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NUMERICAL INVESTIGATION OF FRICTION EFFECTS ON HOT ROLLING BEHAVIOR OF AA2024 ALUMINUM ALLOY

Review article

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Abstract

This study investigates the effect of friction on the mechanical and thermal characteristics of the hot rolling process of AA2024 aluminum alloy using three dimensional finite element simulations performed in DEFORM-3D. A thermomechanically coupled model incorporating a shear friction law was employed to analyze the influence of different friction conditions on rolling force, stress state, strain distribution, and workpiece temperature. The results indicate that the rolling force increases almost monotonically with increasing friction factor, while the peak compressive stress at the workpiece center remains nearly unchanged, suggesting that friction mainly affects the overall rolling load through contact conditions rather than internal stress levels. Higher friction promotes strain localization at the workpiece edges, increasing the risk of edgerelated defects. In addition, increasing friction leads to a slight rise in the workpiece temperature after rolling due to enhanced frictional heat generation. Based on the simulation results, a moderate friction factor in the range of 0.3–0.5 is recommended to balance rolling load reduction, strain uniformity, and thermal conditions. The findings provide useful guidance for friction control and lubrication selection in industrial hot rolling of AA2024 aluminum alloy.

Keywords: Aluminum alloy AA2024, Hot rolling, Friction coefficient, Finite element simulation, Rolling force.

ЧИСЛЕННОЕ ИССЛЕДОВАНИЕ ВЛИЯНИЯ ТРЕНИЯ НА ПОВЕДЕНИЕ ПРОЦЕССА ГОРЯЧЕЙ ПРОКАТКИ АЛЮМИНИЕВОГО СПЛАВА АА2024

Обзор

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Аннотация

В данной работе исследуется влияние трения на механические и тепловые характеристики процесса горячей прокатки алюминиевого сплава АА2024 с использованием трехмерного численного моделирования методом конечных элементов в программном комплексе DEFORM-3D. Термомеханически связанная модель, основанная на законе сдвигового трения, была применена для анализа влияния различных условий трения на силу прокатки, напряжённое состояние, распределение деформаций и температуру заготовки. Результаты показывают, что сила прокатки практически монотонно возрастает с увеличением коэффициента трения, в то время как максимальное сжимающее напряжение в центральной части заготовки остается почти неизменным. Это указывает на то, что трение в основном влияет на общий уровень прокатной нагрузки за счет контактных условий, а не за счет изменения внутренних напряжений материала. Повышенное трение способствует локализации деформации в краевых зонах заготовки, что увеличивает риск возникновения дефектов, связанных с краями. Кроме того, увеличение коэффициента трения приводит к незначительному повышению температуры заготовки после прокатки вследствие усиленного тепловыделения при трении. На основании результатов численного моделирования рекомендуется использовать умеренное значение коэффициента трения в диапазоне 0,3–0,5, обеспечивающее компромисс между снижением прокатной нагрузки, равномерностью деформации и тепловыми условиями процесса. Полученные результаты могут служить практическим руководством при выборе условий трения и смазочных материалов в промышленной горячей прокатке алюминиевого сплава АА2024.

Ключевые слова: алюминиевый сплав АА2024, горячая прокатка, коэффициент трения, конечно-элементное моделирование, сила прокатки.

Introduction

AA2024 aluminum alloy, which belongs to the Al-Cu-Mg alloy family, is extensively applied in aerospace and transportation structures due to its high strength to weight ratio, good fatigue performance, and resistance to damage [1], [2], [3]. In industrial production, hot deformation processes especially hot rolling are essential not only for shaping the material but also for determining its final properties and process stability.

In hot rolling operations, the interaction between the roll surface and the workpiece inevitably introduces friction, which strongly affects material flow behavior, rolling load, and product quality [4]. Adequate friction is necessary to ensure stable biting conditions, while excessive friction leads to higher rolling forces, increased torque, and additional heat generation. It also contributes to nonuniform distributions of stress and strain, particularly near surface and edge regions. Due to the severe contact conditions, shear-based friction models are commonly adopted instead of classical Coulomb formulations in bulk forming simulations [4], [5].

