

MODELING THERMAL SHOCK-BASED CRACKING BEHAVIOR OF ARMOR MATERIAL FOR FUSION REACTOR

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ABSTRACT

Objective: This study presents a computational model for studying the mechanical effects of thermal shock over armor material used for fusion reactor.

Methods: The simulation study comprises transient thermal shocks over the bulk substance for 1 ms.

Result and Conclusion: Latter on the cracking behavior is predicted by extending the virtual crack growth for screening out the efficacy of the used material and its composition.

Keywords: Crack modeling, Finite element analysis, Armour material.

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INTRODUCTION

The combination of tungsten and tantalum material has been considered the most appropriate material for the application of developing armor for nuclear fusion reactors, where it is subjected to face higher degree of temperature caused due to plasma in fusion devices [1-6]. Such material is known for its high melting point, high thermal conductivity, very low oxidation with hydrogen, and tremendously small rate of sputtering erosion to bear high thermal expansion. Fusion reactors such as IETR or DEMO are directed to bear high temperature thermal fluxes of around 20 MW/m² against particle bombardment which leads to more oxidation of the armor wall as time passes [1,7-9].

Such transient thermal loads are prompted by three distinct sorts of plasma precariousness occurring amid tokamak operation, plasma interruption, and vertical displacement event [2]. These occasions show diverse pulses of thermal flux which extents and vitality discharge scales, individually [10]. There are a lot of trial reports on the negative effect of thermal shocks on the microstructural features of tungsten-based materials [3-6,11]. Normally, a powerful electron or plasma beam is utilized to recreate transient shocks within short pulses of time. One of the most prominent research works on this point is the electron-beam irradiation test consider directed by Linke *et al.* [6]. By means of rehashed electron pillar blazing with ELM-like load conditions approximating ~1 MJ/m² within the pulse timing of ~1 ms, they watched an orderly pattern of progression of cracks and advancement in the lighted surface layer as a component of the information vitality, base temperature, number of heartbeats, and material review. Average cracking elements were splitting and surface roughening because of plastic strains. At lower base temperatures, specifically beneath the pliable to fragile temperature, tungsten materials displayed basic resistance for crack progression [12-17].

This finding provides a computational framework to screen out the resistance feature of composite material for finding its suitability to bear the appropriate thermal fluxes; as such effects lessen the lifetime of tungsten layer representing a significant. The aftereffects of the thermal shock lead to tests reproducing loads, showing a nearby connection between the stacking parameters (control thickness, base temperature, and so on) and subsequent cracking designs. For more comprehension, this relationship is numerically studied for modeling cracking properties. We do a thorough parametric evaluation of the

cracking on tungsten composites under average transient shocks under the average load parameters within the nuclear fusion reactors such as IETR and DEMO.

METHODS

We have used T-S fuzzy inference engine to model a new tungsten alloy based on bond strength from density function analysis. Here, the computationally deduced weighted sum for simple mesh model of the composite and its linear subsystems are readily analyzable and it has been used for synthesis problems with successful demonstration of numerical results approximating the experimental work. Latter on the simulated values of Young's modulus of this material is used for thermal shock analysis. The model of the fuzzy inference is given as follows:

Here, the decomposition principle from density functional analysis is used for the composite material before the process for structuring the hierarchy of molecular properties to capture the statistical effects of every element to numerically derive the suitable composition. This step requires handle of various key parameters for a comprehensive multi-criteria conjunction. Thus, the so-formed structure of data into different hierarchical levels with regard to the properties or attributes of the problem considered can be represented as fuzzy set X the membership function is given by μ_A which takes the value of the interval [0,1], i.e., $m_A: X \rightarrow [0,1]$. Thus, the fuzzified membership values can be represented as:

$$X = \frac{m_A(n_1)}{n_1} + \frac{m_A(n_2)}{n_2} + \dots + \frac{m_A(n_p)}{n_p}$$

Where the trapezoidal membership function for m_A is given as:

$$m_A(n) = \begin{cases} 0, & x \in [-\infty, l] \\ \frac{n-1}{n-m_1}, & x \in [l, m_1] \\ 1, & x \in [m_1, m_2] \\ \frac{u-n}{u-m_2}, & x \in [m_2, u] \\ 0, & x \in [u, +\infty] \end{cases}$$

Here, m_1 and m_2 are the two membership functions, followed by l and u are the respective upper and lower limits where the sub-membership functions are bounded within $l \leq m_1 \leq m_2 \leq u$.

