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Analysis of Using Damping Alloys to Improve Vibration and Strength Characteristics in the Automotive Industry

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Abstract: The basic idea of the study is to evaluate the acoustic, vibration, physical-mechanical and damping properties of steels, and to produce steels with nanostructured coatings with enhanced damping properties, providing noise and vibration reduction. The study represented the excitation by mechanical shocks of a steel plate, each with a different level of damping. It has been determined that the sources of vibration damping in metallic-paper, encapsulated (MGB) steels MBG-1, MBG-2, MBG-3 with nanostructure coating in the amplitude-dependent region are elastic twinning, diffusion-free reversible phase transformation and magnetic-elastic energy dissipation. As a result of the studies conducted, new damping metallic materials based on iron have been developed.

Keywords: coating, impact, noise, vibration, production factors of industry

1. Introduction

Any vehicle in terms of user comfort is certainly evaluated based on the noise and vibration characteristics inside the passenger compartment. To effectively control noise levels in the passenger compartment, a qualitative analysis of mechanical noise sources is required by determining the sound power contribution from each component. The causes of the emergence/amplification of noise in the passenger compartment inside a moving vehicle are quite varied: wheel noise caused by tyre contact with the road surface, aerodynamic noise caused by turbulent flows around the vehicle, and engine noise. Moreover, the noise characteristics change depending on the speed of the vehicle, for example during acceleration. Consequently, the reduction in overall passenger compartment noise is limited to reducing the noise generated by a specific source in specific driving conditions. Thus, to reduce the noise level in the passenger compartment and improve the acoustic comfort of the vehicle, the bodywork design needs to be optimised¹⁾.

It should be noted that noise pollution is recognised as one of the main hazards that have a negative impact on the life quality. And transport-related low-frequency noise is the source of the greatest prevalence of such²⁾. The impact noise is the most common and harmful production factor of industry³⁾. In the automotive industry, one of the most important research issues is a comprehensive analysis of the vibration and strength characteristics. The concepts of noise, vibration, harshness (NVH) are used to assess and analyse vibroacoustic and strength characteristics⁴⁾.

Mechanical vibration represents oscillations that occur during the operation of mechanisms. The sources of vibration and the types of vibration motion and their distribution are complex subjects and depend largely on the specific characteristics of the systems under investigation. Mechanical vibration, caused by the oscillation of a mechanical system with respect to its equilibrium position, is in many cases an undesirable phenomenon, for example when driving vehicles or using household appliances. Furthermore, mechanical vibration in a vehicle can be accompanied by additional noise, which has a negative impact not only on comfort but also on health, and is a compelling reason to take appropriate action. Thus, mechanical vibration can be eliminated during the design of the construction (car engine) by using suitable materials for vibration damping⁵⁾.

The studies being carried out to reduce noise and vibration include dealing with the source of the noise itself and its propagation path. The most effective way to suppress noise is to reduce the level of noise at its source by using materials with high damping properties⁶⁾. Standard steels are used for the following applications: gear wheels and couplings of hoisting machines, travelling wheels, running wheels, toothed sectors and crowns, half couplings, complete tires, brake discs of casting machines, hubs of gear couplings and other parts for which high strength is required⁷⁾⁻⁹⁾.

The purpose of this study is to study the acoustic, vibration, physical-mechanical and damping properties of steels. Fundamental in the article is the study of ways to

reduce noise and vibration in steel. The theoretical basis of the study is to investigate the potential use of damping alloys as a solution to reduce noise and vibration in the automotive industry.

The study's contribution lies in identifying the sources of vibration damping in MBG-1, MBG-2, and MBG-3 (NSC) steels, which are elastic twinning, diffusion-free reversible phase transformation, and magnetic-elastic energy dissipation. Overall, the study's contribution lies in providing insight into the potential of damping alloys and coatings to reduce noise and vibration in the automotive industry and highlighting the importance of continued research and innovation in this field to meet the stringent noise reduction requirements.

