DOI: 10.34185/1991-7848.itmm.2025.01.034

MODEL OF THE INFLUENCE OF THE STRESS STATE ON THE STRAIN RATE CURVE DURING HIGH-TEMPERATURE DEFORMATION OF SILICON NITRIDE-BASED CERAMICS

Hnylytsia I. D.[1], Hrushetskyi M. V.[2]

[1]*Ivano-Frankivsk National Technical University of Oil and Gas, Ph.D., associate professo, Ukraine*

[2]*Vasyl Stefanyk Prykarpathian National University, Postgraduate student , Ukraine*

Abstract. *The deformation rate curves of ceramic materials of known compositions based on silicon nitride with high (Si_3N_4-5wt.%Y_2O_3-5wt.%Al_2O_3), medium (Si_3N_4-5wt.%Y_2O_3-2wt.%Al_2O_3) and low (Si_3N_4-2wt.%Y_2O_3-1wt.%Al_2O_3) content of sintering activators during high-temperature deformation according to the direct extrusion scheme were analyzed. The nature of the influence of the rotation of elongated grains on the processes of mass transfer and the rate of deformation is described. The stress state in the deformation zone is considered. The influence of moment stresses on the rotation of elongated grains is shown. The influence of the stress state and the rotation of elongated grains on the curve of the rate of deformation is considered. A mathematical model of non-uniform rotation of elongated $\beta-Si_3N_4$ grains in an inhomogeneous stress field in the transition cone of the matrix is considered. The presence of a constant velocity section on a typical strain rate curve during high-temperature deformation according to the direct extrusion scheme is explained.*

Keywords: *silicon nitride, deformation, deformation mechanism, rotation of elongated grains, model of deformation process.*

The change in normal longitudinal stresses from the outer edge of the punch to the central axis for each individual elongated grain of the β-phase in the structure of the silicon nitride material, the position of which is not coaxial with the axis of symmetry of the matrix, means the presence of a moment of forces that tries to orient the grain along the lines of normal longitudinal stresses. Grain rotation can occur when the shear stress acting on the boundaries is unbalanced, resulting in a moment that rotates the grain. This is observed when, in a two-phase material, the resistance to grain boundary sliding is different from the resistance to interphase sliding.

There are generalized models of material deformation in which the vectors of movement and rotation of particles of the medium play a significant role, and the tensors of deformations and stresses are asymmetric, that is, models that are sensitive to moment stresses. Media that allow moment stresses are called Cosser continua, and the theory that describes moment stresses has become known in the literature as the moment or asymmetric theory of elasticity.

Thus, during high-temperature deformation of silicon nitride materials according to the direct extrusion scheme, there are conditions that determine the rotation of elongated grains of the β-phase in a gradient stress field. The rotation of grains in the stress field occurs with the assistance of grain boundary sliding and viscous flow of the liquid intergranular phase, and after its crystallization, such rotation occurs due to grain boundary sliding with the participation of grain boundary layers of the uncrystallized intergranular phase. Grain rotation due to the Cosser effect is one of the reasons for the formation of a texture of the extruded material directed along the direction of deformation.

In the general case, it can be assumed that the distribution of elongated grains of the β-phase, which are present in the structure of the material before extrusion, along the angle of inclination to the axis of symmetry of the matrix is approximately uniform. In other words, we assume that in the structure of the initial sintered sample before deformation, the number of elongated grains is the same for each value of the angle of inclination of the latter to the longitudinal (or transverse) axis of symmetry of the extrusion die.

The magnitude of the moment of forces arising due to the gradient of normal longitudinal stresses will depend on the magnitude of the projection of the grain size onto the plane perpendicular to the line of normal longitudinal stresses (Figure 1).

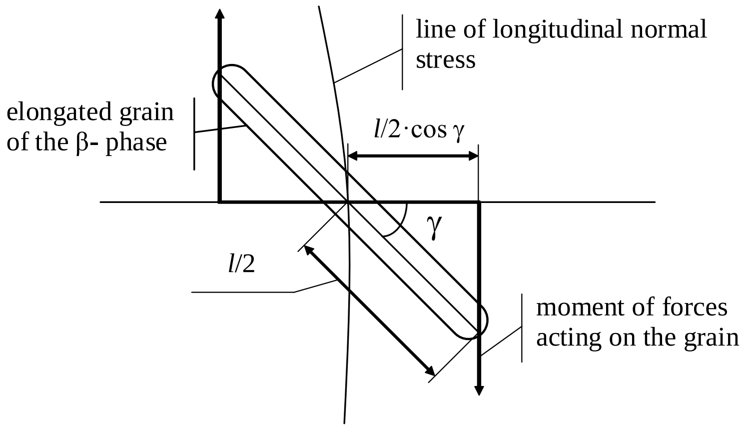

Figure 1 – Dependence of the moment of force causing grain rotation on the grain inclination angle

Thus, the magnitude of the moment of force acting on an elongated grain of the β-phase depends on the angle of inclination, or more precisely on the cos of this angle, of each specific grain to the plane perpendicular to the line of normal longitudinal stress passing through the center of the grain:

$$M \approx P \times \frac{l}{2} \times \cos\gamma \tag{1}$$

where M is the moment of force acting on an elongated grain of the β-phase; l is the length of the grain of the β-phase; P is the specific pressure on the punch; γ is the angle of inclination of the grain to the plane perpendicular to the line of normal longitudinal stress.

