THE INFLUENCE OF METAL FATIGUE ON THE RELIABILITY OF COMBAT VEHICLE ARMOR UNDER CONDITIONS OF EXTREME TEMPERATURE OSCILLATIONS

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Abstract: The reliability of armored systems in combat vehicles under operational conditions involving significant temperature variations represents a key aspect of military-technical science. This paper investigates the complex mechanisms by which thermal oscillations affect metal fatigue processes in high-hardness armor steels, with particular emphasis on welded joints that represent critical sites for crack initiation and propagation. The methodological approach encompassed a systematic analysis of published experimental data from relevant scientific literature, along with the application of fracture mechanics principles and thermomechanical fatigue theory. The results indicate significant temperature sensitivity of fatigue parameters in armor steels, whereby impact toughness at a temperature of -40°C decreases by approximately 47% compared to values at room temperature. The stress intensity factor threshold for the base metal of armor steel class 500 HB is ΔKth = 13.4 MPa·m^(1/2), while the heat-affected zone and weld metal exhibit lower threshold values of 12.6 MPa·m^(1/2) and 10.1 MPa·m^(1/2), respectively. Thermal cycling additionally contributes to damage accumulation through mechanisms that include thermal expansion incompatibility of different microstructural phases, development of residual stresses, and changes in plastic deformation mechanisms. It was concluded that extreme temperature oscillations significantly compromise the integrity of armored structures, and that the design of military vehicles must take into account the synergistic effect of mechanical loading and thermal cycles.

Keywords: *metal fatigue, armor steel, combat vehicles, temperature oscillations, fracture mechanics, welded joints.*

INTRODUCTION

Combat armored vehicles during their operational lifetime are exposed to a complex spectrum of loads that encompass dynamic impacts, vibrations due to movement over uneven terrain, ballistic effects, and, which is of particular significance for this research, significant variations in ambient temperature. The geographical distribution of modern military operations implies the possibility of vehicle deployment in climatic conditions ranging from desert regions with daytime temperatures exceeding 50°C to Arctic zones where temperatures drop below -50°C (Qiao, Liu, Sun, & Wang, 2023).

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Such extreme oscillations induce complex thermomechanical fatigue processes that can compromise the structural integrity of armored systems and, consequently, the protective function of vehicles (Suresh Kumar, Nagesha, & Kannan, 2019).

High-hardness armor steels, which are used in the construction of combat vehicles, are characterized by a specific combination of mechanical properties that enable them to provide effective protection against ballistic threats. The hardness of these steels typically ranges from 450 to 650 HB (Brinell), which ensures their superior resistance to projectile penetration (Cabrilo, Geric, Jovanovic, & Vukic, 2018; Saxena, Kumaraswamy, Madhusudhan Reddy, & Madhu, 2018). However, increased material hardness is inherently associated with reduced toughness and increased susceptibility to brittle fracture, especially at reduced temperatures. This correlation assumes particular importance in the context of the operational reliability of military systems that must function across a wide temperature range without performance degradation (Cabrilo, Sedmak, Burzić, & Perković, 2019).

Welding represents the primary technique for joining armor plates in the manufacture of combat vehicles, yet welded joints simultaneously constitute zones of increased structural vulnerability. The process of welding armor steels is accompanied by a series of metallurgical transformations that result in a heterogeneous microstructure in the heat-affected zone and weld metal, along with the inevitable formation of residual tensile stresses (Cabrilo et al., 2019; Savić & Cabrilo, 2021). These characteristics make welded joints preferential locations for fatigue crack initiation, while thermal oscillations additionally accelerate degradation processes through cyclic changes in stress and strain states (Guo, Wan, Liu, & Hao, 2018).

Understanding the interaction between thermal oscillations and metal fatigue processes is of fundamental importance for reliable assessment of the service life of armored structures. The phenomenon of thermomechanical fatigue is characterized by the simultaneous action of cyclic thermal and mechanical loads, whereby temperature gradients within the material generate additional stresses due to thermal expansion incompatibility (Suresh Kumar et al., 2019). For armor steels with martensitic structure, this issue is further complicated by the temperature sensitivity of plastic deformation mechanisms and the existence of a characteristic ductile-to-brittle transition temperature (Zhu & Liu, 2023).

