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INFLUENCE OF TECHNOLOGICAL FACTORS ON THE TRIBOLOGICAL NATURE OF METAL MATRIX NANOCOMPOSITES

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Abstract:

This paper investigates the influence of technological factors on the tribological behavior of metal matrix nanocomposites. The study focuses on the relationship between fabrication technology, thermomechanical conditions, and friction and wear processes occurring during sliding contact. Experimental tribological tests demonstrate that nanophase-reinforced metal matrix composites exhibit significantly lower friction coefficients and wear rates compared to the base metal. An increase in nanophase content leads to improved friction stability and promotes the formation of protective tribological layers on the contact surface. Microstructural observations reveal a reduction in the thickness of the plastically deformed surface layer and a limitation of deformation propagation into the bulk material. The results indicate that the tribological performance of metal matrix nanocomposites is governed not only by material composition but also by processing conditions and surface evolution during friction. These findings

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provide a scientific basis for the design of wear-resistant materials for tribologically demanding applications.

Keywords: Metal matrix nanocomposites; tribology; friction coefficient; wear behavior; nanophases; processing factors.

Annotatsiya:
Ushbu maqolada metall matritsali nanokompozitlarning tribologik tabiatiga texnologik omillarning ta'siri tizimli ravishda tahlil qilinadi. Tadqiqotda nanofazalar bilan mustahkamlangan metall matritsali kompozitlarning ishqalanish va yeyilish xatti-harakati ishlab chiqarish texnologiyasi, termomekanik sharoitlar hamda ishqalanish jarayonida shakllanadigan sirt qatlamlari bilan bog'liq holda o'rganildi. O'tkazilgan tribologik sinovlar natijalari sof metallga nisbatan nanokompozitlarda ishqalanish koeffitsienti va yeyilish tezligining sezilarli darajada kamayishini ko'rsatdi. Nanofaza miqdorining oshishi ishqalanish jarayonining barqarorlashuviga va himoya tribo-qatlamlarning shakllanishiga olib kelishi aniqlandi. Mikrostrukturaviy kuzatuvlar sirt qatlamida plastiklikka uchragan zonaning yupqaroq bo'lishini va deformatsiyaning chuqur tarqalishining cheklanishini tasdiqladi. Olingan natijalar metall matritsali nanokompozitlarning tribologik samaradorligini oshirishda texnologik omillarni kompleks tarzda tanlash muhim ahamiyatga ega ekanligini ko'rsatadi.

Kalit so'zlar: metall matritsali nanokompozitlar; tribologiya; ishqalanish koeffitsienti; yeyilish; nanofazalar; texnologik omillar.

Аннотация:
В данной статье рассматривается влияние технологических факторов на трибологическую природу металлических матричных нанокомпозитов. Исследование направлено на установление взаимосвязи между технологией

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получения, термомеханическими условиями и процессами трения и изнашивания в нанокомпозитных материалах. Экспериментальные трибологические испытания показали, что введение нанофаз в металлическую матрицу приводит к снижению коэффициента трения и скорости износа по сравнению с исходным металлом. Установлено, что увеличение объемной доли нанофаз способствует стабилизации процесса трения и формированию защитных трибологических слоёв на поверхности. Микроструктурный анализ выявил уменьшение толщины пластически деформированного слоя и ограничение глубины деформации. Полученные результаты свидетельствуют о том, что трибологические свойства металлических матричных нанокомпозитов в значительной степени определяются не только составом материала, но и технологическими условиями его формирования. Работа представляет практический интерес для разработки износостойких материалов.

Ключевые слова: металлические матричные нанокомпозиты; трибология; коэффициент трения; износ; нанофазы; технологические факторы.

INTRODUCTION

Metals and alloys are widely used as primary structural materials in modern mechanical engineering and industrial technologies. Due to the presence of multiple slip planes in their crystal structure and a system of free electrons, these materials exhibit high plasticity and are easily deformed under mechanical loading [1]. Although these characteristics make metals technologically convenient materials, they also lead to serious tribological problems during service conditions [2].

The relatively low hardness of metals and alloys and their sensitivity to chemically active environments increase their susceptibility to friction and wear. Intensive wear occurring in bearings, piston mechanisms, mechanical joints,

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pumps, and other components exposed to friction results in a sharp increase in maintenance costs, a decrease in energy efficiency, and an intensification of environmental burdens associated with the replacement of worn parts [3]. Therefore, the development of metal materials with high wear resistance or the ability to exhibit tribologically adaptive behavior during operation is considered one of the most pressing scientific and technological challenges [4].