Where, $l, m_1, m_2,$ and u are derived from the statistical properties of a series of suitable composites allow. This is converted into a continuous system by outlining of several alloys' properties as we have performed the finite element analysis simulation on polycrystalline tantalum carbide XW-YCo-ZTaC (Co is used as a binder and TaC provides heat resistance). The composition values differ from range $X \approx 42-67,$ $Y \approx 24-54,$ and $TaC \approx 12-34,$ where its relationship fracture toughness-temperature and oxidation at three temperature sets are given by three equations, namely, element stiffness, mass, and damping matrices:

$$[k]^e = \int_{V^e} [B]^T [D] [B] d(vol)$$

$$[M]^e = \int_{V^e} [N]^T \rho [N] d(vol)$$

$$[C]^e = \int_{V^e} [N]^T \mu [N] d(vol)$$

Here, $[B]=\delta N$ (δ -linear operator, $[N]$ - element function of geometric structure). Thus, the volume is uncertain as depending on the uncertainty of the geometrical function. Material stiffness is given by $[D]$. ρ and μ are the material density and damping factor, and V is the volume of the elements for all edges e of the mesh. This sums up the integrator equations for modeling material properties and geometrical properties for element shape variation under thermal load. In this event, both component volume and mechanical properties are characterized as fuzzy sources of input; figuring the component networks is performed by coordinating a fuzzy integrator over a fuzzy volume for each component of the lattice. The mesh refinement and parallel computations are achieved using the techniques mentioned in the studies done by Ankush [18,19].

RESULTS AND DISCUSSION

Fig. 1 exhibits the outcome of the thermal simulation as the temperature grows as function of time for a power density corresponding to the value of 1.30 GW/m² and a base temperature of 800°C for the most suitable material 36W-22Co-29TaC (extracted from fuzzy inference). The top surface is heated to the temperature up to over 900°C in a pulse of 1 ms.

Once heating is stopped, the surface temperature received temperature drop to 821°C within 1ms. This simulation result follows the numerical result following the reported analytical in Carslaw and Jaeger [12]. For the one-dimensional heat flux conduction issue experienced when chilling off sample 1D composite whose infinitely huge surface is exposed to heat and was affirmed by surface temperature estimations by quick infrared and noticeable imaging in the reported tests [13]. This result exhibits the temperature variation at different surface depths of the composite material as only the surface layer had gone through an oxidative temperature. At a depth of 480 μm, the maximum temperature is below 540°C.

Fig. 1: Variation of the oxidation and fracture properties of the most converge material at three temperatures, i.e. 90°C, 100°C, and 111°C

Figs. 2 and 3 demonstrate surface deterioration and the crack outspread course as a component of the separation from the stacking focus. In the stacking zone, the surface load in outspread bearing is compressive amid heat fluxes ($t \leq 1$ ms) and pliable amid cooling ($t > 1$ ms). Since tungsten and tantalum composite is expected to carry on in perfect plastic properties, the crack close to the top surface amid heating is constrained by the little yield quality of tungsten at high temperature. After the specimen is chilled off, high crack progression is observed close to the top surface. The deterioration of the material in spiral course is seen close to the edge of the stacking zone at the top surface. The out of surface disfigurement in the stacking zone is found toward the end of cooling, as shown in Fig. 4. The vertical dislodging is subjectively in great concurrence with the aftereffects of a profilometry check changed over into a profundity profile along the center of the stacking region in the test of thermal shock [10]. Because of incompressibility of the material amid plastic twisting, the locale outside the stacking region sinks down. The out of surface twisting and the sinking of material outcome in the ductile worry close to the edge of the stacking region. Besides, the compressive plastic distortion close to the edge of the stacking zone is bigger than in the focal piece of it. Therefore, the crack spreads and its course is bigger close to the edge of the stacking region.

CONCLUSION

This study presents the simulation study of 36W-22Co-29TaC composite material and its cracking behavior under transient thermal shock loads was investigated. The fuzzy inference method is used to model the most stable compound with high mechanical properties to screen out the best material suited for the purpose. This type of automated discovery of material could lead to more findings of relevant composite

