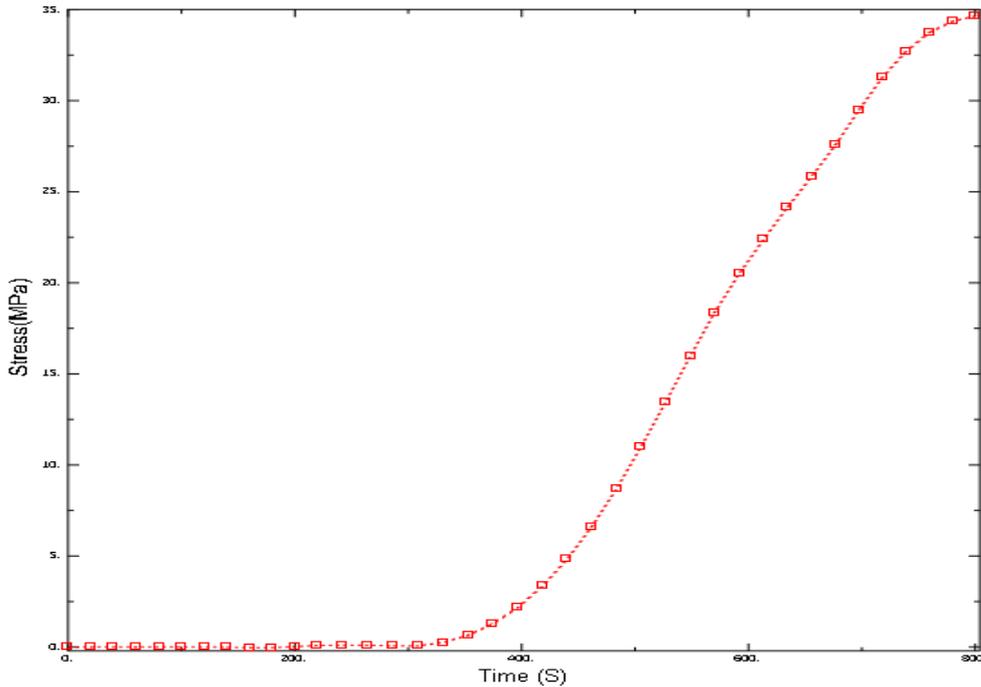


Fig. 3 Evolution of stress with the time test

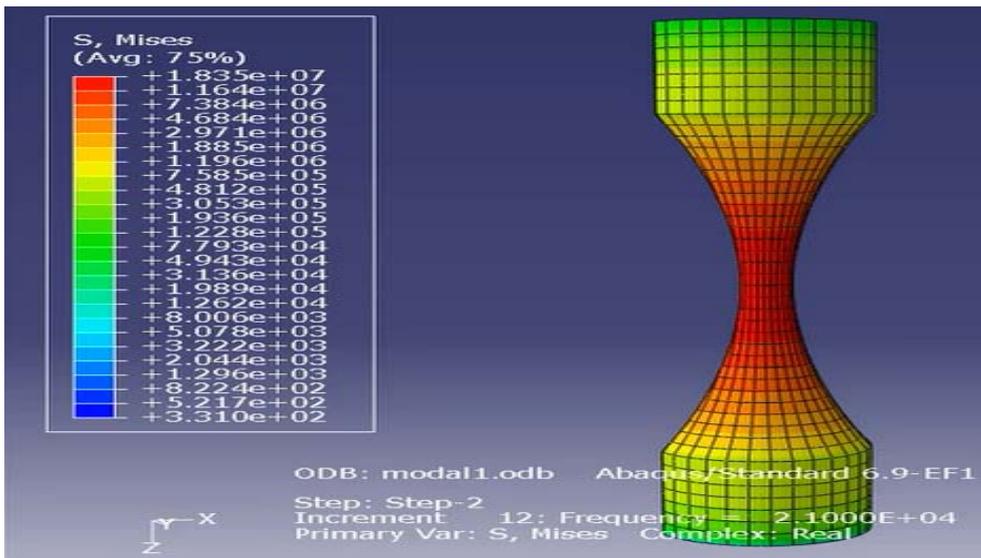


Fig. 4 Local effective plastic strain for complete steel

The coefficients of thermal expansions for various mineral crystals in a structure vary; therefore, in order to maintain the continuity of structure deformation at different temperatures, the inherent crystals cannot be in free-form deformation as a function of temperature, given their coefficients of thermal expansions, resulting in constraints among particles, a large deformation of micro units in the compression and a small deformation from stretching, which is referred to as thermal stress because of the instance.

When the temperature increases, a large number of micro-cracks will inevitably be generated within the structure and gradually expand with increasing temperature, significantly reducing the Young's modulus for macro issues, while the ability of resistance to deformation decreases, which indicates that thermal stress for high temperature effect can cause damage to structures, namely thermal damage. In our study, we used the Young's modulus as a variable of damage, characteristic of the effect of temperature on the properties of structure damage.

