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Effect of Shot-Peening Duration on Surface Integrity of Selective Laser Melted Steel Components

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ABSTRACT

Additive manufacturing, particularly Selective Laser Melting (SLM), has emerged as a transformative technology for fabricating complex metallic components; however, surface roughness, porosity, and tensile residual stresses remain major challenges limiting its industrial deployment. Addressing these issues requires efficient post-processing strategies capable of enhancing surface integrity without altering SLM parameters. In this study, Fe–Ni–Cu steel alloy specimens were fabricated using an EOSINT M-250 Xtended SLM machine equipped with a 100 W fiber laser, and the influence of shot-peening duration on their mechanical and surface properties was investigated. Four samples were prepared—one as a reference and three subjected to peening for 4, 6, and 9 min. Comprehensive analyses were performed, including microhardness testing, surface roughness measurements, SEM observation, Clemex image analysis, and X-ray diffraction residual-stress assessment. Results showed that extending the peening duration from 4 to 9 min progressively improved surface quality and stress state: surface roughness decreased by 66.3%, microhardness increased by 20.8%, and the initial tensile residual stress of +135 MPa was converted into a compressive stress of about –322 MPa. Surface porosity also dropped from ≈ 21% to below 10%, confirming effective pore closure and densification of the upper layers. These findings demonstrate that controlled shot-peening, particularly within the 6–9 minute range, is a simple yet highly efficient post-processing method for improving the surface integrity and mechanical performance of SLM-fabricated Fe–Ni–Cu steel components.

Keywords: Additive Manufacturing, Selective Laser Melting (SLM), Shot-Peening, Surface Integrity.

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1- Introduction

One of the key advantages of additive manufacturing is its ability to produce components with highly complex geometries that are either impossible or extremely time-consuming and costly to fabricate using conventional methods [1, 2]. A wide range of materials and techniques are employed in additive manufacturing. Among them, metal-based systems and processes are significantly more expensive and technically complex compared to polymer-based 3D printers. Therefore, further research is necessary to optimize the fabrication of metallic parts with improved properties, and potentially via more cost-effective approaches. Despite its benefits, 3D printing (additive manufacturing) also has several limitations, including low processing speed, poor surface quality, and the presence of tensile residual stresses on the surfaces of printed parts [3, 4]. Surface quality [5] and residual stress [6] are critically important in engineering components. While surface quality has aesthetic and ergonomic implications, more importantly, rough and porous surfaces are prone to crack initiation and are more susceptible to fatigue and corrosion-related damage. Residual stresses on the surface of a part are also of particular concern. Tensile residual stresses are generally considered detrimental, as they promote the initiation and propagation of fatigue and static cracks, thereby reducing the overall service life of the component. In contrast, compressive residual stresses on the surface are beneficial, contributing to enhanced durability and performance. Shot peening is a widely used surface treatment method for mitigating surface porosities and converting tensile residual stresses into compressive ones. It is commonly applied in industries such as medical devices, aerospace, and automotive engineering [7, 8]. This technique is also highly effective in sealing surface pores of parts produced by Selective Laser Melting (SLM) [9, 10]. The benefits of shot-peening include improved mechanical strength and fatigue resistance, even for components with complex geometries. In addition to enhancing material properties, the peening process can create a textured surface resembling fine casting grain, which may be advantageous in specific applications. Numerous studies have been conducted in this area, which will be reviewed in the following sections [11-13].

