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MECHANICAL PROPERTIES OF A POLYURETHANE-BASED COMPOSITE MODIFIED WITH BORON NITRIDE

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Abstract. In this study, a novel polyurethane (PU) based composition was developed for the first time, characterized by the incorporation of a minimal amount of additives (0.05 wt%), which significantly enhanced the mechanical properties and structural compatibility with high-density polyethylene (HDPE). The effect of the inorganic additive boron nitride (BN) on the physico-mechanical properties and structural behavior of PU was investigated under various external influences, including temperature, electrical discharges, and mechanical stress. The concentration of BN in the PU composition ranged from 0.01 to 0.1 wt%. The results demonstrated that a BN content of 0.05 wt% in the PU matrix was optimal, leading to an approximately 15% increase in the mechanical strength of the resulting film. Experimental findings indicate that this enhancement in strength is associated with changes in the supramolecular structure of the material. While the activation energy of mechanical stress (U) and its intrinsic value (U_0) remained unchanged for both unmodified and BN-modified PU, the addition of BN at the optimal concentration altered the structural sensitivity coefficient (α). This modification reflects a shift in the structural responsiveness of the polymer and a corresponding improvement in mechanical strength (σ).

Keywords: polyurethane, composite, durability, boron nitride, activation energy.
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1 Introduction

The rapid advancement of technology necessitates the development and application of new materials with enhanced properties, as well as the investigation of their physical characteristics (Wang et al., 2012; Mehrabova et al., 2022). Currently, polymer composite materials are widely utilized across various sectors due to their versatile properties.

The broad adoption of polymeric materials for technical applications is largely attributed to their favorable structural and mechanical characteristics, which in some cases are comparable to those of metals, while offering the additional advantage of low density. These materials also enable substantial tunability of physico-mechanical properties through the incorporation of various fillers.

Among these, polyurethane (PU) stands out as a promising polymer for the production of components used in personal electric transport. The application of elastomers - particularly polyurethane - in manufacturing can contribute to significant cost reductions in the production of electric transport systems.

Polyurethanes exhibit a wide range of diverse properties. They can exist in forms ranging from viscous liquids to solid materials, and from amorphous to crystalline structures. Their

hardness can vary from the elasticity of soft, highly elastic rubbers to the rigidity of hard plastics. Among these, polyurethane elastomers are of particular practical interest due to their high tensile strength, excellent tear resistance, favorable dielectric and mechanical properties, wear resistance, and durability against ozone and radiation exposure. In terms of certain physico-mechanical parameters, polyurethanes not only outperform all types of rubbers and elastomers but in some cases even surpass metals. They impart a unique combination of properties to products that are unattainable with conventional rubber materials.

Saddique et al. (2024) explores the mechanical behavior of polyurethane-based composite materials as a function of filler content. It has been demonstrated that aramid fibers represent a highly promising reinforcing filler, capable of significantly enhancing the tensile strength of polyurethane matrices. Additionally, in recent years, there has been growing interest in low-filled polymer systems - those incorporating minimal filler content - as a strategy to achieve improved physical, mechanical, and electrical performance (Fajardo et al., 2016; Das et al., 2020).

The study of the temperature-time dependence of polymers is one of the fundamental approaches for investigating their mechanical and electrical properties. Such studies enable the identification of the kinetic mechanisms underlying mechanical failure and provide insight into the rupture processes, the role of chemical bonds, and the magnitude of the activation energy required to break those bonds (Burdikova et al., 2020; Hasanov et al., 2001). Of particular importance is the investigation of how various external factors influence the temperature dependence of a polymers tensile strength (σ_{pr}), especially since polymeric dielectrics are often subjected simultaneously to mechanical loads, radiation, electric fields, and elevated temperatures in many practical applications.

Polyurethanes are widely used in both mechanical and electrical engineering due to their versatile properties. However, they also present certain limitations, such as relatively low mechanical strength and the tendency to accumulate residual plastic deformation under prolonged mechanical stress.

The experimental data obtained in this study may serve as a foundation for the development of new polyurethane-based composite materials, which could be applied across multiple industrial sectors. These limitations can be addressed by the appropriate selection of organic and inorganic additives. Therefore, the aim of this work is to develop advanced composite polymer materials by investigating the effects of additive type (e.g., powders, fibers) and concentration on the mechanical and structural properties of polyurethane.