One of the promising approaches to addressing this problem in recent years is the development of metal matrix nanocomposite materials. These materials are obtained by combining a metal or alloy matrix with reinforcing phases in the nanometer size range. The fact that at least one dimension of the reinforcing components lies within the nanometer scale fundamentally distinguishes their strengthening mechanisms from those of conventional metal matrix composites containing micron-sized fillers [5]. As a result, such nanocomposites offer the possibility of mitigating the traditional trade-off between strength and ductility [6].

Theoretical and experimental studies indicate that the introduction of nanoscale phases into a metal matrix effectively restricts dislocation motion, activates load transfer mechanisms, and promotes the formation of deformation-resistant structures in the surface layer [7]. These synergistic effects are particularly significant under friction and wear conditions, leading to a substantial improvement in the tribological performance of metal matrix nanocomposites.

Various types of nanophases are employed in metal matrix nanocomposites designed for tribological applications [8]. These include hard particles belonging to carbide, boride, nitride, oxide, and sulfide groups, as well as carbon-based materials with unique size- and structure-dependent characteristics. Such nanophases perform reinforcing, load-bearing, or friction-reducing functions within the metal matrix. In particular, the lubricating properties of certain nanophases facilitate the formation of protective layers during operation, thereby reducing the wear rate [9].

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METHODS AND METHODOLOGY

Metals and alloys are widely used as primary structural materials in modern mechanical engineering and industrial technologies. Due to the presence of multiple slip planes in their crystal structure and a system of free electrons, these materials exhibit high plasticity and undergo easy deformation under mechanical loading [10]. While these properties make metals technologically advantageous materials, they also give rise to serious tribological problems during service.

The relatively low hardness of metals and alloys, along with their sensitivity to chemically active environments, increases their susceptibility to friction and wear [11]. Intensive wear occurring in bearings, piston mechanisms, mechanical joints, pumps, and other components subjected to friction leads to a significant increase in maintenance costs, a reduction in energy efficiency, and an intensification of environmental burdens associated with the replacement of worn parts. Therefore, the development of metal materials with high wear resistance or the ability to exhibit tribologically adaptive behavior during operation represents one of the most urgent scientific and technological challenges [12].

In recent years, metal matrix nanocomposite materials have attracted considerable attention as one of the promising approaches to addressing this problem. These materials are produced by combining a metal or alloy matrix with reinforcing phases in the nanometer size range [13]. The presence of at least one nanoscale dimension in the reinforcing components fundamentally distinguishes their mechanical strengthening mechanisms from those of conventional metal matrix composites containing micron-sized fillers. As a result, such nanocomposites provide an opportunity to mitigate the traditional trade-off between strength and ductility [14].

Theoretical and experimental studies demonstrate that the introduction of nanoscale phases into a metal matrix effectively restricts dislocation motion, activates load transfer mechanisms, and promotes the formation of deformation-resistant structures in the surface layer. These synergistic effects are particularly

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important under friction and wear conditions, significantly enhancing the tribological performance of metal matrix nanocomposites [15].

Metal matrix nanocomposites intended for tribological applications incorporate various types of nanophases. These include hard particles belonging to carbide, boride, nitride, oxide, and sulfide groups, as well as carbon-based materials with unique size- and structure-dependent characteristics. Such nanophases perform reinforcing, load-bearing, or friction-reducing functions within the metal matrix [16]. In particular, the lubricating properties of certain nanophases facilitate the formation of protective layers during operation, thereby reducing the wear rate.