Si et al. [14] investigated the effect of ultrasonic shot-peening on improving cavitation erosion resistance in Al-2024T351 components produced via additive manufacturing. Their findings revealed that ultrasonic peening led to grain refinement of the Al-2024T351 alloy, induced compressive residual stresses, and enhanced hardness. They concluded that ultrasonic shot-peening significantly improves resistance to cavitation-related erosion. Pathak et al. [15] conducted a study on the surface integrity of gear wheels fabricated by SLM and subjected to laser peening. They observed that increasing laser power up to 100 J/cm² improved surface quality; however, beyond this threshold, a slight decline in surface smoothness and quality was noted. Qin et al. [16] examined the effect of shot-peening on the high-cycle fatigue behavior of nickel-based superalloys. GH4169 specimens were fabricated and treated under varying peening intensities. The results indicated that excessive peening introduced high tensile residual stresses, which in turn reduced fatigue life. Alharbi [17] carried out a study on the effect of ultrasonic shot-peening on 316L stainless steel parts produced via SLM. The optimized peening parameters reduced residual stresses from +450 MPa to −350 MPa (compressive). Additionally, increasing peening duration from 5 to 10 min resulted in a 10% increase in surface hardness, but no further hardness gain was observed when extended to 15 min. However, surface roughness was reduced by 46%. Gundgire et al. [18] examined the effects of shot-peening on both additively manufactured and conventionally produced 316L stainless steel specimens. They studied the influence of severe peening on microstructure and residual stress, observing similar residual stress behavior in both peened reference samples and 3D-printed samples. Shot peening introduced deeper compressive residual stresses, which are beneficial for improving fatigue resistance and mitigating stress corrosion cracking. Slawik et al. [19] studied the effects of laser peening and conventional shot-peening on the microstructure of Ti6Al4V fabricated using SLM. X-ray diffraction (XRD) stress measurements revealed distinct differences in micro-stress behavior between laser-peened, shot-peened, and untreated samples. Uzan et al. [20] investigated the impact of shot-peening on the fatigue strength of AlSi10Mg parts produced via SLM. Optimized mechanical and electrochemical polishing of peened surfaces—removing approximately 25–30 µm—led to a significant improvement in fatigue resistance, particularly under high-cycle fatigue regimes.

The main innovation of this study in its focused investigation of the effect of shot-peening duration on metal components manufactured via SLM—a topic that has received limited quantitative and structural analysis in previous research. Unlike many studies that concentrate on directly optimizing the internal parameters of the SLM process, this research adopts a complementary strategy by proposing the use of a fast, cost-effective, and industrially scalable surface treatment—shot-peening—to enhance surface properties, reduce porosity, and increase surface hardness without modifying the 3D printing settings. A distinctive feature of this study is the establishment of an experimental framework for analyzing the effect of peening time, identifying the depth of the affected zones, and simultaneously quantifying changes in hardness, surface roughness, and porosity. This approach provides a practical means to improve the performance of SLM-fabricated parts for use in high-performance and sensitive industries, without increasing manufacturing time or cost.

Shot peening has attracted significant attention as a practical post-processing solution for metallic parts fabricated by additive manufacturing, particularly in industries requiring high surface integrity and fatigue reliability. In the aerospace sector, this technique is used to improve the fatigue life of turbine blades, gears, and structural brackets produced by SLM. In the biomedical field, shot peening enhances the mechanical strength and biocompatibility of porous metallic implants, helping to achieve both surface densification and osseointegration. In the automotive industry, it is employed to extend the service life of transmission and suspension components fabricated by metal additive manufacturing. Furthermore, in tooling and mold-making, shot-peening effectively seals surface pores, improving wear resistance and dimensional stability under cyclic thermal loads. Therefore, the industrial motivation for this study lies in providing an optimized, low-cost, and scalable surface treatment process for SLM-fabricated components, enabling their safe and durable use in critical engineering applications.

2- Materials and Methods

To investigate the effect of the shot-peening process, Fe-Ni-Cu alloy specimens with the compositions listed in Table 1 were fabricated using the SLM method. The samples had dimensions of 10×10 mm and were produced under constant processing conditions, as detailed in Table 2. An industrial SLM machine, EOSINT M-250 Xtended, was used for fabrication. All samples were built simultaneously and in the same orientation to ensure uniform processing conditions.

Table 1 Elemental composition (wt.%) of the material used

Element	Fe	Ni	Cu
wt.%	70.5	22	7.5

Table 2 Additive manufacturing parameters for the fabricated samples

SLM Parameter	Laser Power (W)	Scan Speed (mm/s)	Scan Strategy	Layer Thickness (µm)	Laser Track Spacing (µm)
Value	100	180	Stripe	40	300

