applied sciences

MDPI

Article

Withstanding Capacity of Machine Guards: Evaluation and Validation by 3D Scanners

Luca Landi *, **Silvia Logozzo**, **Giulia Morettini** and **Maria Cristina Valigi**

Department of Engineering, University of Perugia, Via G. Duranti 93, 06125 Perugia, Italy; silvia.logozzo@unipg.it (S.L.); giulia.morettini@unipg.it (G.M.); mariacristina.valigi@unipg.it (M.C.V.)
* Correspondence: luca.landi@unipg.it

Abstract: Ballistic penetration of machine guards is a topic of great significance for ensuring safety and avoiding projection of objects out of the working space of machines. Although standardized tests are performed according to EU Directive 2006/42/EC, they have some limitations because they are carried out using a given penetrator that perpendicularly impacts a given surface of about 500 × 500 mm. Nevertheless, the withstanding capacity of those guards depends on a lot of different design parameters and physical quantities that have not been fully investigated. This paper is focused on the study of the influence of the machine guard size on the withstanding capacity to ballistic penetration throughout theoretical models and experimental tests based on an innovative method involving the use of 3D optical scanners for inspection. The experimental analyses described in this work, compared to theoretical results, demonstrate that a maximum plastic deformation area can be defined, independently of the plate size, given the same material, thickness, and penetrator. This result allows to set proper new ranges for standardized tests, overcoming the limitation of using specific sample sizes.

Keywords: ballistic penetration; 3D scanner; deformation analysis; machine guards; ejection risk

Citation: Landi, L.; Logozzo, S.; Morettini, G.; Valigi, M.C. Withstanding Capacity of Machine Guards: Evaluation and Validation by 3D Scanners. *Appl. Sci.* **2022**, *12*, 2098. https://doi.org/10.3390/app12042098

Academic Editor: Young Hoon Kim

Received: 13 January 2022
Accepted: 15 February 2022
Published: 17 February 2022

1. Introduction

The study and implementation of methodologies to evaluate and increase the safety of production systems is fundamental in the industrial field; thus, risks and safety of workplaces must be analyzed in many industrial environments [1–4]. Machine guards play a fundamental role in protecting operators and other people standing nearby the working zone from ejection of harmful debris [5].

The methodologies and standards for the design and validation of machine guards are reported in ISO 14120-annex B [6]. According to this regulation, a machine guard is defined as a physical barrier, designed as part of the machine for the protection of operators. These protections are divided into several types: fixed, movable, motorized, with total segregation, with automatic closing, etc. Commonly, machine guards are made of steel, aluminum, or plastic materials [7–10]. Nevertheless, the use of polymeric materials is increasingly widespread due to their easy processability and transparency, which allows to observe the manufacturing area.

Annex B of ISO 14120 presents the test criterion to investigate the withstanding capacity to ballistic penetration of machine protection panels and their suitability for industrial machines. For some typologies of machine tools, tests on guards are regulated by specific type C standards and described by some annexes, such as ISO 16090-1 [11], which regulates machining centers for metallic materials, ISO 19085-1 [12], specific for woodworking machines, and ISO 23125 [13], related to metal turning machines.

Ballistic tests prescribed by the standard regulations are performed using compressed air guns that supply kinetic energy to a steel projectile, with standardized shape and size [6,11–13]. The projectile impacts on a flat test guard of given dimensions at a speed close to the maximum predictable velocity of the machine tool or at a specified fixed velocity. A single shot is considered valid to predict the guard safety and the test results are read and analyzed based on the visualization of the damage reported by the test panel after the impact: the presence of through-hole cracks implies that the test has failed, and the machine guard cannot be installed. Only test panels presenting plastic deformation and no through-hole cracks are considered safe [6].

Many test parameters can influence the withstanding capacity of the guards and primarily the shape of the impacting projectile.

The influence of the projectile shape was investigated by Stecconi [14] and Landi [15] using an experimental approach and performing tests with three different penetrators on polycarbonate panels of 4 mm thickness. Results showed that penetrators with a cylindrical shape and flat head were better-retained by the panels than prismatic [6] and truncated-cone projectiles [11].

Other important specifications can be defined during the design of machine guards and must be considered during the tests, such as the free open window and the constraint overlapping size of the panel subjected to the ballistic impact. This overlapping parameter is very important for the design of polycarbonate vision panels on metallic guards, which is fixed at 25 mm for a standardized panel of 500 $\times$ 500 mm in size.

Many other test parameters affect the withstanding capacity of panels to ballistic penetration, but some of them are difficult to set and fully control during the tests.

Thus, due to a certain number of parameters which cannot been controlled, an inevitable uncertainty affects the current standard impact tests, and a big effort should be made to reduce the unreliability of results. The uncertainties of the test results are related to the material delivery conditions, impact angle, shape of the projectile head, size of the sheet, and stiffness of the frame. Some of these parameters are difficult to control, such as material delivery conditions, impact angle, and velocity. For instance, during its flight, the projectile may be subjected to rotation effects, which affect the impact angle. Furthermore, the impact velocity can be controlled for just 5% of the value.