Recent research has emphasized that lubrication and tribological conditions play a crucial role in controlling friction and improving process performance during hot rolling operations [6]. At the same time, tribological mechanisms at elevated temperatures remain essential for understanding the complex interactions between contacting surfaces, including adhesion, wear, and thermal effects [7], [8]. Furthermore, numerical and experimental studies have shown that contact conditions significantly influence the coupled thermomechanical response of the material during deformation processes [9].

A growing number of recent studies have focused on the influence of process parameters on deformation behavior and material performance in aluminum alloys. For instance, rolling parameters and deformation conditions have been shown to strongly affect material flow and surface integrity [10], [11]. Advanced thermomechanical processing routes, including combined forming techniques, have also been explored to enhance the microstructure and mechanical properties of aluminum alloys such as AA2024 [12], [13], [14]. In addition, the role of friction-related phenomena in modifying surface conditions and material response during deformation has been highlighted in recent investigations [15].

Despite these developments, many previous works have mainly addressed isolated aspects such as rolling force, lubrication conditions, or microstructural evolution. Comprehensive studies focusing on the combined influence of friction on internal mechanical and thermal responses such as stress distribution, strain localization, and temperature evolution remain limited, particularly for AA2024 aluminum alloy. A more integrated understanding of these coupled effects is necessary for improving process control and minimizing defects in industrial rolling operations.

Therefore, the present work aims to investigate the effect of friction on the mechanical and thermal behavior of AA2024 aluminum alloy during hot rolling using a three dimensional thermomechanically coupled finite element model implemented in DEFORM-3D. The influence of different friction conditions on rolling force, stress state, strain distribution, and temperature evolution is systematically analyzed. The results provide useful insights for optimizing friction control and lubrication strategies in practical hot rolling processes.

Research methods and principles

The material considered in this investigation is AA2024 aluminum alloy, which is widely applied in structural components requiring high strength. The material behavior was obtained from the DEFORM-3D database, where the flow stress is defined as a function of strain, strain rate, and temperature. The corresponding stress strain relationships at a strain rate of 100 s^{-1} are presented in Fig. 1.

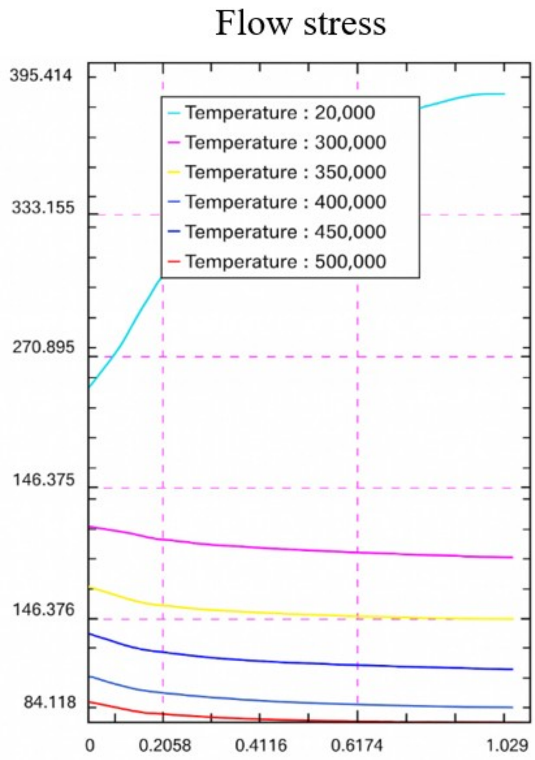

Figure 1 - Stress strain relationships at a strain rate of 100 s⁻¹
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A three-dimensional model of the hot rolling process was created using Autodesk Inventor and then imported into DEFORM-3D in STL format. The initial dimensions of the workpiece were 60 × 15 × 4.5 mm. Two rolls with a diameter of 140 mm and a length of 200 mm were used. Due to their significantly higher rigidity compared to the workpiece, the rolls were treated as rigid bodies. The configuration of the rolling process and the contact region are illustrated in Fig. 2.