In this work, experimental results are presented on the temperature-time dependence of the mechanical strength of polyurethane films and the effect of boron nitride (BN) additives on these characteristics. This research provides a fundamental approach for investigating the kinetic nature of mechanical failure, enabling conclusions about the fracture mechanism, the role of chemical bonding, and the activation energy required for bond rupture.

2 Experimental Methodology

Polyurethane (PU) grade SKU PFL-100 (chemical formula [3/4A 3/4 OCOHN 3/4 A' - NHCOO 3/4]) with a tensile strength limit of 21 MPa, was chosen as a research object. Boron nitride (BN), a binary compound of boron and nitrogen (resulting from the reaction of boron oxide B_2O_3 with ammonia NH_3), was used as an additive. BN disperses well in melts and pasty compositions. BN does not oxidize in oxygen at temperatures up to ∼700°C. It is known that BN is used as a filler to improve mechanical and electrical properties, thermal conductivity, and can function without lubrication in electrical insulation materials, particularly in the insulation of electrical machines. The size of the additive was less than 50μm.

Additives in the amount of 0,01-0,1wt% by weight were introduced into the raw PU material through mechanical mixing in the melt, a method commonly used due to its simplicity and ease of industrial application. Experimental studies showed that increasing the filler content

beyond a certain point leads to the formation of various heterogeneities and deterioration of the dielectric and mechanical properties. This indicates a non-monotonic relationship between the polymer's characteristics and filler content, proving the effectiveness of very small amounts of additives (0,01-0,1 wt%). The samples for the study were prepared in the form of films with a thickness of $50 - 60\mu$m by pressing on a PG-60 hydraulic press.

Prior to introducing the additive into the polyurethane (PU) matrix, boron nitride (BN) was dispersed using sieve analysis to determine and standardize particle size. The sieve analysis apparatus comprises a vibratory drive and a set of sieves selected to span the full range of particle sizes present in the bulk material, typically involving 5 to 6 sieves. A sieve pan is placed at the bottom of the setup to collect the finest fraction of the material. The vibratory drive generates both vibration and shaking motions, ensuring efficient particle separation as the sieves are securely mounted on the device. The sieving duration is generally set to 10 minutes for coarse particles and up to 20 minutes for fine materials, with timing controlled via an integrated timer.

The results of multiple experimental investigations, including mechanical, dielectric, optical, and structural analyses, confirmed the homogeneous dispersion of BN particles within the polyurethane matrix, validating the effectiveness of the preparation method.

The uniformity of the film was determined by measuring the thickness across its entire area. The thickness of the films was measured using an optical thickness gauge N3B-2, as well as a micrometer. The thickness value of the sample represents the arithmetic mean of 10 measurements. For mechanical strength testing, the samples were prepared in a double-blade shape with dimensions of 22 mm in length and 2 mm in width. The mechanical durability (σ), defined as the time elapsed from the application of load to the point of sample rupture under various load levels, was measured at room temperature (22 °C) using a tensile testing machine (Fig. 1). This equipment is designed for testing small-sized specimens and enables the application of a constant tensile stress until failure occurs. The tests were conducted at a clamping speed of 1 mm/min, with a permissible error margin of ±0.3 mm/min.