2. Materials and Methods

The object of the study includes melted iron-based steels with nanostructured coating (NSC) – MBG-1, MBG-2, MBG-3. With the existing data on the influence of the chemical composition of alloys on the damping properties, it is possible to conclude that metallic materials with a high level of damping properties can be developed. The principles of alloying alloys in this work are based on the study of state diagrams of Fe-C, Fe-Cr, Fe-Ni; Fe-Si; Fe Xie. State diagrams determine the phase composition of the alloy under equilibrium conditions depending on the temperature and concentration of the components. They also make it possible to qualitatively characterize many physicochemical, mechanical, and technological properties of alloys (Table 1)¹⁰.

Table 1. Characteristics of the alloys studied.

No.	Steel grade	Chemical composition of steels, % weight						Mechanical properties			
		C	Si	Mn	Cr	Ni	REM*	σ_B , MPa	δ , %	Ψ , %	KCU, J/cm ²
1	MBG-1	0.42	0.25	0.45-	0.35	≤0.45	(0.03)	600	8	20	26
2	MBG-2	0.48	0.30	0.40-	0.55	0.6-	(0.05)	620	8	20	26
3	MBG-3	0.51	0.38	0.50-	0.65	0.7-	(0.08)	720	8	20	28

Note: REM – rare earth metals, KCU – impact strength.

The nanostructure coating was formed using the well-known physical vapor deposition (PVD) method based on the generation of the substance in the vacuum space of the chamber with the supply of reaction gas (N₂, O₂, CH₄, etc.)^{11, 12}. The differences in PVD technologies lie in the principles of substance generation, the varying degrees of ionisation of the vapour-ion flux, as well as the design and technological features of the units (Figure 1). The most widely used in coating tool production practices are low-voltage vacuum-arc evaporation systems called arc-PVD or cathodic-ion bombardment (CIB). The advantage of a

CIB is considered to be the fairly rapid action of the evaporating substance¹³.

The coatings were applied using 3 evaporation cathodes with droplet phase separators in a nitrogen reaction gas atmosphere (PN₂=3.10-3 Pa). Multi-component coatings of Ti-Al-N with crystallite sizes ranging from 10 to 100 nm have been obtained. The morphology and composition of the samples were studied using a JSM-6700F field raster electron microscope with a JED-2300F energy dispersive spectrometry attachment from the JEOL Company, Japan.

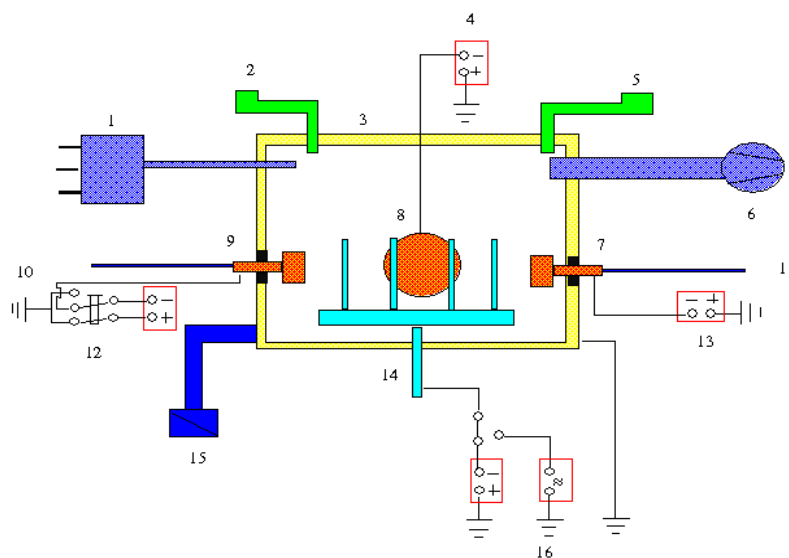


Fig. 1: Nanostructure coating device.