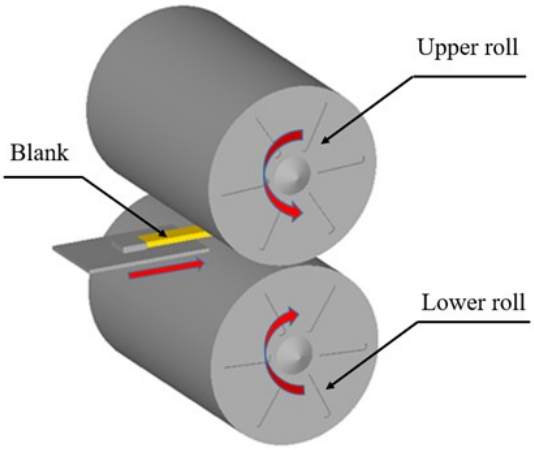

Figure 2 - The configuration of the rolling process
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The numerical simulation was carried out using a three-dimensional finite element approach. The workpiece was modeled as a plastically deformable body and discretized into tetrahedral elements, consisting of 110,695 elements and 22,696 nodes (Fig. 3a). To ensure numerical stability under large deformation, automatic remeshing was implemented throughout the simulation.

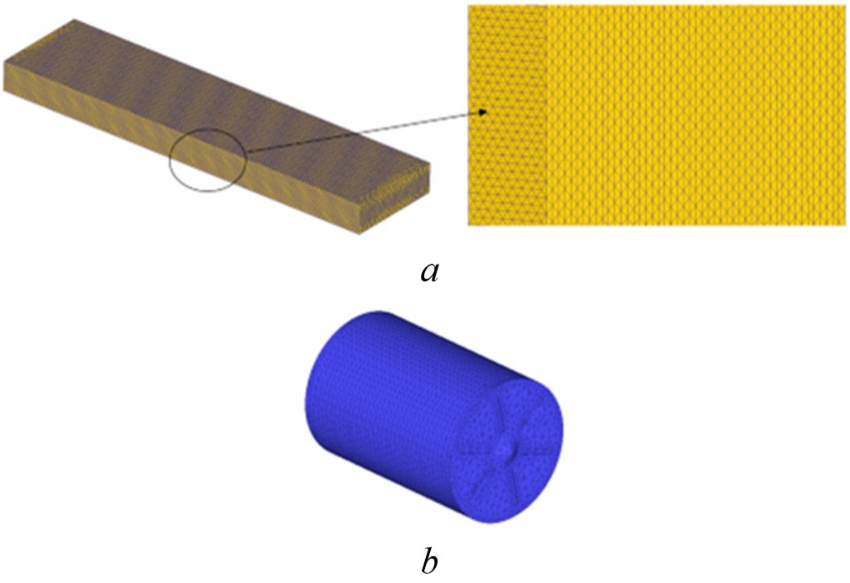

Figure 3 - Meshing model for parts:
a - plastically deformable body; *b* - roll
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The rolls were also discretized using 37,847 elements and assigned the material properties of SKD61 (AISI H13) tool steel (Fig. 3b). Although considered rigid, discretization of the rolls is necessary for accurate representation of contact interaction, heat transfer, and frictional effects at the interface.

A coupled thermomechanical formulation was adopted to account for the interaction between deformation and temperature evolution. Heat transfer mechanisms included conduction between the rolls and the workpiece, convection between the workpiece surface and the surrounding environment, and thermal radiation. A portion of the plastic deformation work and frictional work was assumed to be converted into heat, contributing to the temperature rise during the rolling process.

The contact interaction between the rolls and the workpiece was described using the shear friction model, which is appropriate for forming processes involving high contact pressure. The shear stress at the interface is expressed as:

$$\tau = mk \tag{1}$$

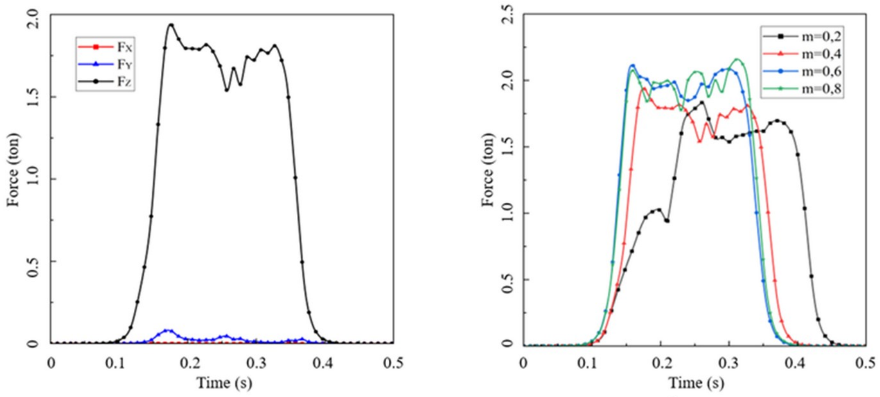
where m is the shear friction factor ($0 \le m \le 1$), and k is the shear yield stress of the material determined according to the Von Mises yield criterion. Four friction factors were considered to represent different lubrication conditions: m = 0.2 (good lubrication), m = 0.4 (moderate lubrication), m = 0.6 (poor lubrication), and m = 0.8 (no lubrication). These values allow a systematic evaluation of the effect of friction on the rolling process.

The rolling process was simulated as a single pass reduction, where the thickness of the workpiece was reduced from 4.5 mm to 3.15 mm. The initial temperature of the workpiece was set to 460 °C, while both the roll temperature and ambient temperature were assumed to be 20 °C. The rolls rotated in opposite directions at a constant speed of 50 rpm. All other parameters were kept unchanged in order to isolate the effect of friction.

Results and Discussion

The simulation results reveal that the force component acting in the thickness direction dominates during the rolling process, while the forces in the rolling and width directions are comparatively small. Therefore, the Z-direction force is used to characterize the rolling load (Fig. 4a).

The evolution of rolling force can be divided into three distinct stages: an initial increase as the workpiece enters the roll gap, a steady region corresponding to stable deformation, and a rapid decrease when the material leaves the deformation zone. As shown in Fig. 4b, the steady state rolling force increases progressively with increasing friction factor.

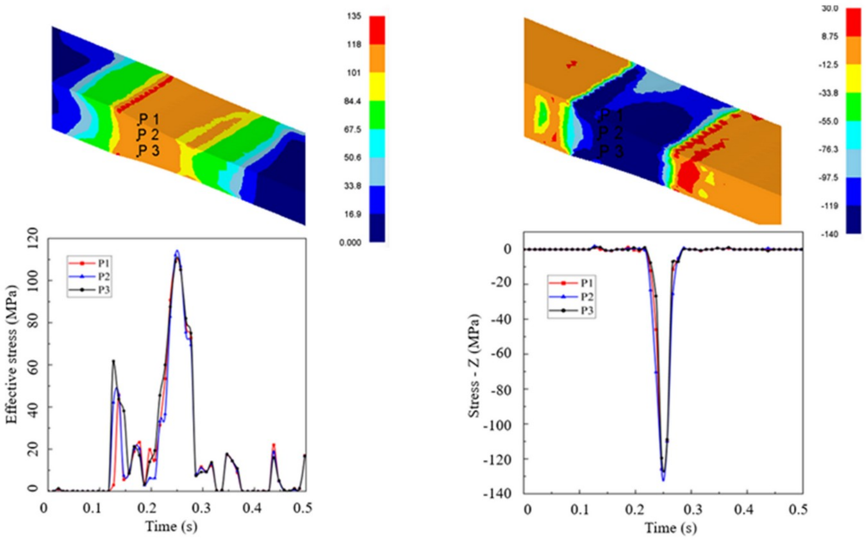


a *b*

Figure 4 - Rolling force time graph:
a - the Z-direction force; *b* - with increasing friction factor
DOI: https://doi.org/10.60797/ENGIN.2026.11.1.4

This behavior is associated with the increased resistance to material flow at higher friction levels, which leads to higher contact pressure. Under low friction conditions, sliding between the roll and the workpiece is more pronounced, resulting in relatively uniform deformation. In contrast, higher friction promotes sticking conditions near the surface, leading to larger velocity gradients and increased rolling load.