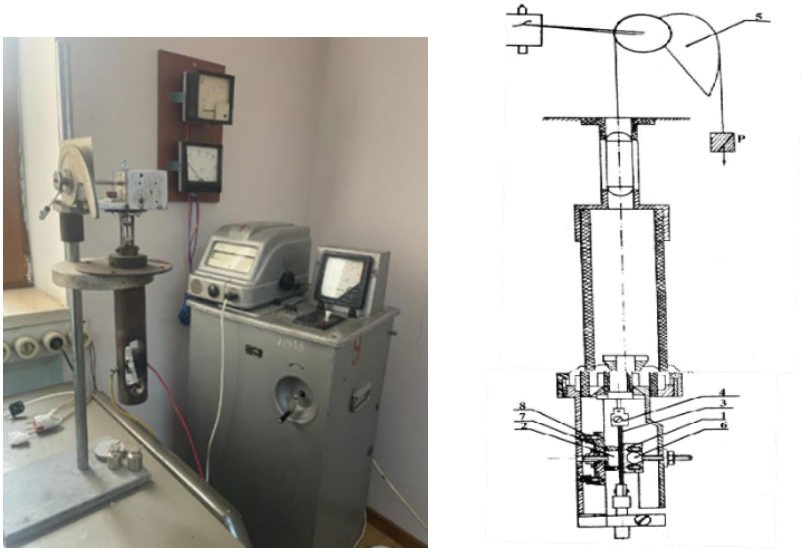

Figure 1: Installation for determining the electrical and mechanical strength of polymer film materials: 1, 2- electrodes; 3- sample; 4- clamps; 5- lever device; 6- ball; 7- safety ring; 8- springs

3 Results and Discussion

Figure 2 presents typical graphs illustrating the logarithmic dependence of durability time (lg $\tau\sigma$) on the applied mechanical stress for polyurethane (PU) films both without additives and with varying concentrations of boron nitride (BN) in the range of 0.01–0.1 wt%. Each data point on the graphs represents the average of 5 to 8 repeated measurements to ensure statistical reliability. As shown in Figure 2, all studied materials exhibit a time-dependent mechanical strength behavior, and the relationship between durability and applied stress follows an exponential trend. (Zhong et al., 2025; Mammadov et al., 2024).

$$\tau - Ae^{-\alpha\sigma} \tag{1}$$

where A - is the coefficient, and α - is the structural sensitivity coefficient, both of which depend on the nature of the material being studied and the test temperature.

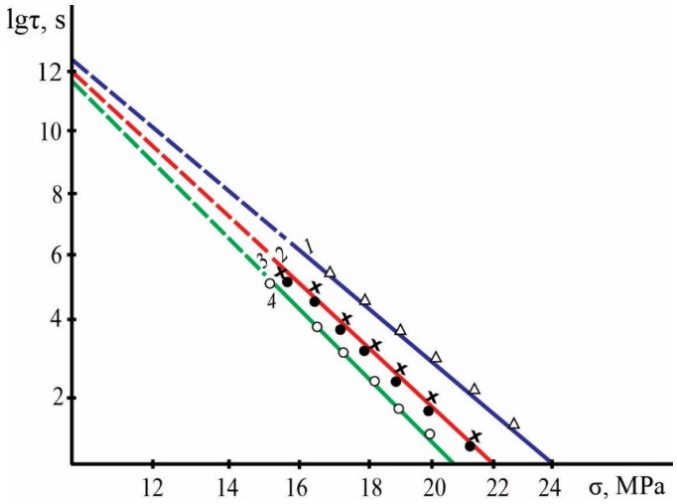

Figure 2: Force dependencies of the mechanical durability of PU films: $1 - PU + 0,05wt\%BN$, $2 - PU(initial)$, $3 - PU + 0,03wt\%BN$, $4 - PU + 0,1wt\%BN$

From Figure 2, it is evident that the introduction of a small amount of boron nitride (BN) into the polyurethane (PU) matrix leads to a noticeable increase in its mechanical strength. Specifically, the addition of 0.05 wt% BN (line 1) results in a significant improvement in the strength properties of PU compared to both the unmodified PU (line 2) and the sample containing 0.03 wt% BN (line 3). However, when the BN content is further increased to 0.1 wt% (line 4), a sharp decrease in mechanical strength is observed.

Based on the experimental results, it can be concluded that the observed enhancement in the mechanical strength of the PU film with the addition of 0.05 wt% BN is associated with changes in the structural sensitivity coefficient, denoted as α. This coefficient depends not only on the inherent nature of the material but also significantly on its supramolecular structure. As noted in earlier studies (Mehrabova et al., 2025; Slutsker, 2008), the physical meaning of the coefficient α lies in its representation of the volume in which the elementary act of converting potential and mechanical energy into thermal energy takes place. According to the theoretical model, mechanical failure is initiated by energy fluctuations arising from thermal motion, with the applied mechanical stress serving to lower the potential barrier, thereby facilitating the transition from the pre-failure to the post-failure state.