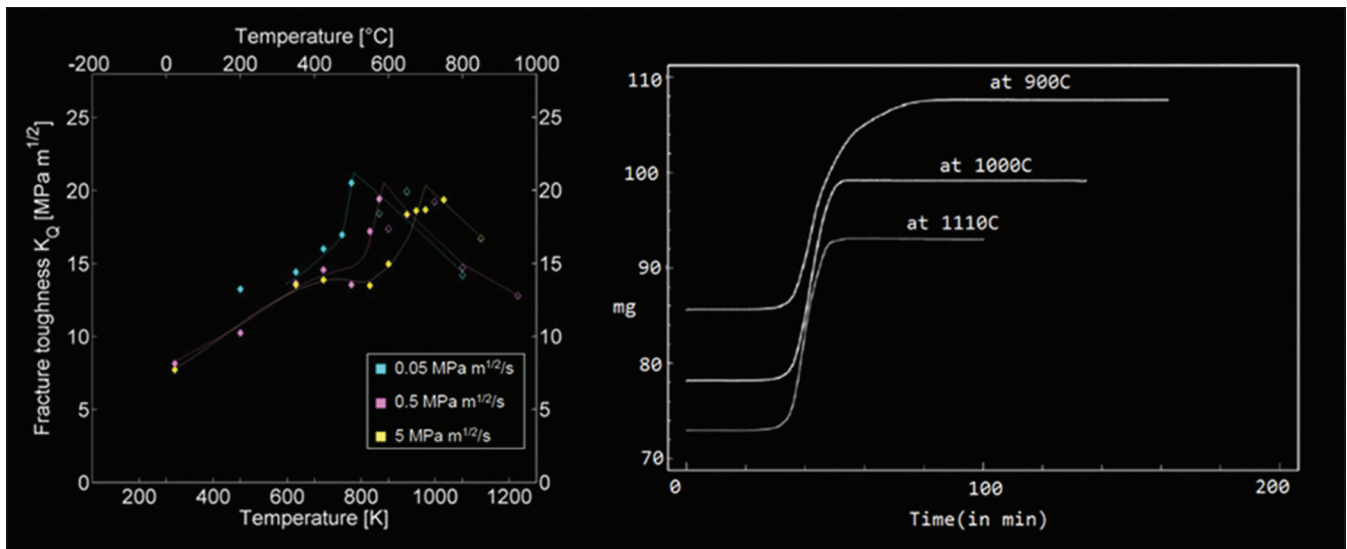


Fig. 1: Variation of the oxidation and fracture properties of the most converge material at three temperatures, i.e., 90°C, 100°C, and 111°C