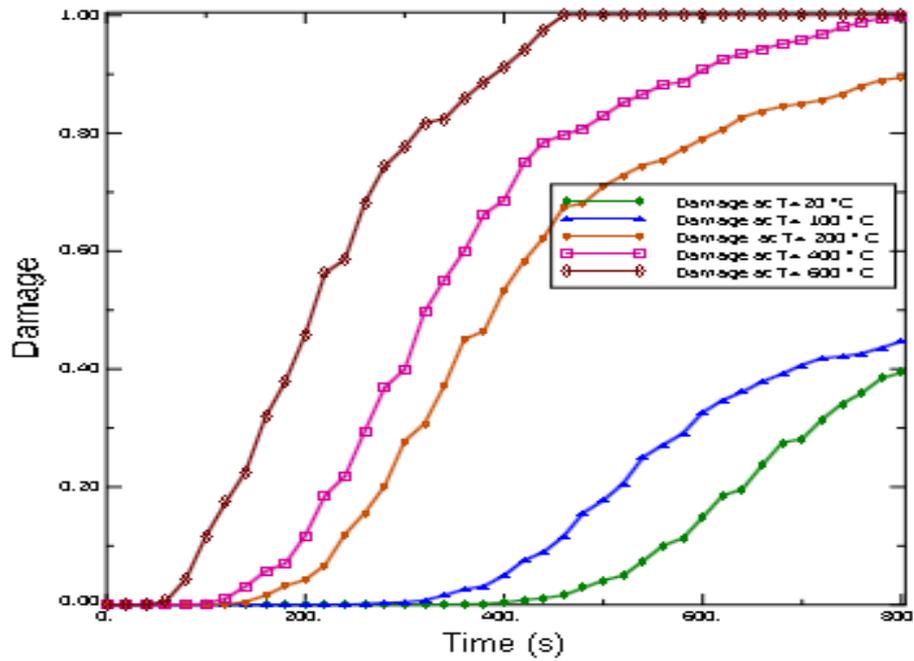


Fig. 5 Damage evolution under thermal loadings

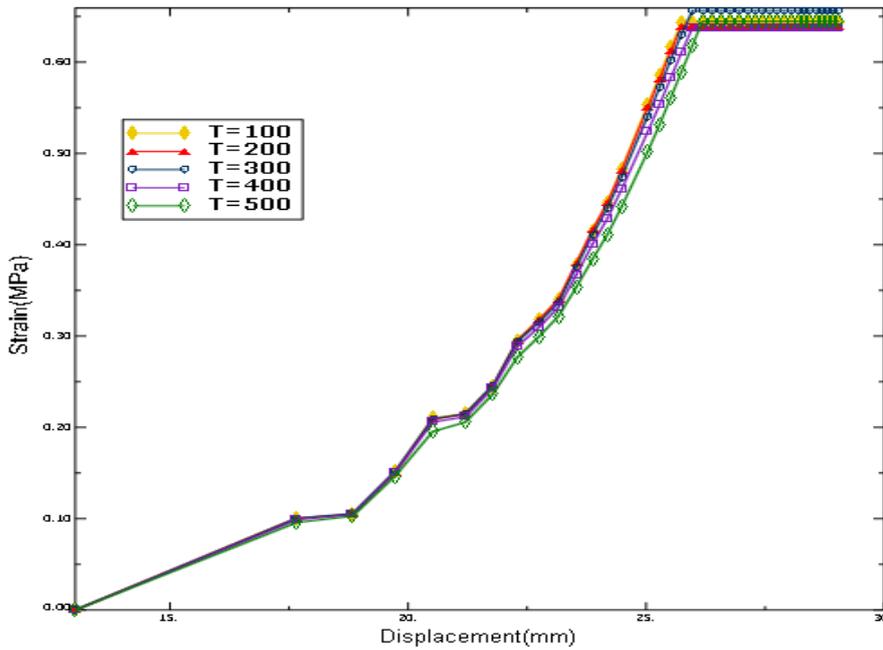


Fig. 6 Axial Stress-strain curves at high temperatures of F114 Carbon Steel

Axial stress-strain curves of F114 Carbon steel at high temperature were obtained based on the axial load and axial displacement from the uniaxial compression test. The value of tangential Young's modulus, E , were calculated from the approximate straight-line section before the peak strength over the entire process of the stress-strain curves.

The results of the stress-strain curves for the F114 Carbon steel under high temperatures are shown in Fig. 6. It shows three stages in the stress-strain curves from room temperature to 600 °C; i.e. the compression stage in which the curves are concave: With the increase in stress, deformation develops rapidly, mainly due to closing of the micro-cracks within the rock caused by the external force. The approximate linear

elastic deformation stage: The curves are approximately linear, the relationship between stress and strain is proportional and the gradient of this line segment is the average Young's modulus.