Note: 1 – gas mixer; 2 – vacuum gauge; 3 – installation chamber; 4 – accelerator-separator power supply source; 5 – temperature control system; 6 – vacuum system; 7, 9 – arc evaporators; 8 – source of separated plasma; 10, 11 – evaporator cooling systems; 12, 13 – evaporator power supplies; 14 – rotary table for instrument location; 15 – chamber heating and cooling system; 16 – source of bias voltage pulse supply to instrument.

The mechanical properties of the developed alloys were determined by standard methods^{10), 14)}. Various methods of investigating damping metallic materials have been extensively used in the study^{15), 16)}. Researchers have analysed the reasons contributing to increased internal friction in some metallic materials, as well as the possibilities of improving this property through mechanical, physical or chemical action¹⁷⁾. This study represented the excitation by mechanical shocks of a steel plate, each with a different level of damping. The arising sound was measured with an "Oktava 101A" noise meter and its signal were recorded on an oscilloscope. Furthermore, when studying the generated noise, the spectrum analyser SI Assistant (sound, infrasound) class 1 was used. The sound pulse was recorded with the MK-102 microphone capsule. This impulse is converted into an

electrical signal, amplified by the MK-102 preamplifier and sent to the input of an accurate impulse noise meter 00017 from the "Rundfunk- und Fernmelde-Technik" (Germany) or the noise meter "Oktava-101A" (Russian Federation). The indicator of the noise meter enables recording of sound pressure levels from 30 to 130 dB with an accuracy of 0.5 dBA.

3. Results

Table 2 presents vibration characteristics of specimens (plates of size 50x50x5 mm) from MBG-1, MBG-2, MBG-3 steels (NSC) after collision with impact balls of diameters $d=7$ mm, $d=8$ mm, $d=9$ mm and $d=11$ mm, as well as vibration acceleration octave levels (VAOL).

Table 2. Vibration characteristics of the developed steels MBG-1, MBG-2, MBG-3 (NSC).

Steel grade	Impact ball diameter, d, mm	Vibration acceleration levels, dB, in octave bands with geometric mean frequencies, Hz											VAOL, dB
		31.5	63	125	250	500	1000	2000	4000	8000	16000	31500	
2	3	4	5	6	7	8	9	10	11	12	13	14	15
MBG-1	7	71	72	76	61	58	54	55	74	84	81	79	91
	8	80	86	86	71	74	60	61	66	65	61	68	93
	9	76	63	62	58	59	55	56	63	61	58	55	96
	11	67	62	59	64	63	65	78	79	82	94	96	99
MBG-2	7	61	63	70	62	58	59	58	58	55	62	55	101
	8	56	58	69	65	62	59	59	61	65	59	61	109
	9	78	101	100	77	74	61	63	66	69	63	69	115
	11	101	99	92	89	66	63	61	64	63	65	61	118
MBG-3	7	71	75	69	63	66	68	73	77	79	81	71	93
	8	78	83	74	67	71	69	75	79	75	81	77	98
	9	91	88	77	67	71	68	67	78	79	89	73	99
	11	103	98	81	81	82	87	92	95	95	100	91	123

MBG-1 steel is a type of steel alloy that has been shown to have excellent vibration damping properties, making it useful in reducing noise and vibration in the automotive industry. During an impact event, the acceleration-time history of MBG-1 steel will typically exhibit a characteristic pattern of high-frequency oscillations, followed by a series of damped oscillations that decay over time (Figure 2). The initial high-frequency

oscillations are due to the sudden deformation of the material caused by the impact, while the subsequent damped oscillations are a result of the inherent damping properties of the steel⁸⁾.

The damping properties of MBG-1 steel are due to the presence of various damping mechanisms, including elastic twinning, diffusion-free reversible phase transformation, and magnetic-elastic energy dissipation.