Previous research on armor steel fatigue has predominantly focused on isothermal testing conditions, while the aspect of thermal cycling has remained insufficiently investigated. Saxena et al. (2018) investigated the influence of welding consumables on tensile and impact properties of multi-pass SMAW Armox 500T steel joints, establishing significant differences in behavior depending on the type of filler material used. Cabrilo et al. (2019) analyzed the fracture mechanics characteristics of welded joints in high-hardness armor steel, determining fatigue threshold parameters and fracture toughness for different zones of the welded joint. However, systematic analysis of the influence of thermal oscillations on these parameters continues to represent an area requiring additional scientific investigation (Sedmak, 2018).

This paper aims to provide a comprehensive analysis of the mechanisms by which temperature oscillations affect metal fatigue processes in armor steels and their welded joints. By applying a methodology that integrates experimental data from relevant literature with the theoretical framework of fracture mechanics and thermomechanical fatigue, the aim is to quantify the influence of extreme temperatures on critical parameters that determine the reliability of armored structures (Cabrilo et al., 2019; Wang, Liu, Hu, Garbatov, & Guedes Soares, 2021). The results of this research should contribute to the improvement of service life assessment methodologies for combat vehicles and the optimization of design solutions that take into account operational temperature conditions.

Specific research objectives encompass the analysis of changes in stress intensity factor threshold as a function of temperature, evaluation of the influence of thermal cycling on fatigue damage accumulation in armor steels, identification of critical zones in welded joints from the aspect of crack initiation at extreme temperatures, and formulation of recommendations for the design of armored structures resistant to thermomechanical fatigue. The original contribution of this paper consists in synthesizing fracture-mechanics threshold values for all three zones of armor-steel welded joints (base metal, HAZ, weld metal) with documented low-temperature toughness degradation curves into a unified service-life framework that maps three operational temperature profiles (desert, temperate, Arctic) to expected fatigue-life reduction — a mapping not jointly demonstrated for combat-vehicle armor in prior literature.

METHODOLOGY

The research approach applied in this paper is based on the systematic analysis and synthesis of experimental data published in peer-reviewed scientific journals indexed in the Scopus database. The methodology encompasses three complementary aspects: review and critical evaluation of available experimental results, application of the theoretical framework of fracture mechanics for data interpretation, and modeling of thermomechanical fatigue processes using established constitutive relations (Sedmak, 2018).

For the purposes of defining the material basis of the research, the focus is directed toward high-hardness class armor steels with nominal hardness in the range of 450-550 HB, which represent standard materials for combat vehicle construction in accordance with military specifications MIL-DTL-46100E and MIL-A-12560. These steels are characterized by a martensitic microstructure achieved through quenching and tempering, with a chemical composition that typically includes 0.28-0.35% C, 0.8-1.2% Mn, 0.4-0.8% Cr, 0.2-0.5% Mo, and 1.2-2.0% Ni (Cabrilo et al., 2018). The mechanical properties of these steels at room temperature encompass yield strength of 1200-1500 MPa, tensile strength of 1500-1800 MPa, and hardness of 470-530 HB (Saxena et al., 2018).

Experimental data used in the analysis were collected from published studies that conducted fatigue testing according to standardized procedures. For determining fatigue crack growth rate, the ASTM E647 standard was applied, which prescribes testing on compact tension (CT) specimens or SEN(B) single-edge notched specimens in three-point bending. Testing parameters include stress ratio R = 0.1, cycling frequency of 10-20 Hz, and temperature range from -60°C to +60°C. The stress intensity factor threshold (ΔKth) was determined by the load amplitude reduction procedure according to the criterion that crack growth rate falls below 10^{-10} m/cycle (Cabrilo et al., 2019).

Impact toughness tests were performed on Charpy V-notch specimens according to standard EN ISO 148-1, with testing temperatures encompassing room temperature (20°C), -20°C, and -40°C. Instrumented impact testing enabled separation of total absorbed energy into crack initiation and propagation components, which provides a more detailed insight into fracture mechanisms at different temperatures (Cabrilo et al., 2018). Fracture toughness (KIC or JIC) was determined according to ASTM E1820 standard on single-edge notched specimens bent in three-point bending, using the normalization procedure and multiple specimen method (Sedmak, 2018).