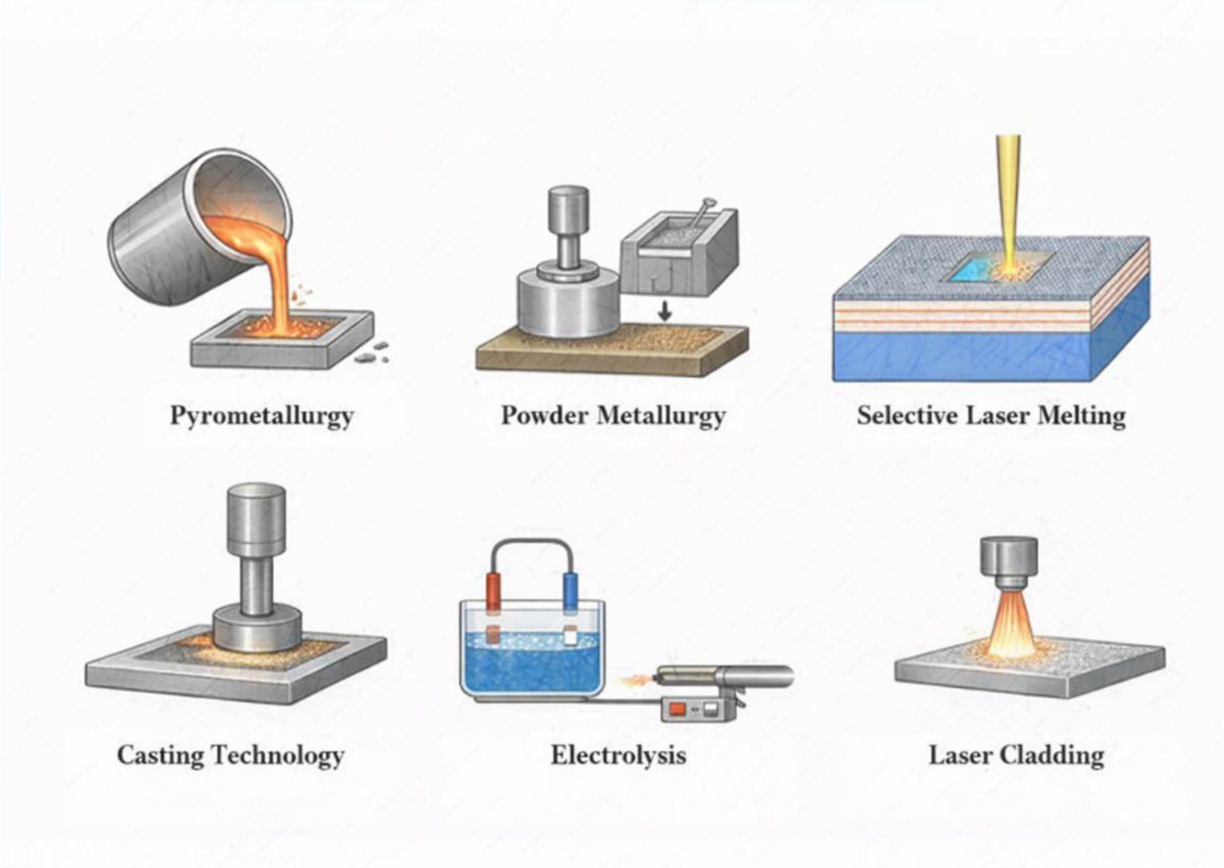

Figure 1. Main technological methods used in the production of metal matrix nanocomposites

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This study is focused on an in-depth analysis of the tribological properties of metal matrix nanocomposites and is aimed at identifying the interrelationship between manufacturing technologies, the resulting microstructural state, and friction and wear processes. Within the research approach, the behavior of the material under service conditions was considered not as a simple combination of isolated factors, but as a complex system of interrelated phenomena. Such a perspective makes it possible to go beyond a purely experimental description of tribological performance and to reveal the underlying physical and mechanical mechanisms governing the behavior of metal matrix nanocomposites [17].

During the study, the fundamental scientific hypothesis was that the friction and wear resistance of metal matrix nanocomposites are primarily determined by the microstructural state formed during the manufacturing process. In this context, the effects of various technological methods on the distribution of nanophases, grain size, the bonding condition between the matrix and reinforcing phases, and the mechanical stability of surface layers were conceptually analyzed [18]. These factors were regarded as the main causes determining whether plastic deformation, abrasive wear, or adhesive wear mechanisms dominate or are suppressed during tribological testing.

The friction process was interpreted from the standpoint of energy exchange, whereas wear was explained as a process associated with the detachment and transfer of material from the surface layer. This approach made it possible to elucidate the complex relationship between the coefficient of friction and the wear rate in metal matrix nanocomposites. In certain cases, an increase in wear rate under conditions of reduced friction coefficient, or the opposite trend, was observed. These phenomena were explained by the stability of tribo-layers formed on the surface, their mechanical strength, and the condition of the interfacial regions.

The load-bearing role of nanophases within the metal matrix was considered one of the key aspects of the study. During deformation, nanophases carry a portion

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of the applied load, thereby reducing the degree of localized plastic deformation in the matrix material. This effect enhances the resistance of the surface layer to damage and contributes to a reduction in the wear rate. At the same time, the formation of dislocation structures around the nanophases and their density were shown to have a significant influence on the stability of the friction process, which was substantiated on a scientific basis [19].