The magnitude of the moment of force will decrease as this angle increases, and the angle itself during extrusion for each grain will gradually increase. An increase in the angle will mean a decrease in the moment of force acting on the grain. Since the *cos* function is nonlinear, the intensity of the reduction in the moment of force acting on the grain will increase as the grain reorients along the line of normal longitudinal stress. If we assume a directly proportional relationship between the speed of rotation of the grain and the magnitude of the moment of force that this rotation causes:

$$V \approx P \times \frac{l}{2} \times \cos\gamma \tag{2}$$

where V is the rotation speed of an elongated grain of the β-phase;
then the above means that the rotation speed of differently oriented grains is different.

The closer the grain approaches a position oriented along the line of normal longitudinal stress, the slower its rotation. Considering the nature of the trajectories of normal longitudinal stresses, and specifically the fact that the angle of misorientation of the longitudinal stress lines with the axis of symmetry of the matrix gradually decreases as it approaches the transitional conical part and is minimal when passing through this cone, it can be assumed that the speed of rotation of the grains increases as it approaches the conical part of the matrix and is maximal when passing through the latter.

From this we can conclude that the main rotation of the grains occurs precisely when passing through the transition cone of the matrix.

Based on the assumption that the moment of force acting on the grain, and therefore the speed of rotation of the grain, depends on the angle of inclination of the grain to the longitudinal axis of symmetry of the matrix according to the cosine law and taking into account the nature of possible trajectories of normal longitudinal stresses, an analysis of the speed of rotation of differently oriented grains and changes in their position (angle of inclination to the longitudinal axis) in time was carried out in a first approximation:

$$\frac{d\gamma}{dt} \approx P \cdot \frac{l}{2} \cdot cos\,\gamma \tag{3}$$

$$d\gamma \approx P \cdot \frac{l}{2} \cdot cos\,\gamma \cdot dt \tag{4}$$

$$\gamma = \gamma_0 + d\gamma \tag{5}$$

where γ_0 is the initial angle of inclination of the elongated grain to the matrix axis.

The analysis shows that with the above-described uneven rotation of elongated grains, there is a certain time interval during which a part of such grains will sequentially pass through a position in which their angle of inclination to the longitudinal axis of symmetry of the matrix will be close to or equal to 45^0.

Therefore, during this time interval, some of the elongated grains will pass through a position in which the values of tangential stresses are maximum and grain boundary sliding is most facilitated.

The hypothesis presented allows us to explain the presence of horizontal sections on the kinetic curves of the deformation rate, that is, to explain the fact of stabilization of the deformation rate at a constant level.

Conclusions. Moment stresses in the deformation zone affect the rotation of elongated grains of $\beta - Si_3N_4$. The passage of elongated grains through a position at an angle of 45^0 to the matrix axis leads to the appearance of a horizontal section on the deformation rate curve.

REFERENCES

1. Cannon W. Roger, Langron Terence G. Review. Creep of ceramics. Part 2: An examination of flow mechanisms // J. Mater. Sci., 1988.-23, № 1.-P.1-20.
2. Belchuk Mark, Watt Dan, Dryden John. Modeling creep in materials with soft boundary phases // Proc. Int. Symp. Adv. Struct. Mater., Montreal, Aug. 28-31, 1988.-New-York etc., 1989.-P.123-129.

3. Gogotsi Yuri, Ostrovoj Dmitry, Traskovsky Vladimir. Deformation and creep of silicon nitride-matrix composites // Mech. Creep Brittle Mater. 2: Proc. Int. Colloq., Leicester, 2-4 Sept., 1991.- London; New-York, 1991.- P.230-241.
4. Eiichi Sato, Naoki Kondo and Fumihiro Wakai. Superplasticity in Si3N4 Associated with Rod-like Grain Alignment // Material Science Forum Vols.- 1997.- 243-245.- P. 115-124.

МОДЕЛЬ ВПЛИВУ НАПРУЖЕНОГО СТАНУ НА КРИВУ ШВИДКОСТІ ДЕФОРМАЦІЇ ПРИ ВИСОКОТЕМПЕРАТУРНІЙ ДЕФОРМАЦІЇ КЕРАМІКИ НА ОСНОВІ НІТРИДУ КРЕМНІЮ

Гнилиця І.Д., Грушецький М.В.

Анотація. *Проаналізовано криві швидкості деформації керамічних матеріалів відомих складів на основі нітриду кремнію з високим (Si_3N_4-5мас.%Y_2O_3-5мас.%Al_2O_3), середнім (Si_3N_4-5мас.%Y_2O_3-2мас.%Al_2O_3) і низьким (Si_3N_4-2мас.%Y_2O_3-1мас.%Al_2O_3) вмістом активаторів спікання при високотемпературному деформуванні по схемі прямої екструзії. Описано характер впливу обертання видовжених зерен на процеси масообміну та швидкість деформації. Розглянуто напружений стан в зоні деформації. Показано вплив моментних напружень на поворот видовжених зерен. Розглянуто вплив напруженого стану та повороту видовжених зерен на криву швидкості деформації. Розглянуто математичну модель нерівномірного обертання видовжених зерен $\beta{-}Si_3N_4$ в неоднорідному полі напружень у перехідному конусі матриці. Пояснено наявність ділянки постійної швидкості на типовій кривій швидкості деформації при високотемпературному деформуванні по схемі прямої екструзії.*

Ключові слова: *нітрид кремнію, деформація, механізм деформації, обертання видовжених зерен, модель процесу деформації.*