Landi et al. [15] investigated the dispersion of results of multiple tests at the same impact speed. The results showed that, considering three identical shots, one completely penetrated the machine guard and the other two were retained by the test panel. Thus, this demonstrated that the single impact test prescribed by the standards does not provide completely reliable results to evaluate the withstanding capacity of machine guards.

The effect of other test parameters was studied in [16] through finite element models to be applied on polycarbonate panels of different size and thickness. Overlap and open window sizes were varied within a specific range. Results of simulations showed a reduction in the withstanding capability to penetration for free impact areas smaller than the standardized one (450 $\times$ 450 mm of free surface and 25 mm of side overlapping). This is probably due to the reduction of the open window for smaller sizes and therefore to a reduction of the material's ability to deform without cracks and consequently to adsorb impact energy. Results were experimentally validated by ballistic impact tests carried out at the Fraunhofer institute in Berlin on polycarbonate panels of different thickness [17]. Therefore, the influence of the test panel size is a very important issue to investigate, especially for vision panels of guards usually made by engineered plastics, such as polycarbonate polymers with wear and scratch prevention films.

Statistical aspects were deeply discussed in [15] and the possibility of reducing uncertainties was discussed in [16], where it was clearly stated that with the current test standards, results are not sufficiently reliable, so different test methods and standards should be envisaged.

In these works, all the uncertainty sources were explained and investigated in full detail, and the authors conclude that a single standardized test is hardly reproducible and repeatable because it is affected by local impact conditions.

For all of these reasons, a review of standardized tests is required in the next years, and more testing is expected to measure the data dispersion of different test procedures [18].

In this paper, ballistic tests based on standard test rigs and with standard projectiles are performed on polycarbonate panels, but using a regression approach as in [15,16]. Thus, a set of impact tests are executed with a proper procedure, and the regression curve is obtained. This allows to evaluate the ballistic limit of the material and to set a proper test velocity, named safe velocity, which allows to obtain a reliable result even when performing a single impact test.

Then, the possibility of retrieving a plastic deformation limit to be correlated with the withstanding capacity of machine guards for a given penetrator and a given thickness is investigated through 3D scanners. A new experimental method to investigate the effect of the panel size on the withstanding capacity of machine guards to ballistic penetration is presented.

The withstanding capacity evaluation is performed by analyzing the plastic deformation after ballistic penetration using 3D optical digitizing techniques to determine the maximum deformed area and the reduction of thickness after the shooting tests.

In recent years, 3D scanners have been used in a wide range of industrial applications [19,20], research activities in biomechanics [21–23], and engineering services [24–26].

The present study represents a contribution to perform a revision of standardizations for withstanding capability tests of machine guards (reduction of ejection risk) by using an innovative method based on 3D metrological scanners.

In Section 2, the theoretical bases of ballistic limit evaluation are presented, together with the materials and methods used to perform the ballistic tests and the deformation analysis based on the new approach. In Section 3, the results of tests performed on non-standardized polycarbonate panels of 300 × 300 mm in size, with an open window of 250 × 250 mm, are shown and compared to outcomes of tests performed on standard panels (500 × 500 mm, with 450 × 450 mm of free surface). Experimental outcomes are also compared to theoretical results and discussed with the aim of investigating whether there is a size limit for the plastic deformation zone, which is independent of the panel size. This result forms the basis for considering new reliable test conditions to evaluate the withstanding capability of machine guards for bigger panels than this retrieved size limit.

2. Materials and Methods

In this paper, 13 sample polycarbonate panels of a 4 mm thickness underwent multiple impact tests: seven panels had a size of 300 × 300 mm, and six of 500 × 500 mm. The size 500 × 500 mm was chosen because it is the standardized one and the authors aim at demonstrating that for bigger panels, the test results are not influenced by the size if the shot is centered on the panel. The size 300 × 300 mm was chosen because it is considered as the smaller size, having a practical usability to guarantee a minimum window for inspection in real machines. Then, deformation tests using optical 3D scanners and inspection software were performed to correlate the withstanding capacity to penetration and the size of the test panel. Finally, all the results were analyzed using the ballistic penetration theory based on the well-known Recht and Ipson (R&I) equation [27] which, so far, is the most reliable theoretical method for calculating the ballistic limit velocity of a panel given its thickness.

2.1. Evaluation of the Ballistic Limit

The ballistic limit velocity (V_{bl}) is "the minimum velocity required by a projectile to completely penetrate a target". The R&I equation establishes an exponential relationship between the ballistic limit velocity (V_{bl}), the impact velocity (V_i), and the residual velocity (V_r) of the projectile using two dimensionless parameters (a and p):

$$V_r = a({V_i}^p - V_{bl}^p)^{\frac{1}{p}} \tag{1}$$

$$a = \frac{m_p}{m_p + m_{pl}} \tag{2}$$

where V_r represents the residual speed after the impact, when the projectile fully penetrates the target, p is an exponential parameter, m_p is the projectile mass, and m_{pl} is the plug mass. It is worth to note that $a \leq 1$; if $a = 1$, the plug is absent.