Following fabrication, the samples were subjected to shot-peening using a dedicated shot-peening machine. The shots were made of steel, with a hardness of 60 HRC, an average diameter of 0.59 mm, and an impact velocity of 45 m/s. The experimental setup of the shot-peening process is shown in Figure 1. Table 3 presents images of the samples after completion of the shot-peening process at specified durations. Microhardness testing was carried out using a 1 N load on the indenter, with a dwell time of 15 seconds. Measurements were repeated at five different points on each sample, and the average value was considered as the representative hardness. To further analyze the effect of shot-peening on porosity and microstructure, the cross-sections of the samples were cut. Standard metallographic preparation—including grinding, polishing, and final etching using Keller's reagent—was performed. To quantify porosity, multiple high-magnification images were captured and analyzed using Clemex image analysis software. To compare the porosity of additively manufactured parts with that of conventionally produced materials, Archimedes density measurement was employed. In addition, to evaluate the influence of shot-peening on surface quality, surface roughness was measured using a Testech TR-200 Plus roughness tester. To enhance measurement accuracy and reliability, roughness was recorded along five paths at different angles. The parameters Ra and Rz were examined. Residual surface stresses were measured using the XRD $\sin^2\psi$ method. The measurements were performed with an XRD device equipped with a Co Kα radiation source to ensure shallow penetration, allowing only surface stresses to be evaluated. The samples were irradiated at several tilt angles (ψ), and diffraction peak positions were recorded at each angle. Strain values were derived from peak shifts, and residual stresses were calculated using the elastic constants of the alloy (Young's modulus and Poisson's ratio).

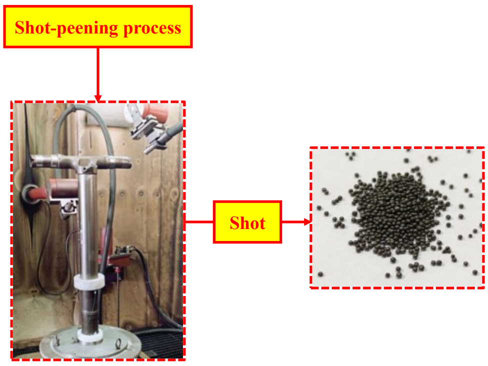
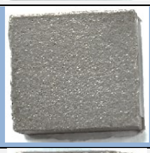
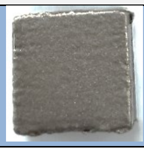


Fig.1 Shot-peening setup and used steel shots

Table 3 Specifications of the samples examined

Sample ID	Shot-peening Duration (min)	Sample Image
Ref.	0	
S1	4	
S2	6	
S3	9	

3- Results and Discussion

3-1- Surface Roughness

To accurately assess surface roughness, measurements were taken along multiple paths on each sample surface in perpendicular directions. The average of the resulting roughness values was calculated and is shown in Figure 2. After 6 min of shot-peening, only a slight improvement in surface quality was observed. Figure 3 presents the SEM images of the sample surfaces. Numerous pores and cavities were visible on the reference sample, while the peened samples exhibited smoother surfaces, with surface pores almost completely sealed due to the impact of the shots. The Ra value in sample S3 showed a 66.3% reduction compared to the reference. This gradual reduction in roughness with increasing shot-peening duration is attributed to the higher number of shot impacts on the surface. Each impact transfers mechanical energy in the form of plastic deformation, which compresses surface irregularities and reduces the height of peaks and valleys. According to the work-hardening principle, longer contact durations subject the surface layers to greater plastic strain, thereby reducing roughness. This effect is particularly significant for parts manufactured using SLM, as their inherently rough and porous surfaces are prone to wear and fatigue. Increasing the shot-peening time results in greater mechanical pressure on the surface layers, leading to material densification and a further reduction in roughness parameters such as Ra and Rz.