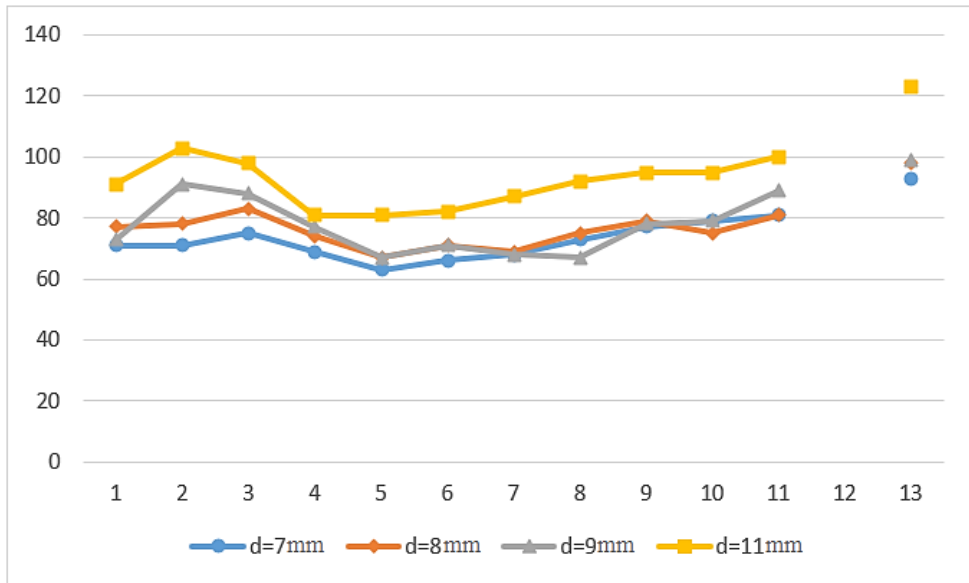


Fig. 2: Vibration acceleration characteristics of MBG-1 steel during impact.

During an impact event, the acceleration-time history of MBG-2 steel will typically exhibit a similar pattern to MBG-1 steel. The initial high-frequency oscillations are due to the sudden deformation of the material caused by the impact, while the subsequent damped oscillations are a result of the inherent damping properties of the steel¹¹⁾. Overall, the vibration acceleration characteristics of

MBG-2 steel during impact demonstrate its excellent vibration damping properties, making it a promising material for use in reducing noise and vibration in the automotive industry (Figure 3). However, the specific acceleration characteristics of MBG-2 steel may differ from those of MBG-1 steel due to differences in the alloy composition and manufacturing process.

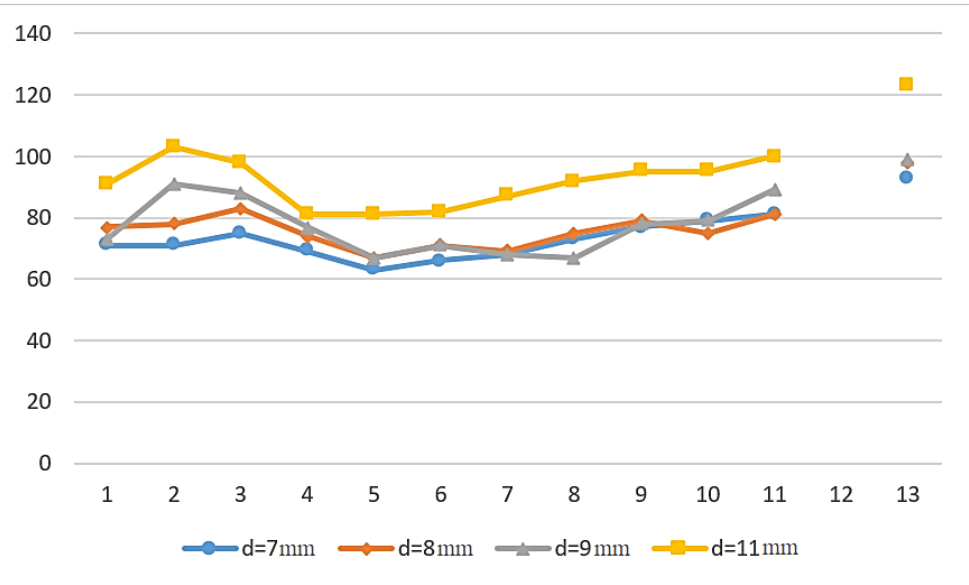


Fig. 3: Vibration acceleration characteristics of MBG-2 steel during impact.