The characteristic parameters of the R&I equation can be found using a statistical approach based on a least squares regression of the data collected from at least five tests [28]. Figure 1 shows a typical R&I curve obtained by regression. The calculated ballistic limit is also highlighted.

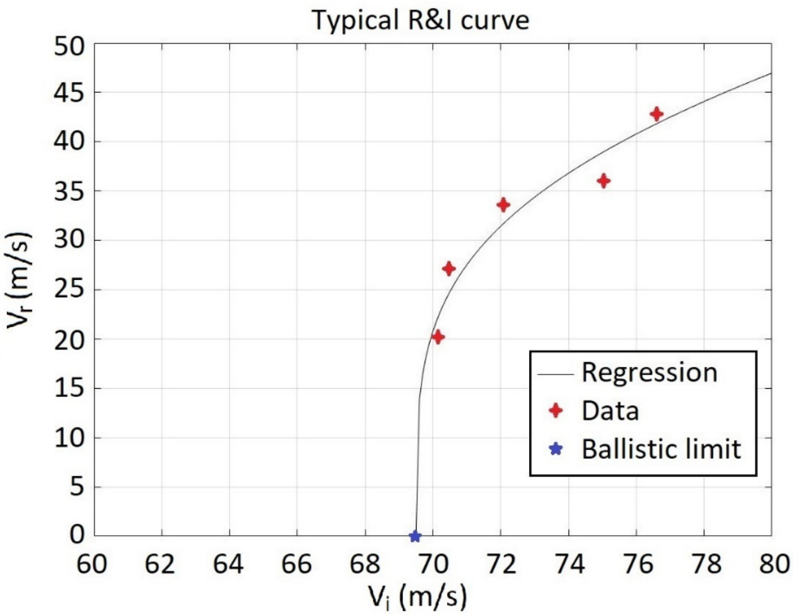

Figure 1. Recht and Ipson curve.

The evaluation of the withstanding limit of machine guards performed following this new approach is reliable and effective. In fact, it allows to consider the dispersion of the results of multiple tests in the evaluation of the ballistic limit. For this reason, regression is a good method to determine the mean or best-fit value of the ballistic limit.

All the tests performed in worldwide laboratories confirmed that, using this approach based on regression, at least five shoots at different initial velocities are sufficient to define V_{bl} with a very good correlation coefficient, R^2, up to 0.99.

When V_{bl} is known, it is possible to use this value to set a safe test velocity (V_{safe}), which allows to perform a single standardized impact test obtaining a reliable result. Nevertheless, according to the conditions of suitability provided by the aforementioned standards, V_{bl} cannot be considered equal to the safe speed (V_{safe}), as a fracture could still begin, and small pieces of material can be ejected outside the machine working zone.

2.2. Impact Tests

Impact tests were performed using the standardized test rig schematized in Figure 2. The test rig comprises the following components: compressed air gun, compressed air tank, and a clamping and support frame with a test panel. To highlight the impact mechanism and measure the impact and residual velocities as requested by the R&I regression technique, the high-speed camera Phantom V710 (Vision Research, Ametek, Wayne, NJ, USA) was employed. Tests were performed at a 10,000 fps frame rate and a resolution of 912 × 304 pixels. The camera was calibrated before the tests. Standard projectiles were used, whose shape and dimensions are shown in Figure 3 and Table 1.

The steel projectile presented the following mechanical properties [6]:

- Tensile strength: 560 N·mm^{-2} $\leq R_m \leq$ 690 N·mm^{-2}
- Yield strength $\leq R_{0.2} \geq$ 330 N·mm^{-2}
- Elongation at rupture: A = 20%
- Hardened to a minimum of 56 HRC over a depth of at least 0.5 mm

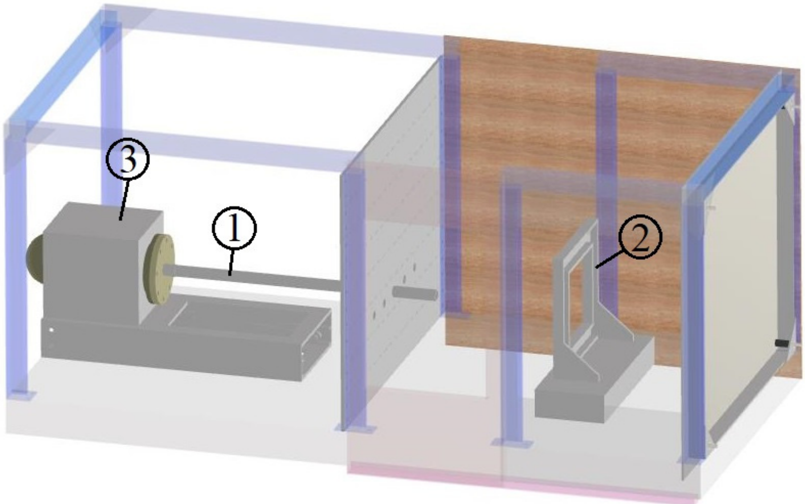

Figure 2. Test rig for ballistic penetration: (1) compressed air gun, (2) clamping and support frame with test panel, and (3) compressed air tank.