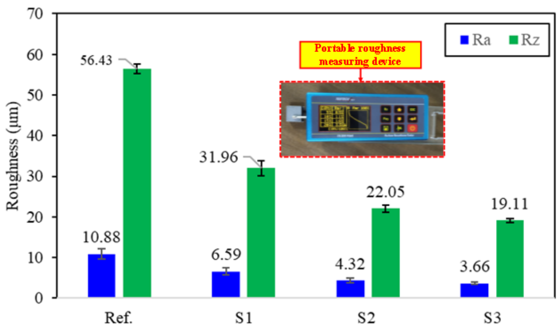


Fig.2 Ra and Rz results as a function of shot-peening duration

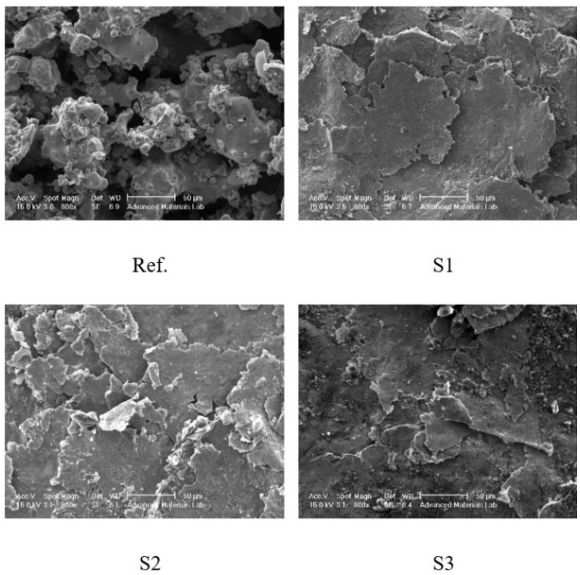


Fig.3 SEM images of the shot-peened sample surfaces

3-2- Hardness

In shot-peening processes applied to parts manufactured via SLM, three distinct zones are of particular importance. Due to the porous and layer-by-layer nature of SLM, these zones are more prominent than in components fabricated by conventional methods. Figure 4 illustrates these critical regions in sample S3. Zone a is the surface layer directly affected by the shot impacts. In this region, the grains are heavily refined and fragmented, and a clear increase in hardness is observed. The depth of this hardened layer was measured to be approximately 45–55 µm. Zone b is characterized by a reduced impact density compared to the surface layer. In this transitional area, some increase in hardness was detected, though not as pronounced as in zone a. Determining the exact boundaries of this transition zone is challenging, but its depth was estimated to be in the range of 50–90 µm. The presence of pores in the upper layers caused significant energy absorption from the shots. These pores effectively acted as dampers, especially in the first two layers. Zone c exhibited only slight or negligible increases in hardness in some areas. These changes were minimal and inconsistent. In fact, this zone cannot be reliably expected to undergo hardening, as the variability in measured hardness values was largely due to the porous structure and the inherent heterogeneity of the material.

The improvement in hardness and surface integrity after shot-peening can be explained by the underlying microstructural mechanisms associated with severe plastic deformation of the near-surface layer. Each shot impact generates a high strain-rate plastic zone, producing dense dislocation tangles, sub-grain boundaries, and localized grain fragmentation. As shown in Figure 4, the outermost layer (Zone a) experienced the greatest plastic strain, leading to extensive grain refinement and a high dislocation density, which directly contributed to the increased hardness. The intermediate region (Zone b) exhibited moderate deformation and partial recovery, while the base material (Zone c) remained largely unaffected.

In addition, the repeated shot impacts caused closure of surface pores and compaction of loosely bonded particles visible in Figure 3, thereby increasing the effective density and load-bearing capacity of the surface. The combined effects of dislocation multiplication, grain subdivision, and pore sealing create a strain-hardened layer with enhanced resistance to further deformation.

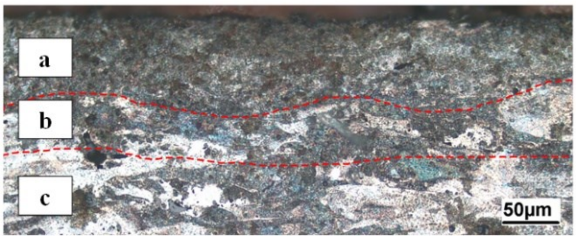


Fig.4 Three key zones formed by the shot-peening process on the part surface: (a) shot-affected zone, (b) transition zone, (c) unaffected zone

Figure 5 shows that the hardness of the sample increased by 20.8% after 9 min of shot-peening compared to Ref. sample. The reason why the effect of shot-peening on sample S3 is significantly greater than on the other samples is that, after 9 min of treatment, the zone a on the surface (as shown in Figure 4) becomes more densified and consolidated, reducing the ability of surface pores to absorb shot energy. As a result, deeper layers of the material are more intensely compacted and hardened, receiving a greater share of the kinetic energy from the shots. During shot-peening, the impact of shot particles transfers substantial kinetic energy to the surface, leading to grain displacement and increased accumulation of crystal defects, such as dislocations and point defects. This defect enhances the material's resistance to further deformation, thereby improving its hardness. Moreover, localized plastic strain, intensified by an increased number of impacts over longer durations, further strengthens the microstructure. In SLM components—where porosity and coarse grains may be present due to the layer-by-layer nature of the process—shot-peening helps compress the surface, reduce defects, and homogenize the microstructure, contributing to overall mechanical enhancement.