In turn, the characteristics of vibration acceleration of MBG-3 steel upon impact demonstrated its excellent vibration damping properties, which made it a promising

material for use in order to reduce noise and vibration in the automotive industry (Figure 4).

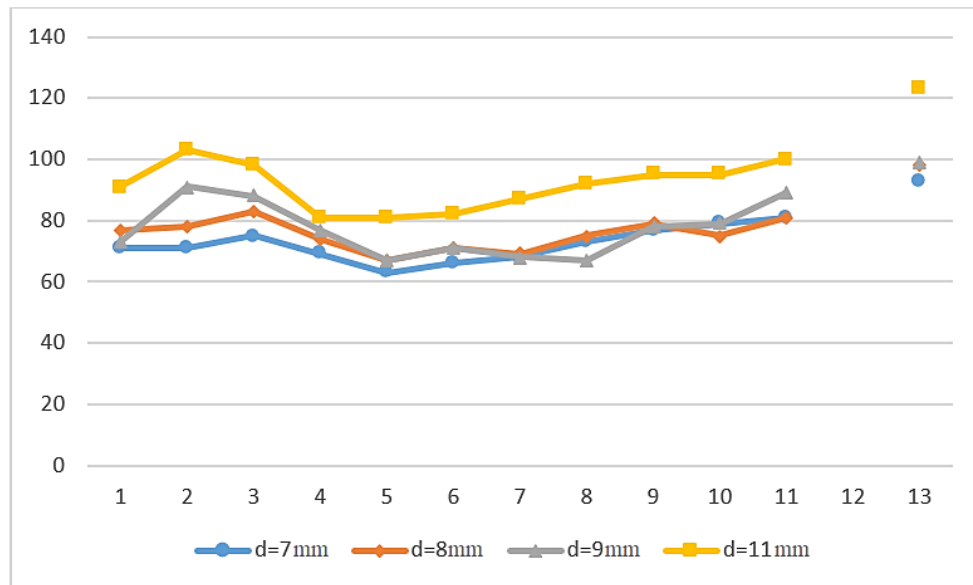


Fig. 4: Vibration acceleration characteristics of MBG-3 steel during impact.

Table 3 displays the results of experimental tests conducted on the MBG-3 steel alloy to evaluate its vibration characteristics.

Table 3. Vibration characteristics of the developed MBG-3(NSC) alloy.

Steel grade	Impact ball diameter, d, mm	Vibration acceleration levels, dB, in octave bands with geometric mean frequencies, Hz											VAOL, dB
		31.5	63	125	250	500	1000	2000	4000	8000	16000	31500	
MBG-3 (NSC)	7	67	68	71	68	61	65	68	71	75	75	81	89
	8	75	78	81	75	65	68	69	73	78	73	78	97
	9	72	88	85	73	65	69	65	63	77	78	89	98
	11	90	102	96	78	79	81	85	92	93	95	98	121

The results in the Table 3 provide valuable information on the vibration characteristics of MBG-3 steel alloy, which can be used in the design and development of noise and vibration control systems in the automotive industry.

Table 4 presents the acoustic characteristics of the samples developed during impact with impact balls of different diameters, as well as the overall sound levels (SL).

Table 4. Acoustic characteristics of steels MBG-1, MBG-2, MBG-3(NSC).