According to the experimental results obtained, the introduction of the optimal concentration of boron nitride (BN) into the polyurethane (PU) matrix leads to an increase in mechanical strength by more than 15%. The optimal additive concentration is application-specific and depends on the functional requirements of the polymer system. Therefore, when incorporating

organic or inorganic additives, it is recommended to determine the optimal content through systematic testing across a range of concentrations. In this study, multiple experimental evaluations of the physico-mechanical properties confirmed the effectiveness of using 0.05 wt% BN as an optimal additive.

It is well established that the linear dependence of lg τ (logarithm of durability time) on applied mechanical stress σ holds true even at varying temperatures (Kerimov et al., 2023; Boubakri et al., 2010). Long-duration mechanical tests were conducted to investigate the temperature-time dependence of the mechanical strength of the developed materials. Based on the results, semi-logarithmic plots were constructed to characterize the relationship between the time to failure and the magnitude of applied mechanical stress.

From a practical standpoint, evaluating mechanical durability across a wide temperature range is particularly valuable. To this end, the stress-dependent durability of PU films—both unmodified and modified with the optimal BN content—was studied within the temperature range of 223–138 K (Zhong et. al., 2024; Yankevich et al., 2023).

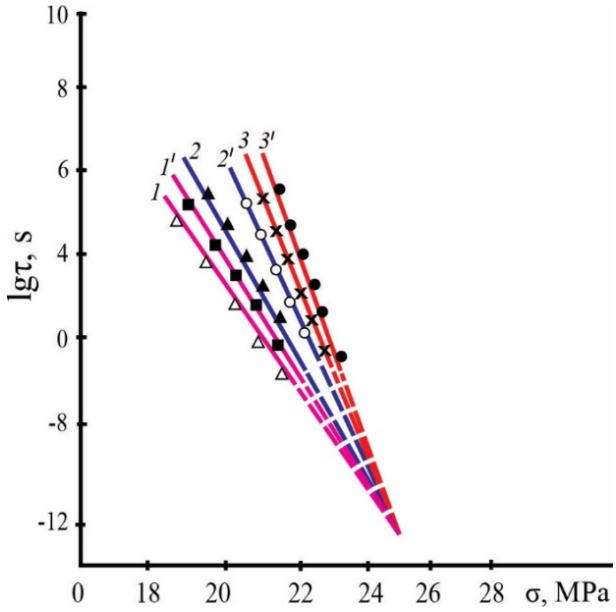

Figure 3: Force dependencies of the durability of PU film (1-3) and its optimal modification with 0.05 wt% BN (1'-3') at various temperatures. 1, 2' - 173 K; 2 - 153 K; 3, 3' - 138 K; 1' - 223 K.

Figure 3 demonstrates that within the investigated temperature range, the well-known durability equation (1) holds for all films at constant temperature. Experimental results indicate that introducing the optimal amount of boron nitride (PU + 0.05 wt% BN) into the polyurethane matrix leads to a notable enhancement in mechanical strength (line 1′), although a slight reduction in lifespan is observed across different temperatures (lines 2′, 3′). In contrast, the unmodified PU films exhibit reduced mechanical strength with increasing temperature, as illustrated by lines 1, 2, and 3. In contrast, the unmodified PU films exhibit reduced mechanical strength with increasing temperature, as illustrated by lines 1, 2, and 3. The variation in mechanical strength with temperature for both pure PU and its modified counterpart is represented by a fan-shaped family of curves. When extrapolated, these lines converge at a single intersection point—referred to as the pole—corresponding to a specific durability value of $\tau_\sigma = 10^{-2}$s. This convergence suggests that the observed increase in mechanical strength of the modified PU with the optimal content (0,05 mass% BN) is likely due to structural changes induced by the additive. These changes may influence molecular mobility and energy dissipation processes, thereby enhancing the material's resistance to deformation and failure under stress.

The experimental data shown in Figure 3 were further used to construct the temperature

dependence of mechanical durability in the coordinates $\lg\tau_\sigma = f(1/T)$ at constant stress σ. These relationships are presented in Figure 4, which displays the logarithmic durability versus inverse temperature for both PU and its BN-modified variant at several fixed stress levels.