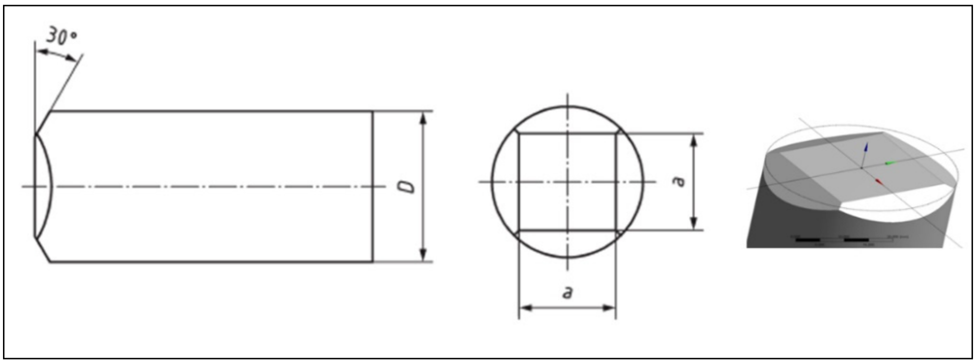

Figure 3. Standard projectile with 3D view of the shaped head.

Table 1. Standard projectile specifications.

Mass (kg)	Diameter (mm)	Flat Impact Area (mm × mm)
0.10	20	10 × 10

Test polycarbonate panels were clamped on all four sides and supported by a steel rigid frame device properly designed to mount the two different panel sizes (Figure 4A). The constraints are adjustable to mount panels of different thicknesses. Furthermore, the clamping device does not come loose during the impact and the window b ensures that the impact area is fully visible by the camera during the test (Figure 4B).

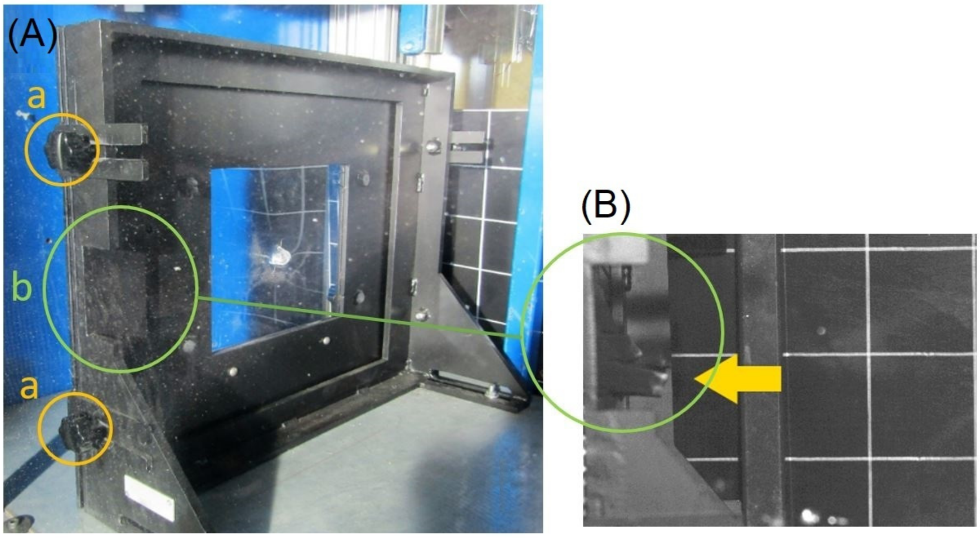

Figure 4. (**A**) Clamping and support system: (a) clamping device, (b) window for camera view. (**B**) Camera framing.

The clamping and support system has a modular structure which allows a quick exchange of the plate sizes. The steel support guarantees a sufficient rigidity during the impact. The clamping frame for standard panels consists of two modules with an open window of 450 × 450 mm, with 25 mm of side overlapping, as prescribed by the standards (Figure 5A). The clamping device is provided by knob screws to allow a simple and fast installation without screwdrivers. The sample guard can be positioned between the two frames and tightened.

A specific module allows to clamp the non-standardized plate sizes (300 × 300 mm, with an open window of 250 × 250 mm and a side overlapping of 25 mm, as prescribed by the standards). A 500 × 500 mm steel plate is placed inside the main frame instead of the standard size plate. The test plate is clamped by a second steel element screwed with four manual knob screws. This clamping and support device guarantees a homogeneity of the clamping forces along the edges (Figure 5B).