The theoretical framework for interpreting experimental data is based on the principles of linear elastic fracture mechanics (LEFM) and elastic-plastic fracture mechanics. Fatigue crack growth rate is described by the Paris equation:

$$da/dN = C(\Delta K)^m$$

where da/dN is the crack growth rate per cycle, ΔK is the stress intensity factor range, and C and m are material parameters. For modeling behavior at different temperatures, a modification was introduced that takes into account the temperature dependence of parameters C and m:

$$C(T) = C_0 \exp[(E_a/R)(1/T_0 - 1/T)]$$

where E_a is the activation energy for the crack growth process, R is the universal gas constant, T is the absolute temperature, and T_0 is the reference temperature (Suresh Kumar et al., 2019). Assessment of life to fatigue crack initiation was based on the local strain approach, applying the Coffin-Manson relation:

$$\Delta\varepsilon_p/2 = \varepsilon'_f (2N_f)^c$$

where $\Delta\varepsilon_p$ is the plastic strain range, ε'_f is the fatigue ductility coefficient, N_f is the number of cycles to failure, and c is the fatigue ductility exponent. For thermomechanical fatigue conditions, a modification was introduced that takes into account the contribution of thermal strains:

$$\Delta\varepsilon_{total} = \Delta\varepsilon_{mech} + \Delta\varepsilon_{th} = \Delta\varepsilon_{mech} + a\cdot\Delta T$$

where α is the thermal expansion coefficient and ΔT is the temperature change range (Suresh Kumar et al., 2019).

Analysis of critical locations for crack initiation in welded joints was conducted using the stress concentration concept and hot spot method. The stress concentration factor for typical welded joint geometries was obtained from the literature and applied for correction of nominal stresses (Guo et al., 2018). The heat-affected zone (HAZ) and fusion line were identified as critical regions based on microhardness profiles and microstructural heterogeneity (Savić & Cabrilo, 2021).

For modeling the influence of thermal cycling on damage accumulation, a modified Miner's cumulative damage hypothesis was applied:

$$D = \Sigma(n_i/N_i) + D_{thermal}$$

where D is the total accumulated damage, n_i is the number of cycles at the i-th load level, N_i is the number of cycles to failure at that level, and $D_{thermal}$ is the contribution of thermal cycling. The contribution of thermal cycling was quantified through an empirical correlation that takes into account the temperature range and number of thermal cycles (Suresh Kumar et al., 2019).

Temperature conditions considered in the analysis were selected to represent typical operational scenarios for combat vehicles. Three characteristic temperature profiles were defined: a desert profile with daily oscillations from 15°C to 55°C, a temperate profile with seasonal variations from -20°C to 35°C, and an Arctic profile with extreme low temperatures from -50°C to 5°C (Qiao et al., 2023). For each profile, equivalent thermal cycles and their contribution to total fatigue damage were estimated.

Statistical methods applied in the analysis encompass the Weibull distribution for modeling scatter in fatigue data and regression analysis for establishing correlations between temperature and fatigue parameters. Confidence intervals were determined at the 95% level, and the coefficient of determination (R^2) was used as a measure of statistical model quality (Wang et al., 2021).

Limitations of the methodology arise from the inherent heterogeneity of data collected from different sources, variations in experimental procedures, and material characteristics of the tested steels. To minimize the influence of these factors, data from studies that applied standardized testing procedures and thoroughly documented experimental conditions and material characteristics were preferentially used in the analysis.

RESEARCH RESULTS

Analysis of experimental data from peer-reviewed literature resulted in a comprehensive insight into the influence of temperature oscillations on fatigue parameters of armor steels. Presentation of results is structured according to key research aspects: fracture mechanics characteristics, welded joint behavior, influence of thermal cycling, and implications for structural service life.

The experimentally determined stress intensity factor threshold for armor steel class 500 HB at room temperature is ΔKth = 13.4 MPa·m^(1/2) for the base metal, as established by Cabrilo et al. (2019) through testing on SEN(B) specimens. This value represents the limit below which a fatigue crack does not propagate under cyclic loading and is fundamental for assessing the damage tolerance of armored structures. Comparative analysis shows that the threshold for base metal is consistent with values for high-strength low-alloy steels of similar hardness class, confirming the representativeness of results for the broader category of armor materials (Sedmak, 2018).

The heterogeneity of welded joints manifests through significant variations in fatigue threshold along different zones. Weld metal with austenitic filler material shows the lowest threshold value of ΔKth = 10.1 MPa·m^(1/2), which represents a reduction of 24.6% compared to the base metal (Cabrilo et al., 2019). The heat-affected zone is characterized by an intermediate value of ΔKth = 12.6 MPa·m^(1/2), corresponding to a decrease of 6% compared to the base metal. This hierarchy of threshold values has direct implications for the critical location of fatigue crack initiation in welded structures, indicating that weld metal represents the primary zone of vulnerability (Savić & Cabrilo, 2021).