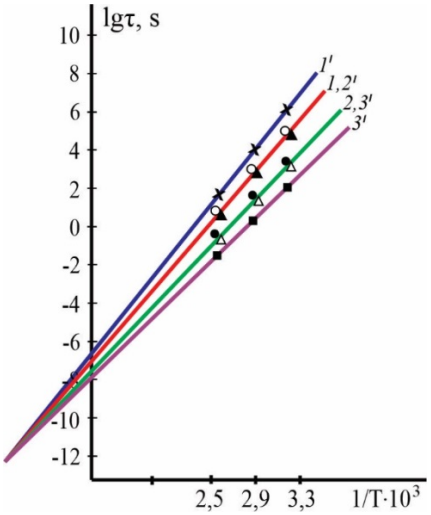

Figure 4: Dependence of the durability of PU films (1-3) and PU + $0,05wt\%BN(1'-3')$; $1,1'-\sigma = 10MPa$, $2,2'-\sigma = 11MPa$, $3,3'-\sigma = 12MPa$

Figure 4 shows that the lines corresponding to different values of mechanical stress (σ) intersect at a point on the ordinate axis when extrapolated to 1/T = 0. The time corresponding to this intersection defines the pre-exponential factor τ_0, which was found to be approximately $\sim 10^{-12}$ seconds for both pure PU and PU modified with 0.05 wt% boron nitride (BN).

It is well established that the functional relationship between durability τ, mechanical σ, and temperature T (K) is described by the following well-known equation (Hajieva, 2021; Boubakri et. al., 2010):

$$\tau = \tau_0 e \frac{U_0 - \alpha\sigma}{KT} \tag{2}$$

where τ (sec)- is the durability; $\tau_0(sec) - s$ the oscillation period of atoms in a solid, U_0 ($\frac{kcal}{mol}$)- effective activation energy, characterizing the process of mechanical rupture, α $\left(\frac{\text{kcal}}{\text{mol}} \cdot MPa^{-1}\right)$- is the structural- sensitivity coefficient, k- is the Boltzmann constant, σ (MPA) - is the stress, $T(K)$ - is the temperature. The value $U_0 - \alpha\sigma$ is referred to as the activation energy of the mechanical rupture process (U).

To determine the intrinsic activation energy U_0 of the fracture process, it is essential to maintain constant structural conditions for the development of thermal fluctuation activity within the studied ranges of temperature and stress. To this end, by selecting specific stress value $(\sigma_1, \sigma_2, \sigma_3)$ the dependence of $lg\tau(\sigma)$ can be transformed into a dependence of $lg\tau(10^3/T)$. Considering this transformation, the activation energy of the fracture process was calculated using formula (2), which can be expressed in the following form:

$$U = U_0 - \alpha\sigma = 2,3(lg\tau - lg\tau_0) \tag{3}$$

where U- is the energy characteristic associated with the fracture process. Fig.5 presents the dependence of the activation energy U_0 on the rupture stress σ. The data demonstrate that the activation energy decreases with increasing mechanical stress, indicating that higher stresses facilitate the fracture process by lowering the energy barrier required for bond rupture.

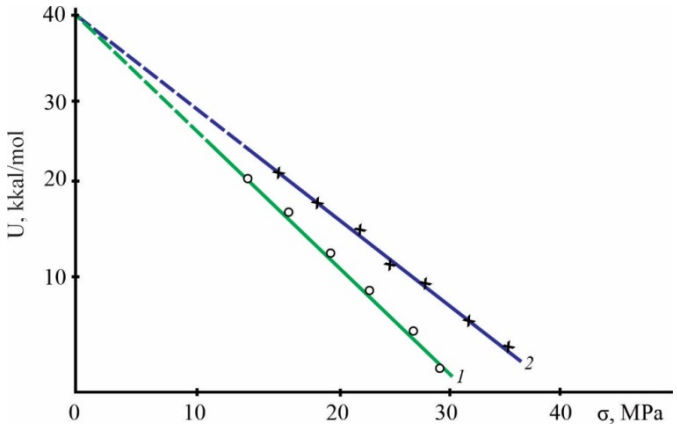

Figure 5: Dependence of the activation energy U_0 of mechanical rupture on stress for PU films: (1) PU + 0.05 wt% BN (optimal modification); (2) unmodified PU.