The stress evolution at different positions through the thickness shows that the compressive stress reaches its maximum within the roll gap (Fig. 5). However, the peak stress at the center of the workpiece remains nearly constant for different friction conditions. This suggests that the internal stress state is mainly governed by the material behavior rather than interfacial friction.



a *b*

Figure 5 - Stress distribution (*a*) and stress time curves (*b*) at points P1, P2, and P3
DOI: https://doi.org/10.60797/ENGIN.2026.11.1.5

Note: m = 0.4

Comparison of different friction conditions shows that the peak compressive stress at the midthickness of the workpiece remains nearly unchanged with increasing friction factor. This observation suggests that the internal stress required to sustain plastic deformation is primarily controlled by the intrinsic flow behavior of the material at the given temperature and strain rate, rather than by interfacial friction.

Therefore, while friction significantly affects the overall rolling force, it has only a minor influence on the internal stress state at the workpiece center. The increase in rolling load associated with higher friction mainly arises from changes in contact conditions and stress distribution near the surface regions, rather than from an increase in internal compressive stress.

Figure 6 presents the equivalent (von Mises) strain distribution in the workpiece after rolling under different friction conditions. The overall deformation pattern remains similar for all friction factors, indicating that friction does not fundamentally alter the global deformation mechanism imposed by thickness reduction.

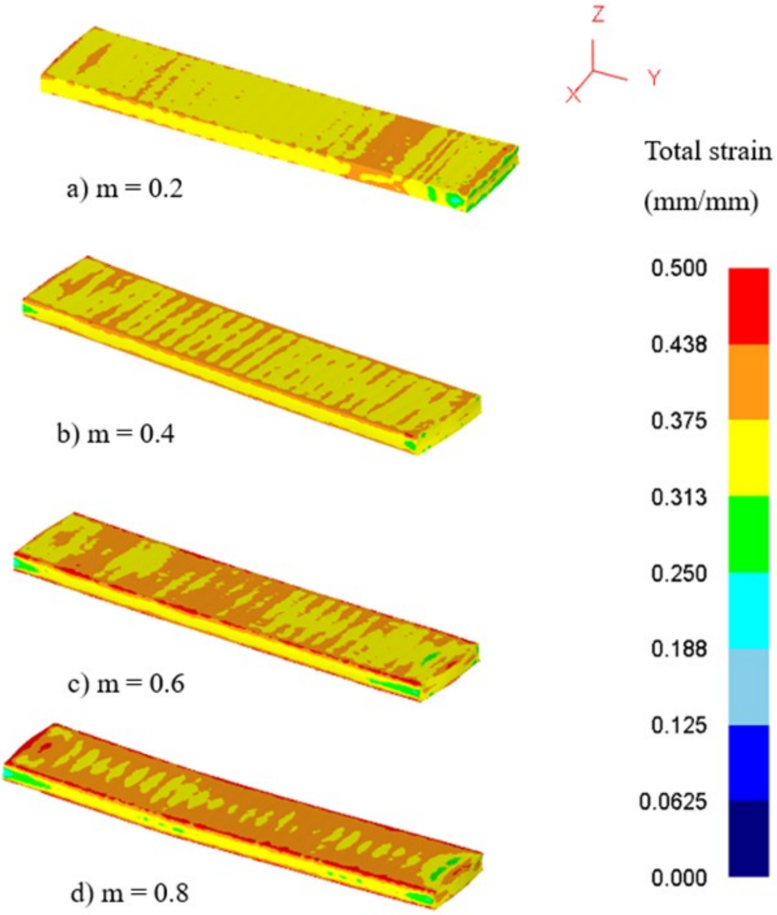


Figure 6 - Strain distribution in the workpiece
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The temperature distribution after rolling (Fig. 7) shows a non-uniform profile along the rolling direction, with higher temperatures observed near the leading end of the workpiece. An increase in friction factor results in a slight increase in temperature due to additional heat generated at the interface.

From an engineering perspective, excessive friction should be avoided, as it increases rolling force and promotes strain localization. On the other hand, too low friction may reduce heat retention. Therefore, a moderate friction condition provides a balanced combination of mechanical and thermal performance.