3-3- Porosity

Using the Archimedes density measurement method, the volumetric porosity percentage of the control sample was determined. The Archimedes density test was conducted according to ISO 3369, at a temperature of 23 °C and 36% relative humidity. The theoretical density of the material in its fully dense state is 7600 kg/m³. The density obtained from the Archimedes test was approximately 6000 kg/m³, indicating a volumetric porosity of about 21%, resulting from the additive manufacturing process.

As noted in Section 2, porosity percentages of the samples were also quantified using image analysis in Clemex software, and the results are presented in Figure 6. To observe the actual morphology of the pores, optical microscopy was used to capture images of various regions in both the control sample and sample S3 (see Figure 7). These regions were specifically selected to contain visible pores and cavities, allowing for a realistic depiction of their shape and distribution.

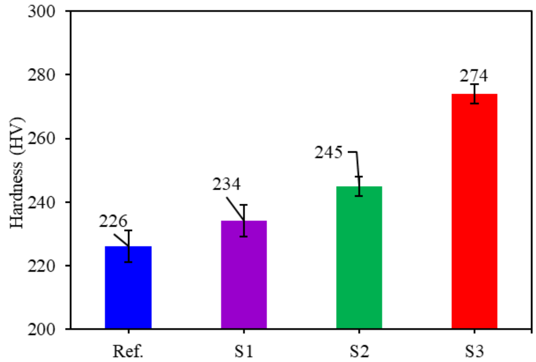


Fig.5 Hardness in different samples

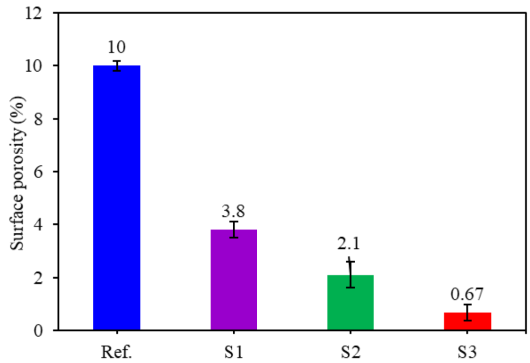


Fig.6 Surface porosity percentage chart for different samples

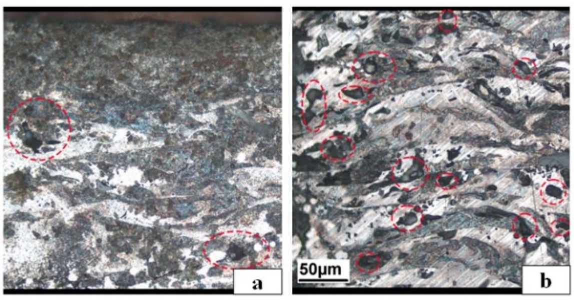


Fig.7 Identification of porous regions at 200× magnification in (a) Sample S2 and (b) Ref. sample

3-4- Residual Stresses

The results of residual stress measurements in the lateral direction (σ_x) on the shot-peened surfaces are presented in Figure 8. It is worth noting that residual stress was measured at three different points on each sample, and the average value was reported for each specimen. According to the results, the as-built sample exhibited tensile residual surface stress of approximately 135 MPa, which is attributed to the thermal nature of the SLM process. These tensile stresses are a direct consequence of the high cooling rates and steep thermal gradients between layers during SLM, leading to non-uniform contraction and the development of surface tension. Such tensile residual stress is considered undesirable in metallic parts, as it promotes the initiation and propagation of cracks—especially under cyclic or fatigue loading conditions. The results demonstrate that shot-peening for various durations (4, 6, and 9 min) effectively reversed the surface stress from tensile to compressive, with the most compressive stress (≈ −322 MPa) observed at 9 min (S3). The magnitude increased progressively from −254 MPa (S1) to −306 MPa (S2) and −322 MPa (S3). However, the difference between 6 and 9 min was relatively small, indicating that the process reached a saturation level in the development of near-surface compressive stresses. The formation of compressive surface stresses during shot-peening is mechanical in nature. From a mechanical work perspective, the surface layers undergo plastic deformation and work hardening due to repeated shot impacts, which leads to the development of compressive stresses after the process ends. In SLM samples, shot peening additionally compacts the surface and seals pores near the surface, thereby amplifying the positive effects of the process on the printed components. As the peening time increased to 6 min, the magnitude of compressive stress increased by approximately 20%. Moreover, the error bar range decreased, indicating improved uniformity in the distribution of residual stresses across the surface. However, further increasing the peening time to 9 min resulted in no significant change in the magnitude of compressive stress, suggesting that a saturation point had been reached in the development of residual compressive stresses. Importantly, the continued decrease in error bar size with increased peening duration reflects a more uniform residual stress distribution, which is beneficial for the structural integrity and fatigue performance of the part.