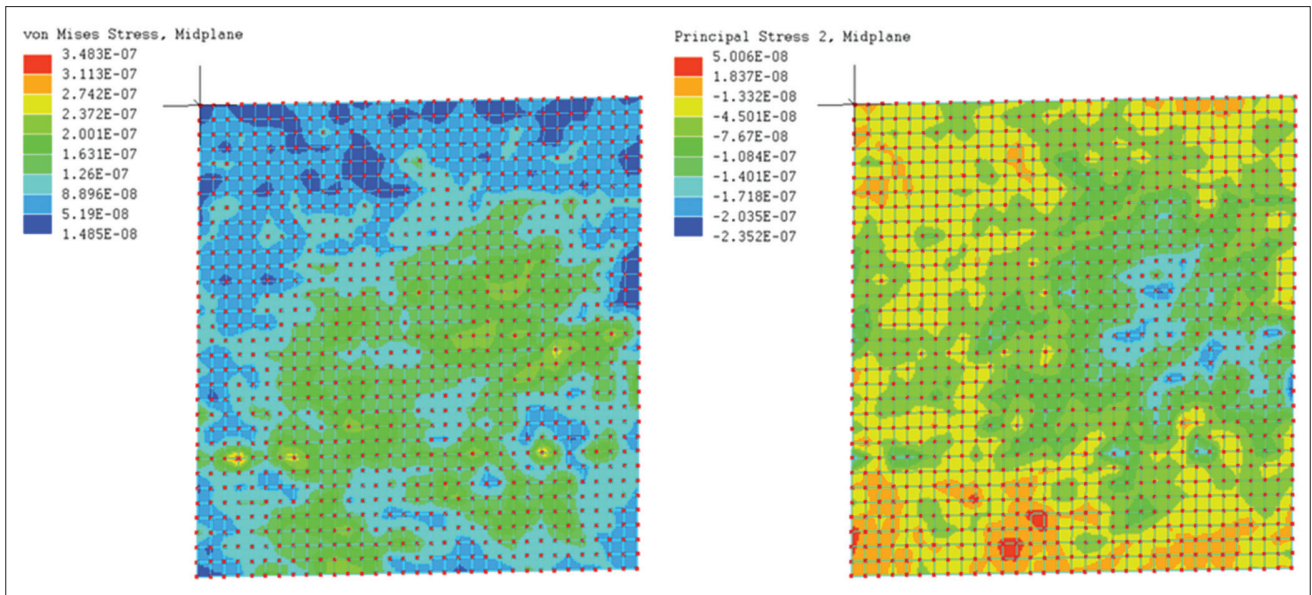


Fig. 2: Stress distribution at 90°C

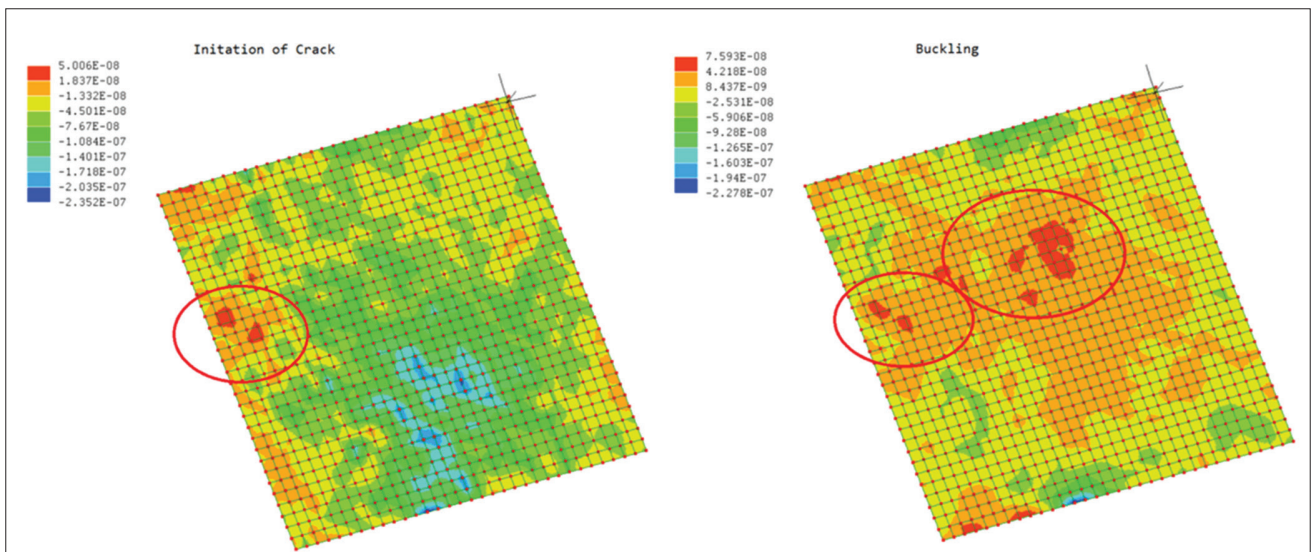


Fig. 3: Stress distribution at 110°C

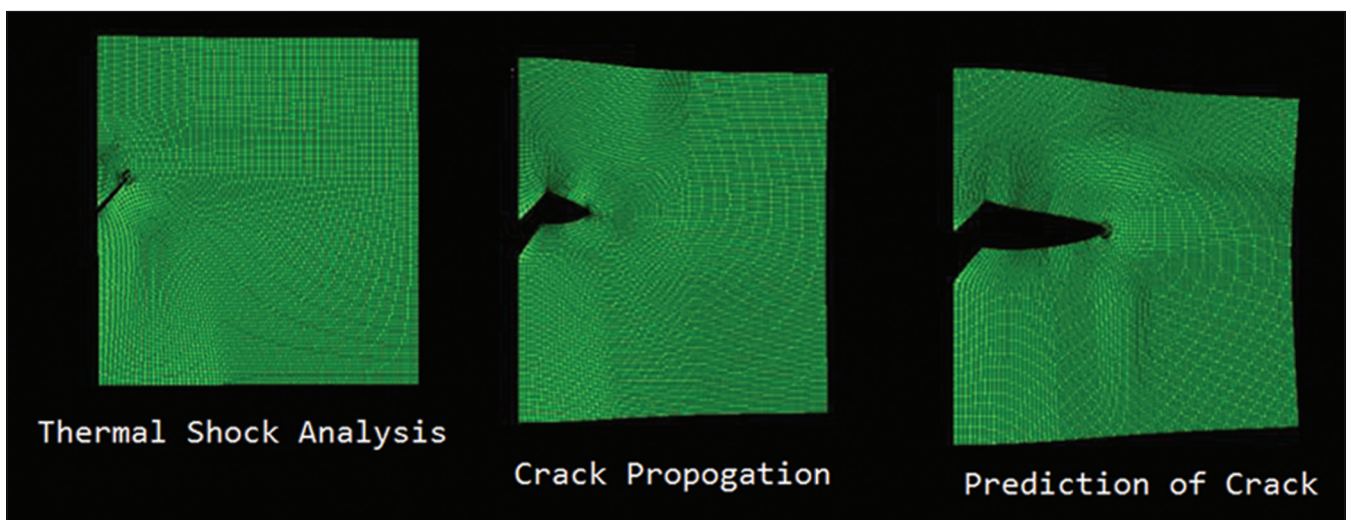


Fig. 4: Results of crack propagation and its prediction for the given composite

materials within the range of power density and base temperature for self-attenuated parametric assessment. Many more material compositions can be simulated to find the right material composition to reduce the oxidation of W at high temperatures. Micromechanics of such polycrystalline material shall be modeled in association with neural networks to predict the cracking behavior of full structure of ITER fusion reactor.

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