The bonding condition between the matrix and nanophases was evaluated as one of the critical factors governing tribological behavior. In cases of strong interfacial bonding, the detachment of nanophases from the matrix is limited, preventing the intensification of abrasive wear. Conversely, relatively weak interfaces promote the release of nanophases onto the surface, where they participate in the friction process as third-body particles, leading to a more complex wear mechanism [20]. These effects were analyzed in an integrated manner within the overall tribological framework.

In addition, particular attention was paid to the evolution of surface layers during friction, including the formation and degradation of plastically deformed layers, mechanically mixed layers, and tribo-layers. The thickness, continuity, and mechanical stability of these layers were interpreted as the main factors determining whether the friction process proceeds in a stable or unstable manner. These layers were not considered as permanent and unchanged structures, but rather as dynamic systems that continuously form and degrade in response to changing friction conditions.

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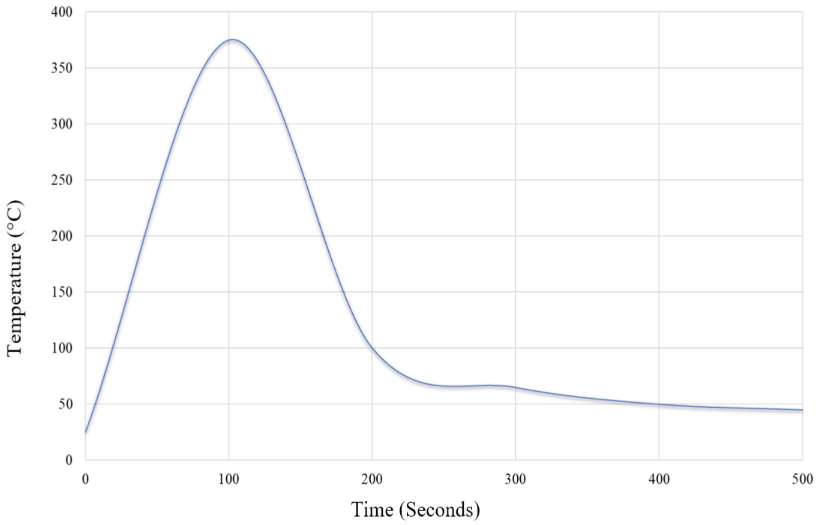

Figure 2. Temperature–time relationship in the surface layer during the friction stir processing.

During the friction stir processing, the temperature evolution in the surface layer is monitored as a function of time, revealing a sharp increase at the initial stage of processing and reaching a maximum value, followed by a gradual decrease due to heat dissipation into the surrounding environment and the base material. This temperature–time profile characterizes the thermomechanical conditions developed throughout the process (Figure 2).

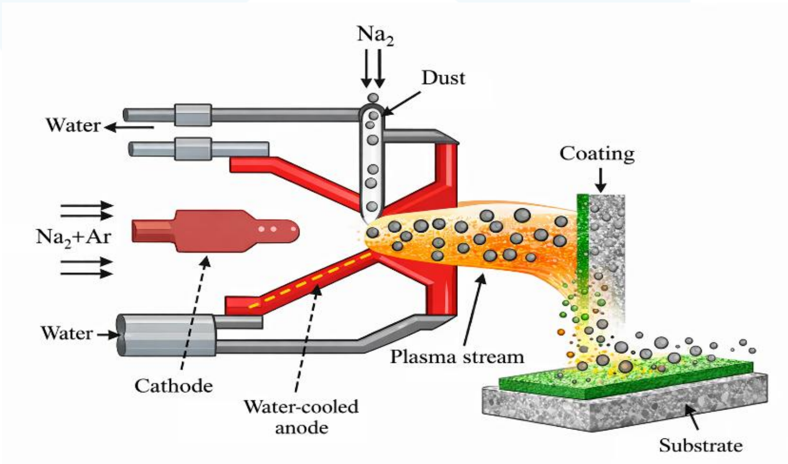

Figure 3. Schematic representation of the reactive plasma spraying process

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In the reactive plasma spraying process, a high-temperature plasma stream generated using a nitrogen–argon gas mixture is employed to direct powder-form material toward the substrate surface. The particles, heated and activated within the plasma flow, impact the substrate and form a dense and homogeneous composite coating, which contributes to improved mechanical strength and enhanced tribological properties of the coating (Figure 3).