Steel grade	Impact ball diameter, d, mm	Sound pressure levels, dB, in octave bands with geometric mean frequencies, Hz						SL, dBA
		1000	2000	4000	8000	16000	31500	
MBG-1	7	41	49	55	61	59	51	65
	8	55	58	61	71	66	56	73
	9	53	65	68	71	65	61	75
	11	61	62	65	73	70	68	81
MBG-2	7	44	56	60	61	58	53	67
	8	59	59	63	69	66	58	72
	9	58	61	65	71	79	58	75
	11	59	58	63	75	78	69	78
MBG-3	7	51	52	51	55	57	58	66
	8	61	62	65	77	71	65	79
	9	63	63	69	78	73	63	81

	11	71	68	68	77	69	70	93
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Acoustic radiation characteristics refer to the sound waves produced by a material or structure as a result of vibration or impact. In the context of the MBG-1, MBG-2 and MBG-3 steel alloy, the acoustic radiation characteristics during impact (Figures 5-7) refer to the sound waves produced by the material as it undergoes

deformation and vibration during an impact event¹⁵).

However, it should be noted that the specific acoustic radiation characteristics of MBG-1 steel during impact may depend on various factors, including the intensity and duration of the impact, the geometry of the sample, and the surrounding environment.

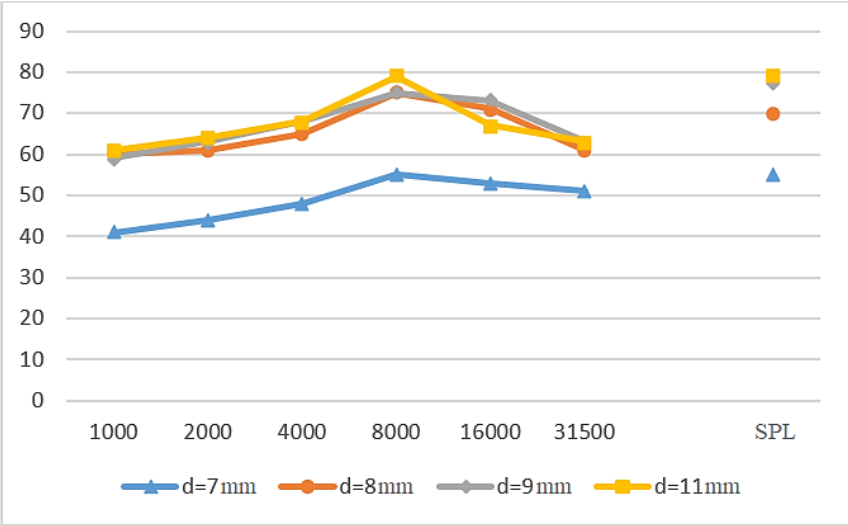


Fig. 5: Acoustic radiation characteristics of sample MBG-1 during impact.

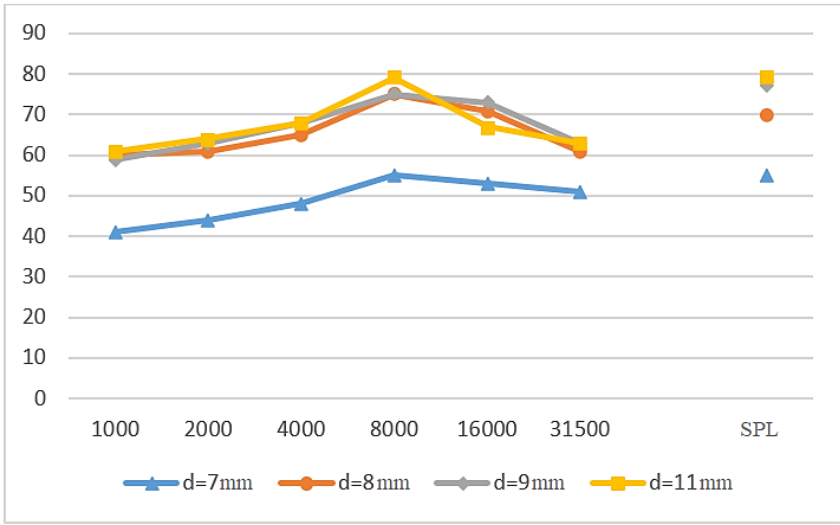


Fig. 6: Acoustic radiation characteristics of sample MBG-2 during impact.