The standardized tests imply a perfect perpendicular impact. Test panels were initially located at 71 cm from the gun barrel, but projectiles rotated and did not impact the test panels with a perpendicular direction. In this paper, shot tests with an impact angle lower than 5 degrees from the perpendicularity were considered as valid. The actual impact angle was measured by the high-speed camera. After some tests, the optimized distance to achieve perpendicularity of the impact was found and fixed at 41 cm. The system was initially calibrated performing the so-called "free shooting" (tests at different constant speeds without the test panel installed).

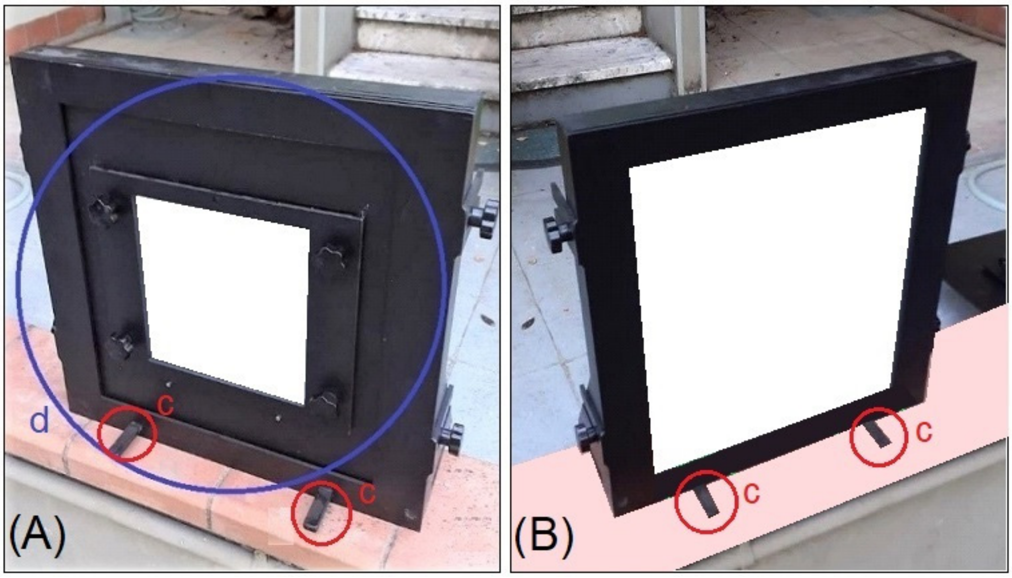

Figure 5. Clamping frame mounting different panel sizes. (**A**) Frame for 500 × 500 mm panels: (c) lower panel supports. (**B**) Frame for 300 × 300 mm panels: (d) smaller panel clamping [29].

In standardized tests, after a single shot with an impact velocity close to the maximum working velocity of the machine, damages on the panels after the impact are evaluated and classified according to the following list [6]:

(a) Crushing/bulging (permanent deformation without cracks)
(b) Incipient fracture (visible only on one surface of the panel)
(c) Through-hole fracture (visible on both sides of the panel)
(d) Penetration
(e) Clamping frame loose
(f) Test panel loose

The standardized test for the guard vision panel is considered to have failed if the projectile opens a crack through the entire thickness of the panel. Thus, the withstanding capability test is "passed" only in the cases (a) and (b). As already discussed in the introduction, this approach does not allow reproducibility and repeatability of the tests and the results are not reliable. In fact, it is demonstrated that multiple standard tests performed on any ductile material plates present an evident dispersion of the results and a low repeatability, even in the same test conditions.

In this paper, 6 impact tests were performed for the 500 × 500 mm panels and 7 for the 300 × 300 mm panels. In the first test, an impact velocity (V_i) higher than the maximum working speed of the machine was imposed, obtaining a full penetration of the guard. V_i was then reduced in the subsequent tests until a residual velocity of 10 m/s was measured. The last test was performed with an impact velocity which does not cause a full penetration of the panel. This allowed to evaluate the residual velocities, V_r, build the R&I regression curve, and evaluate the ballistic limit, V_{bl}.

The panels were chosen with a thickness of 4 mm because this was the only one among the standardized thicknesses that was able to be perforated with the energy available with the current guns in Italy.

2.3. Deformation Tests by 3D Scanners

Deformation measurements were performed by FreeScan UE7 by Shining 3D, a metrology grade portable 3D laser scanner (Figure 6).

The 3D optical digitizer has the following performance parameters:

- Resolution: 0.05–3 mm
- Single shot accuracy: 20 μm

- Volumetric accuracy: 20 μm + 40 μm/m

The test guards were mounted on the clamping and support device already used during the ballistic impact tests and coated with a sublimating 3D scanning spray, to allow the optical scanning procedure on transparent surfaces. Then, high-reflective black contour targets were positioned on the frame to generate the positioning model for the scanning instrument. This allowed to have a reference frame for the measurements also when the 3D scanner was moved manually around the sample (Figure 6) to obtain a real-time 3D digital model of the panel.

Figure 6. Sample panel during 3D scanning with FreeScan UE7.