RESULTS AND DISCUSSION

The conducted studies demonstrated that the tribological properties of metal matrix nanocomposites are closely related to their manufacturing conditions, the resulting microstructure, and the surface layers formed during the friction process. The obtained results confirm that the coefficient of friction and the wear rate differ significantly between pure metals and materials reinforced with nanophases.

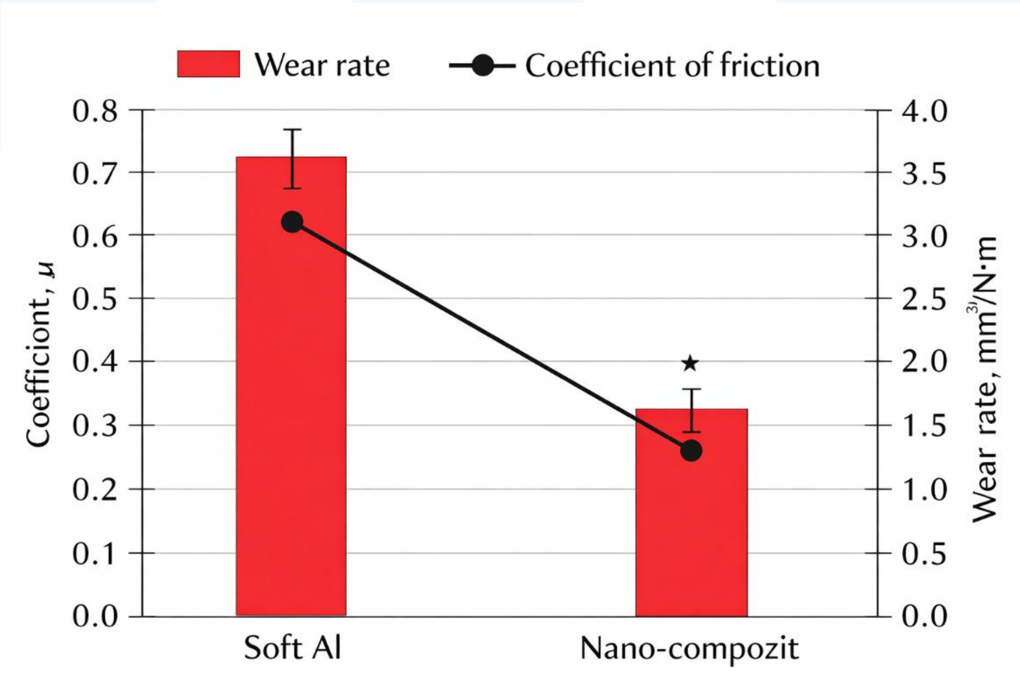

Figure 4. Comparison of the coefficient of friction and wear rate for pure aluminum and metal matrix nanocomposites

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According to the results of the tribological tests, the samples reinforced with nanophases exhibited a relatively stable coefficient of friction during the sliding process. This behavior can be attributed to the formation of protective tribo-layers on the surface as well as the load-bearing function of the nanophases. During friction, nanocomposites showed fewer sharp fluctuations in friction force, indicating a more stable deformation behavior of the surface layer.

The results obtained for the wear rate demonstrated a significant advantage of nanocomposite materials. The presence of reinforcing phases limits the plastic deformation of the matrix material and suppresses the development of abrasive and adhesive wear mechanisms. As a result, the rate of material removal from the surface is reduced and the wear process is slowed down. This observation is further confirmed by surface morphologies obtained after the tribological tests.