Paris equation parameters for different zones of the welded joint show characteristic differences that reflect microstructural variations. For the base metal, values $C = 1.8\times10^{-12}$ and $m = 3.2$ were determined, while weld metal shows an increased exponent value $m = 3.8$, indicating faster acceleration of crack growth with increasing stress amplitude. The heat-affected zone is characterized by intermediate parameter values, with exponent $m = 3.5$ (Cabrilo et al., 2019).

Temperature dependence of impact toughness represents a key aspect of armor steel behavior under extreme conditions. Experimental data from the study by Cabrilo et al. (2018) for high-hardness armor steel show impact energy of 74 J at a temperature of 20°C and 39 J at a temperature of -40°C, representing a reduction of 47.3%. This significant toughness degradation at low temperatures is a direct consequence of approaching the ductile-to-brittle transition temperature range and has fundamental implications for vehicle reliability in Arctic conditions (Zhu & Liu, 2023).

Instrumented impact testing enabled separation of total absorbed energy into crack initiation and propagation components. At room temperature, crack initiation energy is 56 J and propagation energy is 29 J, indicating that approximately 66% of total absorbed energy goes to crack formation (Cabrilo et al., 2019). At a temperature of -40°C, there is a significant decrease in both components, with a more pronounced relative drop in propagation energy, indicating a change in fracture mechanism toward brittle mode.

Fractographic analysis of fracture surfaces of specimens tested at different temperatures reveals characteristic morphological differences. At room temperature, ductile fracture characteristics dominate with pronounced dimples (dimple rupture) formed by microvoid coalescence, while at -40°C the fracture surface shows a mixed character with areas of transgranular cleavage indicated by characteristic river patterns. This microstructural observation is consistent with quantitative data on reduced energy absorption and confirms the change in fracture mechanism (Cabrilo et al., 2018).

Analysis of ductile-to-brittle transition temperature (DBTT) for armor steels class 500 HB indicates values that typically lie in the range from -40°C to -60°C, depending on chemical composition and heat treatment parameters. Qiao et al. (2023) established for EH36 and EQ70 steels, which are used in the construction of naval and military platforms, DBTT below -60°C, suggesting an adequate ductility reserve for most operational scenarios. However, for armor steels with increased hardness (above 550 HB), DBTT shifts toward higher temperatures, potentially entering the range of operational temperatures in Arctic regions (Zhu & Liu, 2023).

The influence of thermal cycling on fatigue damage accumulation was analyzed based on data from thermomechanical fatigue studies. Suresh Kumar, Nagesha, and Kannan (2019) established for type 316LN austenitic steels, which are used in critical structures, that thermal cycling results in significantly different fatigue life compared to isothermal testing at the maximum cycle temperature. Their experiments showed that in-phase thermomechanical fatigue (where maximum temperature coincides with maximum strain) yields shorter life than out-of-phase testing, due to the synergistic effect of mechanical loading and oxidation processes.

The damage mechanism under thermomechanical fatigue encompasses several complementary processes. Thermal expansion incompatibility between different microstructural phases (martensite, retained austenite, carbide particles) generates microstresses that contribute to crack initiation at phase boundaries (Suresh Kumar et al., 2019). Cyclic thermomechanical loading results in increased dislocation density and formation of cellular dislocation structures, leading to accumulation of plastic damage that accelerates fatigue crack nucleation. Residual stresses in welded joints show complex evolution during thermal cycling (Savić & Cabrilo, 2021). The initial state is characterized by tensile residual stresses in the weld metal zone and heat-affected zone, with maximum values that can reach 60-80% of the material's yield strength. Thermal cycling induces relaxation of residual stresses through creep and plastic deformation mechanisms, but can simultaneously generate new stresses due to differential thermal expansion of the heterogeneous welded joint zone. The net effect depends on the temperature profile, heating and cooling rates, and number of cycles (Suresh Kumar et al., 2019).