It is also important to note that extending the shot-peening duration beyond 9 min is not expected to further improve the surface or mechanical properties. This is because the accumulation of compressive residual stress and strain hardening typically approaches a saturation point once the near-surface dislocation density reaches equilibrium. Beyond this limit, additional shot impacts merely cause repeated plastic deformation of already-hardened grains, which can lead to surface over-hardening, strain localization, or even microcrack initiation. Such excessive treatment may deteriorate rather than improve surface integrity. Therefore, the 9-minute duration identified in this study represents the optimal compromise between mechanical enhancement and surface preservation for SLM-fabricated Fe–Ni–Cu alloy components.

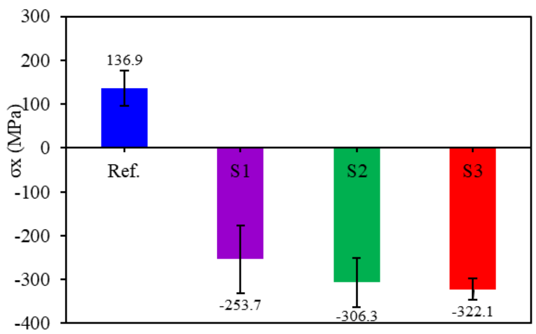


Fig.8 Variation of surface residual stresses with shot-peening duration in the SLM-fabricated steel sample

4- Conclusion

This study investigated the effect of shot-peening duration on the mechanical, surface, and structural properties of parts fabricated by SLM. Four samples with identical manufacturing conditions were prepared, one serving as the reference and the other three subjected to shot peening for 4, 6, and 9 min. Microhardness testing, Archimedes density measurements, SEM imaging, and porosity analysis using Clemex software were employed to evaluate the effects of the process. The investigation also focused on identifying the three distinct structural zones formed because of shot-peening.

The main outcomes of the study can be summarized as follows:

• Shot peening significantly improved surface quality and mechanical performance by reducing surface roughness and porosity while increasing hardness.

• Compressive residual stresses developed progressively with increasing duration, changing the surface stress from tensile (+135 MPa) to compressive (−254 MPa at 4 min, −306 MPa at 6 min, and −322 MPa at 9 min).

• The near-surface region exhibited the most pronounced improvement in the depth range of approximately 45–55 µm, where densification and work hardening were most effective.

• Further extension of the peening duration beyond 9 min produced no substantial benefit, indicating that the process had reached a saturation stage in terms of residual stress and plastic strain accumulation.

From an industrial perspective, these results confirm that air-blast shot-peening can effectively enhance the surface integrity and reliability of SLM-fabricated Fe–Ni–Cu alloy components. The 6–9 minute peening range provides an optimal balance between strengthening and surface preservation, making the method promising for applications in aerospace, biomedical, and tooling industries.

Although this research was limited to the effect of peening duration, other parameters such as shot size, impact velocity, and impact angle also play crucial roles in defining the final surface characteristics. Future studies will investigate these variables using a multi-factorial experimental approach and extended testing (fatigue, wear, and corrosion) to develop comprehensive process guidelines for industrial post-processing of additively manufactured steels.

Ethics Approval:

The scientific content of this article is the result of the authors' research and has not been published in any Iranian or international journal.

Conflict of Interest:

This article includes some results from the corresponding author's doctoral dissertation. There are no other conflicts of interest to declare.

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