It can be seen from Figure 5, that all data points corresponding to different temperatures lie on a same straight line, expressed by the equation $U = U_o - \alpha\sigma$, which characterizes the activation energy of the mechanical rupture process. In this expression, U_0 represents the activation energy at zero applied stress and is determined by extrapolating the linear dependence U=f(σ) at $\sigma = 0$ ($U_0 = 2,3kTlg\frac{\tau_0}{\tau}$).

The value of U_0 characterizes the energy required to break the bonds during material failure. For PU films, the values of U_0 ranged from 35 to 46 kcal/mol, which corresponds to the energy of chemical bonds (Zeynalov et al., 2023; Mahat et al. 2016). The structurally sensitive coefficient α, determined from the slope of the $U=f(\sigma)$, (α = 2,3 kTtgα) varies between the original PU film and its optimal modification, indicating differences in structural response under stress.

The obtained values of τ_0, U_0 and α for the PU film and its optimal modification are summarized in Table 1. For comparison, the values of mechanical strength σ for both films at $lg\tau = 0$, T = const are also included.

Table 1: Values of U_0, α, τ_0 and σ for PU and its optimal modification

Material	τ_0 (sec)	$U_0, \frac{kcal}{mol}$	$\alpha\left(\frac{\text{kcal}}{\text{mol}} \cdot MPa^{-1}\right)$	σ, MPa at 163 K
PU (original)	10^{-12}	38	0,102	22
PU + 0,05 mass% BN	10^{-12}	38	0,091	24,5

As shown in Table 1, the coefficients U_0 and τ_0 remain constant in both cases and are unaffected by the addition of the BN additive to the PU matrix. However, the additive significantly influences the value of the structural coefficient α and, consequently, the mechanical strength (durability) of the PU. Specifically, a decrease in strength corresponds to an increase in α, whereas a reduction in α results in improved mechanical strength of the material.

For solid polymers, U_0 is typically associated with the energy required to break chemical bonds within the polymer chain. Therefore, in cases where the chemical structure of the polymer remains unchanged, the activation energy U_0 should also remain constant. The observed changes in mechanical strength under various conditions, reflected in the variation of the structurally sensitive coefficient α, suggest alterations in the physical, rather than chemical, structure of the material. These structural changes are primarily attributed to modifications in the supramolecular organization, particularly the nature and density of intermolecular bonds.

Thus, the influence of external factors, such as additive incorporation, alters the mechanical strength properties not by changing the intrinsic chemical bonds, but by affecting the extent of their mechanical loading and the overall structural configuration of the polymer.

These findings support the assertion that the rupture mechanism of polyurethane (PU), both with and without the BN additive, primarily involves the breaking of the same chemical bonds (Mirzadeh et al., 2022; Kosyanchuk et. al., 2017). Consequently, the introduction of the BN additive in an optimal amount leads to a significant enhancement in the mechanical strength of the PU film, while the value of the activation energy U_0 remains unchanged. This constancy in U_0 reinforces the conclusion that failure occurs through the disruption of chemical, rather than intermolecular bonds.

Therefore, the observed increase in mechanical strength upon the incorporation of 0.05 wt% BN into the PU matrix is most plausibly attributed to the formation of a more stable supramolecular structure. Such a structure enhances the load-bearing capacity of the material without altering its fundamental chemical framework (Mehrabova et al., 2024; Zeynalov et al., 2024).

3.1 Conclusion

The influence of a small amount of inorganic additive, boron nitride BN, on the mechanical strength of PU has been systematically investigated across a range of temperatures. It was established that the incorporation of BN at an optimal concentration of 0.05 wt% leads to a significant enhancement in the mechanical strength of PU films under all tested conditions. This improvement is not accompanied by changes in the activation energy of mechanical rupture U_0, which remains constant for both unmodified and modified PU films. The invariance of U_0 suggests that mechanical failure continues to occur via the rupture of chemical bonds within the polymer chains.

Importantly, the observed increase in strength is attributed to a reduction in the structurally sensitive coefficient α, indicating that the mechanical performance of the material is governed by physical, rather than chemical, changes in its supramolecular structure. Specifically, an inverse relationship between mechanical strength and α was confirmed: as mechanical strength increases, the value of α decreases, and vice versa. These findings confirm that the additive enhances the material's structural organization at the molecular level, improving its load-bearing capacity without altering its fundamental chemical integrity.

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