The 3D digital models of the panels were triangular meshes in STL (Standard Triangulation Language) format, and they were used to perform the deformation analysis by means of Geomagic Control X (3D Systems, Inc., Santa Clara, CA, USA), a certified 3D inspection software. Solid CAD (Computer-Aided Design) representations of all the undeformed test panels before the impact tests were generated inside the software to allow the comparison with the deformed models.

The phases of the digital deformation analysis were:

1. The CAD and STL files of each sample were superimposed and aligned using the undeformed edges as a reference. The undeformed areas were selected around the clamping lines. The alignment criterion was based on the best-fit mesh-to-surface.
2. 3D deformation map generation. This map highlights all the deviations between the new and the deformed panel, displaying each deformation range with a specific color.
3. Delineation of specific deformation diameters. This operation allowed to evaluate a threshold diameter corresponding to the separation between deformed and undeformed zones.
4. Characterization of deflection and thicknesses. Transversal sections of the deformed zones allowed to measure the minimum thickness of the panel after the impact and its position over the deformation zone. Furthermore, the maximum permanent deflection of the panel was measured.

3. Results

Tables 2 and 3 show the results of the ballistic tests, respectively, for 500 × 500 mm panels and 300 × 300 mm panels in terms of initial velocity, residual velocity, and energy lost during the impact, ΔE.

Table 2. Results of the ballistic test on 500 × 500 mm panels.

Test No.	V_i (m/s)	V_r (m/s)	ΔE (J)
1	91.0	50.6	284.4
2	87.1	47.8	263.5
3	85.4	39.8	283.4
4	83.2	35.6	281.3
5	79.6	20.0	294.8
6	61.5	N.P. *	189.1

* No penetration.

Table 3. Results of the ballistic test on 300 × 300 mm panels.

Test No.	V_i (m/s)	V_r (m/s)	ΔE (J)
1	89.8	53.8	258.1
2	87.1	43.8	283.7
3	85.0	35.3	298.6
4	82.6	37.8	269.4
5	81.2	32.46	277.1
6	78.7	14.6	298.9
7	61.8	N.P. *	177.8

* No penetration.

Table 4 reports the best-fit values of the R&I parameters and the total residual error (e_r) for all the tested panels.

Table 4. R&I characteristic parameters and sum of squared residual error (e_r) for 500 × 500 mm panels and 300 × 300 mm panels.

Data	500 × 500 mm Panels	300 × 300 mm Panels
V_{bl} in m/s	78.8	78.4
a	0.8	0.8
p	3.1	3.1
e_r	12.0	60.2

Comparing the results related to the two different panel sizes, one can observe that no substantial variation was evidenced between the two panel formats. In fact, the R&I laws obtained from the experiments on the two panel sizes were practically superimposable and the ballistic limit for both the test conditions was close to 78 m/s [29] (Figure 7).

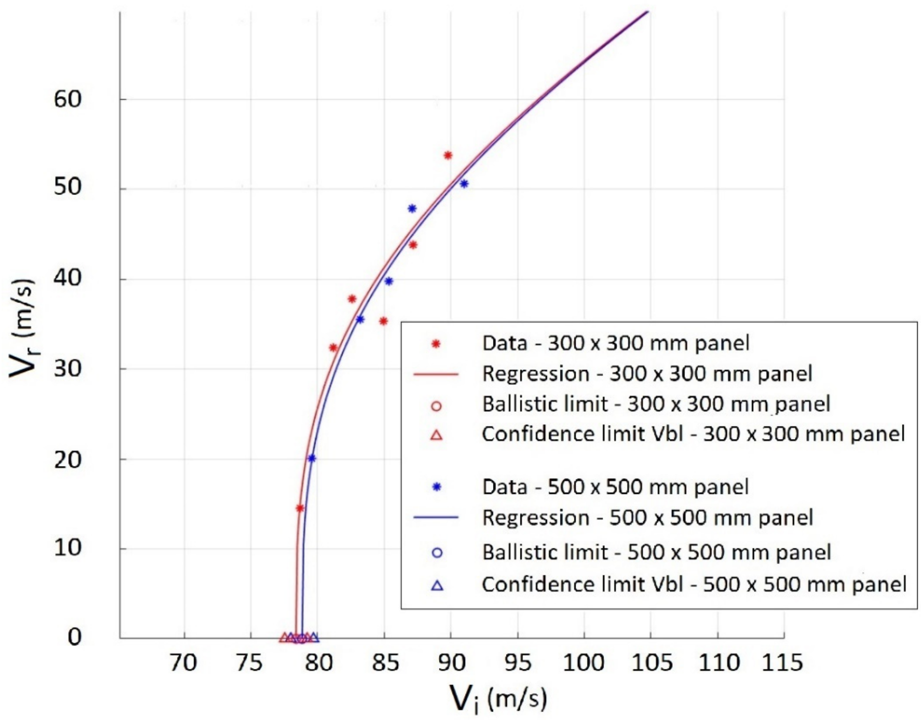

Figure 7. Comparison of R&I laws for the two different plate sizes.