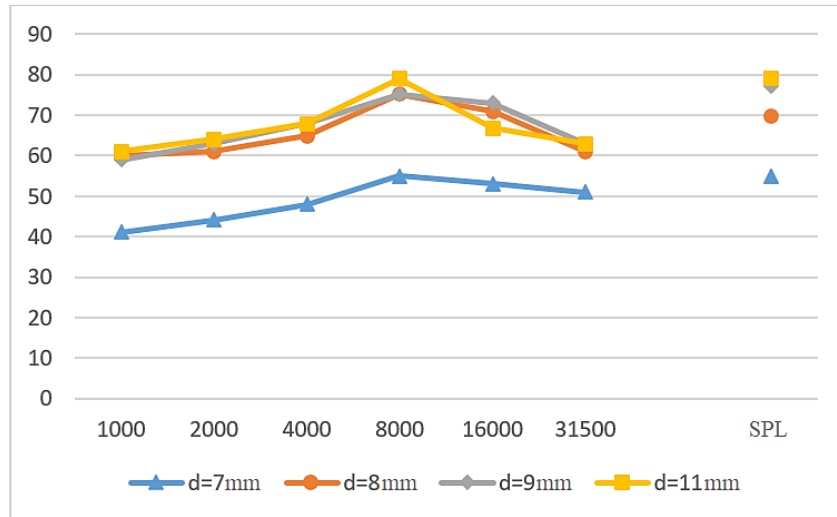


Fig. 7: Acoustic radiation characteristics of sample MBG-3 during impact.

However, I would like to pay special attention to Acoustic characteristics of alloy MBG-3(NSC) (Table 5).

Table 5. Acoustic characteristics of alloy MBG-3(NSC).

Steel grade	Impact ball diameter, d, mm	Sound pressure levels, dB, in octave bands with geometric mean frequencies, Hz						SL, dBA
		1000	2000	4000	8000	16000	31500	
MBG-3 (NSC)	7	41	44	48	55	53	51	55
	8	60	61	65	75	71	61	75
	9	59	63	68	75	73	63	79
	11	61	64	68	79	67	63	81

Also, for a better understanding Acoustic radiation characteristics of sample MBG-3(NSC) during impact was completed Figure 8.

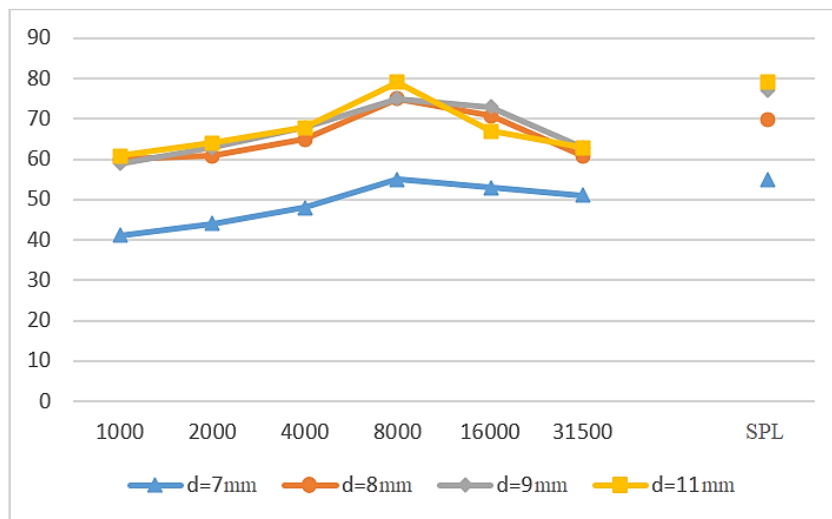


Fig. 8: Acoustic radiation characteristics of sample MBG-3(NSC) during impact.