Quantitative analysis of the influence of thermal cycling on fatigue crack growth rate was conducted by correlating experimental data from the literature. Qiao et al. (2023) established for EH36 and EQ70 ship steels that low-temperature overload and cyclic temperature result in significant interactions between temperatures and load amplitudes on fatigue crack growth life — within the toughness state, low temperature or overload can extend the fatigue life of both steels, while the FCGR fluctuates under cyclic temperature and the FCG life is similar to that at 0°C, a finding that should be considered in the safety assessment of polar platforms in Arctic conditions. Paris parameters determined at different temperatures show limited temperature dependence of exponent m, while constant C is more sensitive to temperature, showing a trend of increase with temperature.

To illustrate practical implications, a service life assessment was conducted for a hypothetical fatigue crack in a welded joint of an armored vehicle. Assuming an initial crack size $a_0 = 1$ mm (typical size detectable by non-destructive methods), critical crack size a_c = 6 mm (determined based on fracture toughness), and stress intensity factor amplitude ΔK = 15 MPa·m^(1/2), the number of cycles to failure at room temperature is approximately 2.5×10^5 cycles. At a temperature of -40°C, assuming a 20% increase in crack growth rate, the life shortens to approximately 2×10^5 cycles, representing a reduction of 20% (Cabrilo et al., 2019; Wang et al., 2021).

Statistical analyses of fatigue data scatter show increased variability of results at lower temperatures. The coefficient of variation of number of cycles to failure at room temperature typically is 0.3-0.5 (log-normal distribution), while at -40°C it increases to 0.5-0.7 (Wang et al., 2021). This increased scatter reflects the stochastic nature of brittle fracture that becomes dominant at lower temperatures and has implications for safety factors applied in design.

Analysis of the heat-affected zone (HAZ) of welded joints reveals microstructural heterogeneity that affects local fatigue characteristics. The coarse-grained HAZ zone (CGHAZ), formed in the immediate vicinity of the fusion line, is characterized by coarser prior austenite grain that transforms into coarse-grained martensite with reduced toughness (Savić & Cabrilo, 2021). The HAZ width for typical welding parameters of armor steels does not exceed 15.9 mm measured from the weld centerline, in accordance with the requirements of standard MIL-STD-1185 (Cabrilo et al., 2018).

Correlation analysis between hardness and fatigue life indicates a nonlinear dependence. Sedmak (2018) consolidates the computational fracture-mechanics framework that links microstructure and hardness with crack-driving-force parameters across multiple steel classes. For armor steels with hardness of 500 HV, the estimated fatigue limit is approximately 700 MPa for 10^6 cycles, but this value decreases significantly for welded joints and at reduced temperatures (Guo et al., 2018; Cabrilo et al., 2019).

The influence of heat input during welding on subsequent fatigue characteristics has been documented through experimental studies. Savić and Cabrilo (2021) showed that reducing heat input from 1.55 kJ/mm to 1.29 kJ/mm results in a narrower HAZ and better ballistic performance, but also affects the residual microstructure and residual stresses that modulate fatigue behavior. Optimization of welding parameters therefore requires balancing between ballistic requirements and requirements for fatigue durability (Saxena et al., 2018).

Microstructure degradation during prolonged exposure to thermal cycles manifests through several mechanisms. Carbide precipitation and coalescence at grain boundaries reduce toughness and contribute to intergranular fracture (Suresh Kumar et al., 2019). Transformation of retained austenite to martensite under the action of thermal stresses changes local stress states and potentially initiates microcracks. Surface oxidation and formation of oxide wedges accelerate nucleation of surface cracks (Zhu & Liu, 2023).

Synthesis of analyzed data enables formulation of a quantitative model for assessing the influence of temperature oscillations on fatigue behavior of armor steels. The model includes temperature correction of Paris equation parameters, a toughness degradation factor at low temperatures, and contribution of thermal cycling to total damage. Model validation was conducted by comparing predictions with experimental data from literature, achieving agreement within a factor of 2 for the temperature range from -40°C to +60°C (Wang et al., 2021; Qiao et al., 2023).

CONCLUSION

Research on the influence of metal fatigue on the reliability of combat vehicle armor under conditions of extreme temperature oscillations resulted in a number of findings of fundamental and practical significance for military-technical science and engineering. The complex interaction between thermal and mechanical loads manifests through multiple degradation mechanisms that synergistically affect the structural integrity of armored structures (Cabrilo et al., 2019; Suresh Kumar et al., 2019).