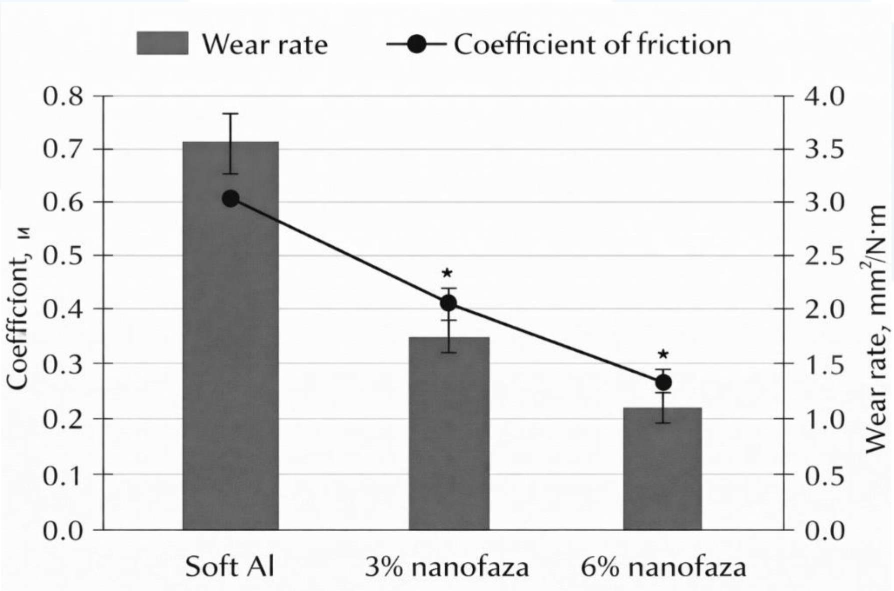

Figure 4. Comparison of the coefficient of friction and wear rate for pure aluminum and metal matrix nanocomposites

Microstructural observations revealed a complex evolution of surface layers during the friction process. In nanocomposites, the plastically deformed surface zone was relatively thinner, and the propagation of deformation into the

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subsurface region was found to be limited. This behavior is associated with the accumulation of dislocations around the nanophases and the more effective distribution of the applied load. At the same time, the mechanically mixed layer and the tribo-layers formed on the surface play an additional protective role during friction.

The thermal conditions inherent to the manufacturing process were also found to have a significant influence on tribological behavior. Temperature–time profiles indicate that high-energy processing leads to the rapid formation of elevated temperatures in the surface layer over a short period. Such thermomechanical conditions promote a more uniform distribution of nanophases within the matrix and enhance interfacial bonding strength. The subsequent cooling stage contributes to the stabilization of the resulting microstructure.

The bonding condition between the matrix and the nanophases emerged as a key factor governing wear mechanisms. Samples with strong interfacial bonding were less prone to nanophase detachment during friction, thereby preventing the intensification of abrasive wear. In contrast, weak interfacial bonding facilitates the release of particles, which act as third-body elements in the friction process and lead to more complex wear mechanisms.

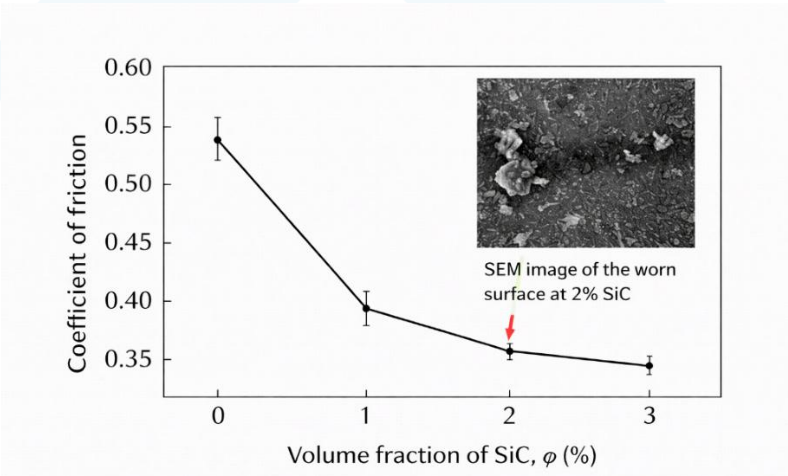

Figure 5. Effect of SiC nanophase volume fraction on the coefficient of friction and the corresponding worn surface morphology

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The obtained results indicate that the tribological properties of metal matrix nanocomposites are governed not only by the material composition, but also by the manufacturing technology and the surface conditions that develop during the friction process. Therefore, achieving high tribological performance requires not only the appropriate selection of the type and content of nanophases, but also a comprehensive consideration of their interaction with the matrix and the thermomechanical conditions of the processing route.

CONCLUSION

This study demonstrated that the tribological behavior of metal matrix nanocomposites is intrinsically linked to the technological factors employed during their fabrication. The experimental results revealed that the coefficient of friction and wear processes are governed not only by the material composition, but also by the manufacturing technology, thermomechanical conditions, and the surface structures formed during sliding.

In metal matrix nanocomposites reinforced with nanophases, high-energy processing promoted a relatively uniform distribution of nanophases within the matrix and enhanced interfacial bonding. This led to the formation of stable protective tribo-layers during friction and resulted in the suppression of abrasive and adhesive wear mechanisms.

Furthermore, variations in technological parameters, particularly processing regimes and thermal effects, had a pronounced influence on the microstructural state of the surface layer. A reduction in the thickness of the plastically deformed zone and a limitation of deformation propagation into the subsurface region were observed, which contributed to the improvement of the tribological performance of the investigated materials.

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