4. Discussion

In the automotive world, the abbreviation NVH is often used to denote noise, vibration and harshness. The main

source of noise is the vehicle's engine and transmission line components. It also includes the interaction of the tyres with the road surface and the movement of the airflow around the car. The automotive industry, facing

the challenges of producing cars with the best design criteria that will meet customer demands in terms of acoustic characteristics, is rapidly evolving in the direction of creating engines with high magnetic flux density and lightweight construction¹⁸). The problems caused by vibration and engine noise are therefore becoming ever more noticeable, making it all the more important to find a solution. Noise in the passenger compartment is a decisive factor when choosing a product for end-users.

In order to reduce vibration, polymers are increasingly being used in the automotive industry¹⁹). Recently, the automotive and aerospace industries have been focusing on lightweight, environmentally friendly materials with sufficient strength and durability. Saravanan and Suresh,²⁰ having investigated material substitutions for gear wheels, concluded that bronze alloy demonstrated better strength than steel and provided better load capacity, high speed and low stress levels. In another study²¹). When analysing the sound and vibration properties of linen fibre-reinforced composites using a data acquisition system and Lab View software, the researchers made the conclusion that the sound absorption coefficient of linen fibre-reinforced composites was 21.42% higher than that of glass fibre-reinforced composites.

Any part of the engine that facilitates movement creates noise and vibration. In order to reduce engine noise levels, the internal components that drive the engine should be designed with the use of low-friction components that will contribute to smooth operation throughout the engine's lifetime²²).

Researchers have analysed the possibility of using shape memory copper-based alloys²³) to meet the damping requirements of metallic materials, and found this to be the best solution. A great deal of research is currently being carried out, as addressing the problems of vibration and noise in the vehicle should be considered at the earliest stages of the engine design process. One of the latest studies (2021) presents a new multiphysics coupling method, combining a finite element method and an optimised meshless method, for the calculation of the motor's electromagnetic-vibration coupling²⁴). The damping coefficient was also determined during sound and vibration analysis using the free oscillation technique in accordance with the ASTM E756 standard²⁵, 26).

Engineers from Material Sciences Corp (MSC) discovered during one of their studies²⁷) that large amounts of damping treatment are used in aluminium vehicles. To avoid this, a lightweight formed laminate (Quiet Aluminium) has been developed, which provides a significant reduction in weight without the need for additional soundproofing materials. The researchers described Quiet Aluminium as the perfect material for electric cars, for which, as previously mentioned, both low weight and increased noise insulation are of great importance.

5. Conclusions

Many fledgling electric vehicle manufacturers prefer aluminium in order to reduce weight. However, its lightness does not automatically mean a reduction in noise levels or the elimination of the noise source. Lightening the weight of the car in this case is actually acceptable for an electric vehicle as a quiet car, but many of the systems and components used to reduce noise eventually add weight. However, a muffled engine noise, even by just a couple of decibels, will contribute to a significant increase in the comfort level inside the cabin and give the car a more premium and prestigious look, isolating passengers from the mechanics of the vehicle.

As a result of the works described in this study it was determined that the sources of vibration damping in MBG-1, MBG-2, MBG-3 (NSC) steels in the amplitude-dependent region are elastic twinning, diffusion-free reversible phase transformation and magnetic-elastic energy dissipation. The nanostructured layer-by-layer coating (2 µm) differs significantly in density and physical-mechanical properties from the alloy matrix, which provides effective damping of sound vibrations.

In conclusion it should be noted that improving automotive noise reduction standards is an inevitable result of the rapid development in the automotive industry. Figuring out how to meet such high standards and stringent requirements is a research problem that automotive engineers face. The addition of acoustic materials has well developed and extended the idea of reducing vehicle noise. Among the acoustic materials, damping materials temporarily meet the requirements for reducing automotive noise due to their excellent performance. In the future, researchers will need to continually explore and introduce innovations in order to improve the characteristics of the damping materials. In this way, they will be able to develop new water-based damping materials with better soundproofing characteristics, more stable physical and mechanical properties, easier storage, faster construction and more environmentally friendly and safer properties for use in reducing automotive noise.

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