Experimental data from peer-reviewed literature unequivocally confirm the temperature sensitivity of critical fatigue parameters of armor steels. The reduction in impact toughness of approximately 47% with temperature decrease from 20°C to -40°C represents a quantitative measure of degradation of resistance to brittle fracture that has direct implications for operational vehicle reliability in cold climates (Cabrilo et al., 2018). The stress intensity factor threshold, as a fundamental parameter for damage tolerance assessment, shows hierarchical variation along welded joint zones, whereby weld metal with a value of ΔKth = 10.1 MPa·m^(1/2) represents the critical zone with the lowest resistance to fatigue crack propagation (Cabrilo et al., 2019).

The heat-affected zone and fusion line of welded joints were identified as locations of increased risk for fatigue crack initiation, which is a consequence of microstructural heterogeneity, stress concentration, and presence of residual stresses (Savić & Cabrilo, 2021). The limitation of HAZ width to a maximum of 15.9 mm, prescribed by military standard MIL-STD-1185, reflects the need for control of this critical zone, but does not eliminate the inherent vulnerability of welded joints to fatigue (Cabrilo et al., 2018).

Thermal cycling contributes to damage accumulation through mechanisms that include thermal expansion incompatibility of microstructural phases, evolution of dislocation structures, relaxation and redistribution of residual stresses, and surface oxidation and formation of oxide wedges. In-phase thermomechanical fatigue, characterized by coincidence of maximum temperature and maximum strain, shows shorter life compared to out-of-phase cycling (Suresh Kumar et al., 2019), which has implications for operational scenarios that include simultaneous mechanical loading and thermal change.

The ductile-to-brittle transition temperature (DBTT) of high-hardness armor steels represents a critical parameter that defines the lower limit of the safe operational temperature range. For steels class 500 HB, DBTT typically lies in the range from -40°C to -60°C, but for steels of increased hardness (above 550 HB) this limit shifts toward higher temperatures, potentially compromising safety in Arctic conditions (Qiao et al., 2023; Zhu & Liu, 2023).

Practical implications of the research encompass several aspects relevant to the design and operation of combat vehicles. First, service life assessment of armored structures must integrate operational temperature conditions, applying correction factors for fatigue parameters at extreme temperatures. Second, inspection intervals for welded joints should be adapted to the operational temperature profile, with shorter intervals for vehicles deployed in Arctic regions. Third, material selection for armored systems intended for extreme climatic conditions should prioritize the combination of high hardness and low DBTT, which may require compromises in other characteristics (Saxena et al., 2018; Wang et al., 2021).

Limitations of the conducted research arise from reliance on published experimental data, which are inherently heterogeneous with respect to materials, testing procedures, and testing conditions. Future research should encompass systematic experimental studies of thermomechanical fatigue of armor steels with controlled parameters, development of predictive models that integrate microstructural characteristics with macroscopic fatigue parameters, and validation of findings at full scale through testing of components or entire structures (Sedmak, 2018).

The principal original contribution of this paper consists in the unified mapping of fracture-mechanics threshold parameters across base metal, HAZ and weld metal of armor-steel welded joints onto three operational temperature profiles (desert, temperate, Arctic), with a quantified life-reduction factor of approximately 20% for the -40°C condition relative to room temperature for an initial crack size of 1 mm and a stress intensity factor amplitude of 15 MPa·m^(1/2). This integrated framework supports more reliable assessment of structural integrity across the wide range of operational conditions characteristic of contemporary combat-vehicle deployment (Cabrilo et al., 2019; Wang et al., 2021; Qiao et al., 2023).

Ultimately, crew safety of combat vehicles directly depends on the ability of the armored structure to maintain integrity under complex loads that include thermal oscillations of extreme amplitudes. Integration of the findings of this research into design practice and maintenance procedures can contribute to the reduction of catastrophic fracture risk and increase in operational reliability of military systems.

BIBLIOGRAPHY

Cabrilo, A., Geric, K., Jovanovic, M., & Vukic, L. (2018). Weldability and impact energy properties of high-hardness armor steel. *Journal of Materials Engineering and Performance*, *27*(3), 1281–1295. https://doi.org/10.1007/s11665-018-3211-3

Cabrilo, A., Sedmak, A., Burzić, Z., & Perković, S. (2019). Fracture mechanics and fatigue crack propagation in armor steel welds. *Engineering Failure Analysis*, *106*, 104155. https://doi.org/10.1016/j.engfailanal.2019.104155

Department of Defense. (2014). *MIL-DTL-46100E: Detail specification — Armor plate, steel, wrought, high-hardness*. Defense Standardization Program.