V. CONCLUSION

Numerical results for the tensile properties of F114 carbon steel are considered in this paper. We illustrated that the proposed method can successfully simulate manufacturing and damage growth in steel structure undergoing finite deformation and large plastic yielding and we indicated the fact that the testing of metal structures requires new contactless methods. The ABAQUS simulation using the Finite Element Analysis methods of fracture mechanics were applied due to the safety assessment of metal structures. Numerical simulations of fracture have benefited from various developments in computational mechanics. The peak stress shows a downward trend from room temperature to 200 °C, increases with rising temperature between 200 °C-600 °C and decreases again when $T > 600$ °C. The damage constitutive equation provide is based on thermal damage. By considering the temperature effect, which showed good agreement in the experiments and using this equation, we were able to describe accurately the effect of heat on the mechanical properties of F114 carbon steel. The stress curves of F114 carbon steel under high temperature are similar to those at room temperature. The steel samples are expressed as brittle from room temperature to 600° C.

REFERENCES

- [1] Hettema, M. H. H, (1999), "A microstructural analysis of the compaction of claystone aggregates at high temperatures". *International Journal of Rock Mechanics and Mining Sciences*, Vol.36(1), pp. 57-68.
- [2] Dougill, J. W, Lau, J. C, Burt, N. J, (1976), *Mechanics in eng. ASCE*. EMD, pp.333-355.
- [3] Wang, Z. B, Xu, D. Y, Wang, X. D, (2001) "Experimental study on concrete thermal damage". *Journal of Hohai University*, Vol. 29(6), pp.94-98.
- [4] Xu, X. C, (2003) "Study on the characteristics of thermal for granite". *Rock and Soil Mechanics*, Vol. 24(sup), pp. 188-191. (In Chinese).
- [5] Xie, W. H, Gao, F, Li, S. C, (2007) "Study on mechanism of thermal damage fracture for limestone". *Rock and Soil Mechanics*, Vol. 28(5), pp. 1021-1025. (In Chinese).
- [6] Zhang, L. Y, Lu, W. T, Mao, X. B (2007) Experimental research on mechanical properties of sandstone at high temperature. *Journal of Mining & Safety Engineering*, Vol. 24(3), pp. 293-297. (In Chinese).
- [7] Zhang, L. Y, Mao, X. B, Lu, A. H, (2009) "Experimental study on the mechanical properties of rocks at high temperature". *Science in China Series E: Technological Sciences*, Vol. 52(3) , pp. 641-646.
- [8] Brünig M (2003a) An anisotropic ductile damage model based on irreversible thermodynamics. *Int J Plast* 19:1679–1713.
- [9] Gurson, A.L., 1977. Continuum theory of ductile rupture by void nucleation and growth. Part I. Yield criteria and flow rules for porous ductile media. *Journal of Engineering Materials and Technology – Transactions of ASME* 99, 2–15.
- [10] Lemaitre J (1996) *A course on damage mechanics*. Springer, Berlin.
- [11] Voyiadjis G, Kattan P (1999) *Advances in damage mechanics: metals and metal matrix composites*. Elsevier, Amsterdam.
- [12] L.L. Mishnaevsky Jr and S. Schmauder, "A model of damage and fracture based on fuzzy sets theory", "ECF11-Mechanisms and mechanics of damage and failure" PMA, University Stuttgart, Germany.
- [13] Feng De-cheng, Tian Lin, Cao Peng. Study of longitudinal cracking during settlement of soil based on extended finite element method (J). *Engineering Mechanics*, 2011, 28 (5): 149-154. (in Chinese).
- [14] Cao Peng, Feng De-cheng, Tian Lin, Jing Ru-xin. "Based on elastic-plastic damage mechanics to research cracking evolution of Cement stabilized base course during maintaining period". *Journal Engineering Mechanics*, 2011, 28 (S1): 99-102,109.
- [15] Fang Xiujun, Jin Feng. "Extended Finite Element Method Based on Abaqus". *Journal Engineering Mechanics*. 2007, 24(7):6-10.
- [16] Bai, Y., Wierzbicki, T., 2008. "Predicting fracture of AHSS sheets on the punch and die radii and sidewall". In: *Proceedings of Numisheet 2008*, Interlaken, Switzerland, pp. 297–306.
- [17] Kim, J.H., Sung, J.H., Wagoner, R.H., 2009. Thermo-mechanical modeling of draw - bend formability tests. In: *Proceedings of IDDRG Conference*, Golden, CO, pp. 503–512.
- [18] Wagoner, R., Kim, J., Sung, J., 2009. Formability of advanced high strength steels. *International Journal of Material Forming* 2, 359–362.
- [19] Bai, Y., Wierzbicki, T., 2010. Application of extended Mohr–Coulomb criterion to ductile fracture. *International Journal of Fracture* 161, 1–20.
- [20] ABAQUS/CAE User's Manual Version 6.9.
- [21] Weibull, W, (1958) "A statistical distribution function of wide applicability." *Journal of Applied Mechanics*, Vol. 18, pp. 293-297.
- [22] Gumbel, E, (1985) *Statistics of Extremes*. New York: Columbia University Press.