Furthermore, the average energy loss after the projectile impact had a slight variation between the two panel sizes, as can be seen from the boxplots in Figure 8.

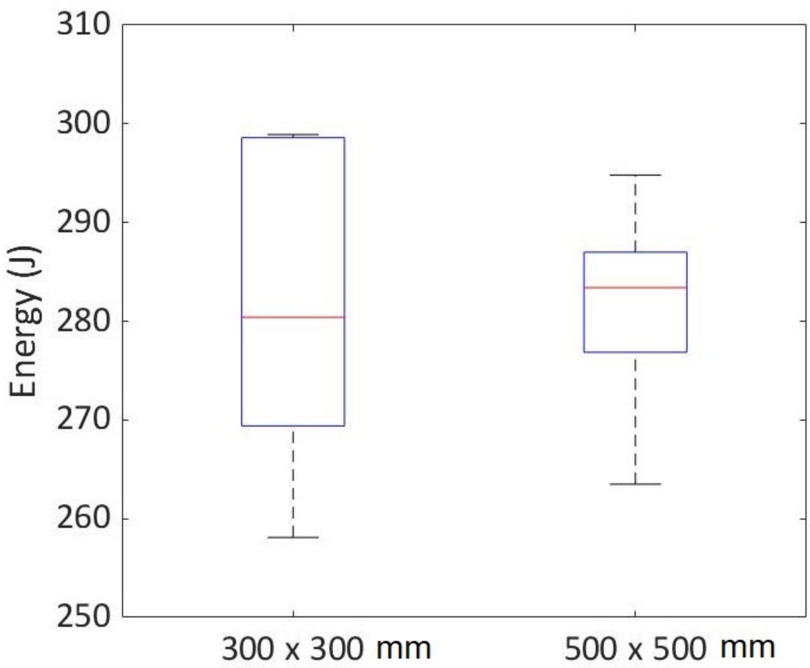

Figure 8. Energy loss in the two test conditions.

Therefore, these results demonstrate that the ballistic withstanding capacity of the polycarbonate was not influenced by the panel size in the range of the considered values, which fit the real working conditions of machine guards. In fact, for industrial machines, guard sizes smaller than 300 × 300 mm are not used in common practice.

Figures 9 and 10 show the results of the deformation analysis on three test panels, two of 300 × 300 mm and one of 500 × 500 mm. The limitation between the yellow and cyan zones represents the threshold curve between the deformed and undeformed areas. The deformed zone can be delimited by a threshold diameter, as represented in the figures.