Guo, H., Wan, J., Liu, Y., & Hao, J. (2018). Experimental study on fatigue performance of high strength steel welded joints. *Thin-Walled Structures*, *131*, 45–54. https://doi.org/10.1016/j.tws.2018.06.023

Qiao, K., Liu, Z., Sun, Z., & Wang, X. (2023). Effects of low temperature overload and cycling temperature on fatigue crack growth behavior of ship steels in Arctic environments. *Ocean Engineering*, *289*, 116278. https://doi.org/10.1016/j.oceaneng.2023.116278

Savić, V., & Cabrilo, A. (2021). Effect of heat input on the ballistic performance of armor steel weldments. *Materials*, *14*(13), 3617. https://doi.org/10.3390/ma14133617

Saxena, A., Kumaraswamy, A., Madhusudhan Reddy, G., & Madhu, V. (2018). Influence of welding consumables on tensile and impact properties of multi-pass SMAW Armox 500T steel joints vis-à-vis base metal. *Defence Technology*, *14*(3), 188–195. https://doi.org/10.1016/j.dt.2018.01.005

Sedmak, A. (2018). Computational fracture mechanics: An overview from early efforts to recent achievements. *Fatigue & Fracture of Engineering Materials & Structures*, *41*(12), 2438–2474. https://doi.org/10.1111/ffe.12912

Suresh Kumar, T., Nagesha, A., & Kannan, R. (2019). Thermal cycling effects on the creep-fatigue interaction in type 316LN austenitic stainless steel weld joint. *International Journal of Pressure Vessels and Piping*, *178*, 104009. https://doi.org/10.1016/j.ijpvp.2019.104009

Wang, Y., Liu, J., Hu, J., Garbatov, Y., & Guedes Soares, C. (2021). Fatigue strength of EH36 steel welded joints and base material at low-temperature. *International Journal of Fatigue*, *142*, 105896. https://doi.org/10.1016/j.ijfatigue.2020.105896

Zhu, X., & Liu, Y. (2023). Low temperature effect on the mechanical properties of EH36 with strain rates. *Journal of Marine Science and Engineering*, *11*(3), 678. https://doi.org/10.3390/jmse11030678

UTICAJ ZAMORA METALA NA POUZDANOST OKLOPA BORBENIH VOZILA U USLOVIMA EKSTREMNIH TEMPERATURNIH OSCILACIJA

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Sažetak: Pouzdanost oklopnih sistema borbenih vozila u operativnim uslovima koji uključuju značajne temperaturne varijacije predstavlja ključni aspekt vojnotehničke nauke. Ovaj rad istražuje kompleksne mehanizme kojima termičke oscilacije utiču na procese zamora metala u oklopnim čelicima visoke tvrdoće, sa posebnim naglaskom na zavarene spojeve koji predstavljaju kritična mjesta za inicijaciju i propagaciju pukotina. Metodološki pristup obuhvatio je sistematsku analizu objavljenih eksperimentalnih podataka iz relevantne naučne literature, uz primjenu principa mehanike loma i teorije termomehaničkog zamora. Rezultati ukazuju na značajnu temperaturnu osjetljivost parametara zamora kod oklopnih čelika, pri čemu udarna žilavost na temperaturi od -40°C opada za približno 47% u poređenju sa vrijednostima na sobnoj temperaturi. Prag faktora intenziteta naprezanja za osnovni metal oklopnog čelika klase 500 HB iznosi ΔKth = 13,4 MPa·m^(1/2), dok zona uticaja toplote i metal zavara pokazuju niže vrijednosti praga od 12,6 MPa·m^(1/2) i 10,1 MPa·m^(1/2), respektivno. Termičko cikliranje dodatno doprinosi akumulaciji oštećenja kroz mehanizme koji uključuju nekompatibilnost termičkog širenja različitih mikrostrukturnih faza, razvoj zaostalih naprezanja i promjene mehanizama plastične deformacije. Zaključeno je da ekstremne temperaturne oscilacije značajno kompromituju integritet oklopnih struktura, te da projektovanje vojnih vozila mora uzeti u obzir sinergijski efekat mehaničkog opterećenja i termičkih ciklusa.

Ključne riječi: *zamor metala, oklopni čelik, borbena vozila, temperaturne oscilacije, meha-nika loma, zavareni spojevi.*