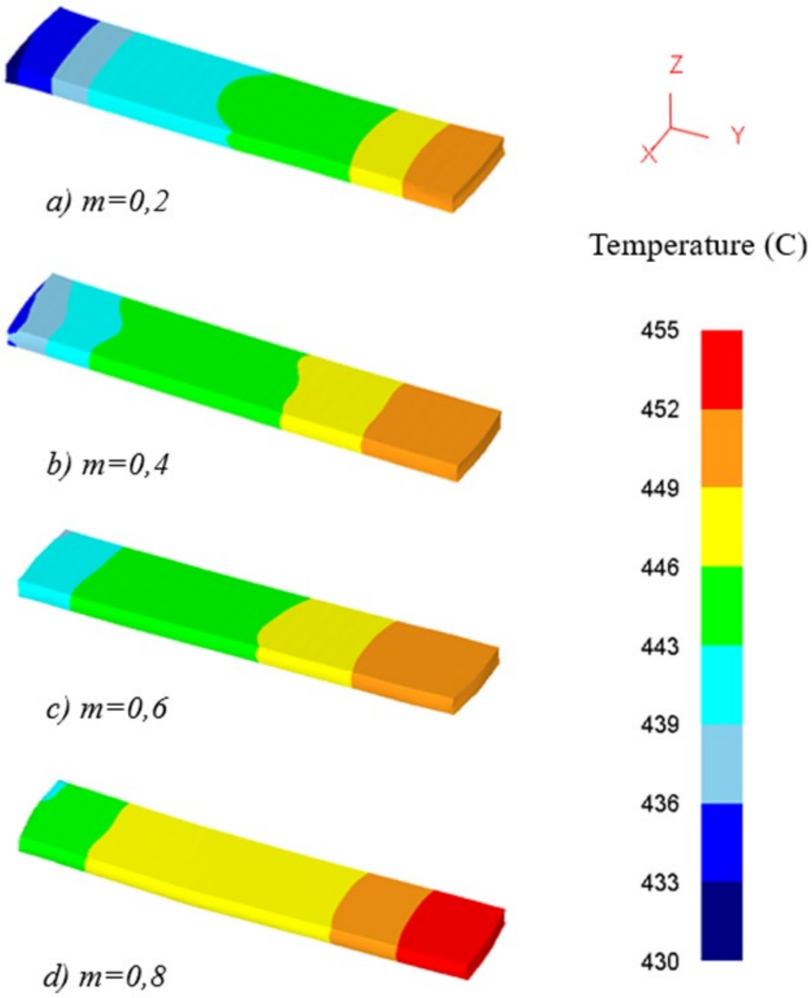

Figure 7 - The temperature distribution in the workpiece

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Increasing the friction factor leads to a slight increase in the average workpiece temperature after rolling. This temperature rise is attributed to additional heat generated by frictional work at the roll workpiece interface. Although the magnitude of the temperature increase is relatively small, it can be beneficial for maintaining thermal conditions during subsequent rolling passes.

From a practical perspective, friction should be controlled at a moderate level to balance competing requirements. Excessively high friction increases rolling force and promotes strain localization at the edges, while excessively low friction may result in insufficient heat retention. Based on the present results, a moderate friction factor in the range of approximately 0.3–0.5 provides a reasonable compromise between rolling load reduction, strain uniformity, and thermal stability in hot rolling of AA2024 aluminum alloy.

Conclusion

This study analyzed the influence of friction on the thermo-mechanical behavior of AA2024 aluminum alloy during hot rolling using a three dimensional finite element model.

The results show that the rolling force increases with increasing friction due to higher resistance at the interface. In contrast, the internal compressive stress at the center of the workpiece remains almost unchanged, indicating that it is mainly controlled by material properties.

Higher friction conditions lead to more pronounced strain localization near the edges, which may increase the likelihood of defect formation. In addition, friction contributes to a slight increase in workpiece temperature as a result of heat generation at the contact interface.

Considering the combined effects of rolling force, strain distribution, and temperature, a moderate friction factor in the range of 0.3–0.5 is recommended for practical applications.

The findings of this work provide useful guidance for improving friction control and lubrication strategies in industrial hot rolling processes.

Конфликт интересов

Не указан.

Рецензия

Все статьи проходят рецензирование. Но рецензент или автор статьи предпочли не публиковать рецензию к этой статье в открытом доступе. Рецензия может быть предоставлена компетентным органам по запросу.

Conflict of Interest

None declared.

Review

All articles are peer-reviewed. But the reviewer or the author of the article chose not to publish a review of this article in the public domain. The review can be provided to the competent authorities upon request.

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