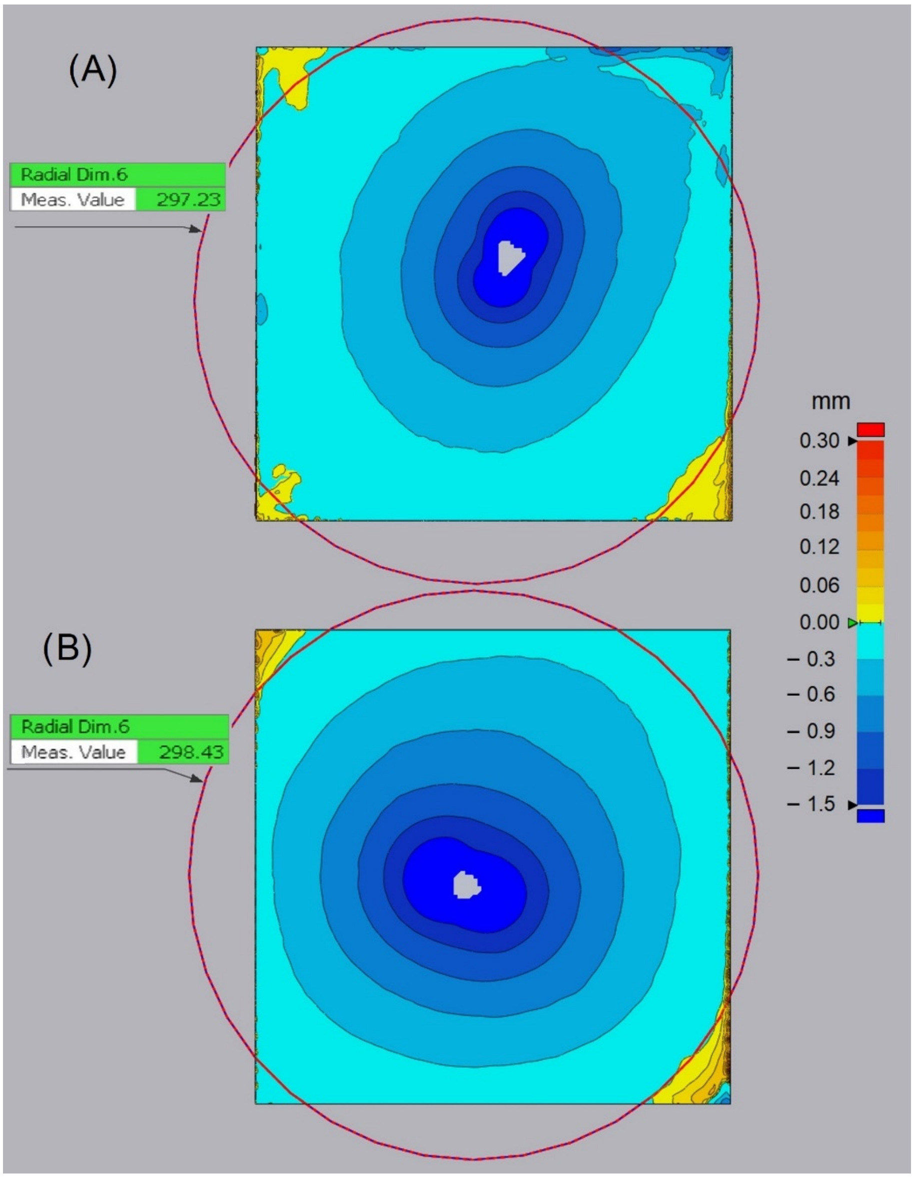

Figure 9. Deformation analysis on two panels 300 × 300 mm with an open window of 250 × 250 mm, and threshold diameter: (**A**) test 6 and (**B**) test 3 of Table 3.

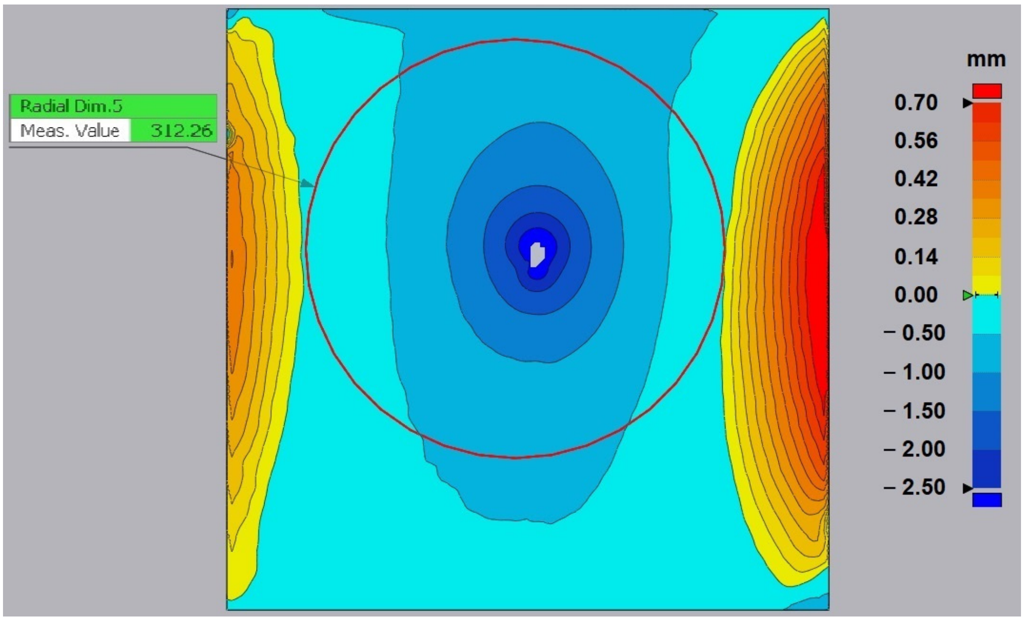

Figure 10. Deformation analysis on a panel 500 × 500 mm with an open window of 450 × 450 mm, and threshold diameter: test 5 of Table 2.

Table 5 reports the values of the threshold diameters found through the deformation analysis by 3D scanners applied to five test panels: three of 300 × 300 mm and two of 500 × 500 mm.

Table 5. Threshold diameters.

Shot Test	Dimension (mm)	Threshold Diameter (mm)
6—Table 3	300 × 300	297.23
3—Table 3	300 × 300	298.43
5—Table 3	300 × 300	290.96
5—Table 2	500 × 500	312.26
4—Table 2	500 × 500	316.84

The 3D scanning technique, which has never been used before in these types of tests, provided "the proof" of the presented empirical findings: the withstanding capacity of polycarbonate machine guards does not depend on the panel dimension in the range of realistic working parameters.

For bigger free vision panels, the same behavior is expected because the major contribution to ΔE is due to plastic deformation of the polycarbonate panel.

The values of the threshold diameters are all distributed around the mean value of 303.14 mm, with a standard deviation of 9.76 mm, and there is an equivalent distribution of impact plastic deformation after the perforation for the two sets of vision panels.

Therefore, the experimental results described in this work, compared with the theoretical ones, demonstrate that a maximum deformation range (constant ΔE) can be defined, independently of the plate size, given the same material, thickness, and penetrator. This result allows to define new ranges for standardized tests, overcoming the limitation of using specific sample sizes if a minimum free area for the plates is used. The 3D deformation analysis also allowed to define the reduced thickness and the "permanent deflection" after the impact (Figure 11).

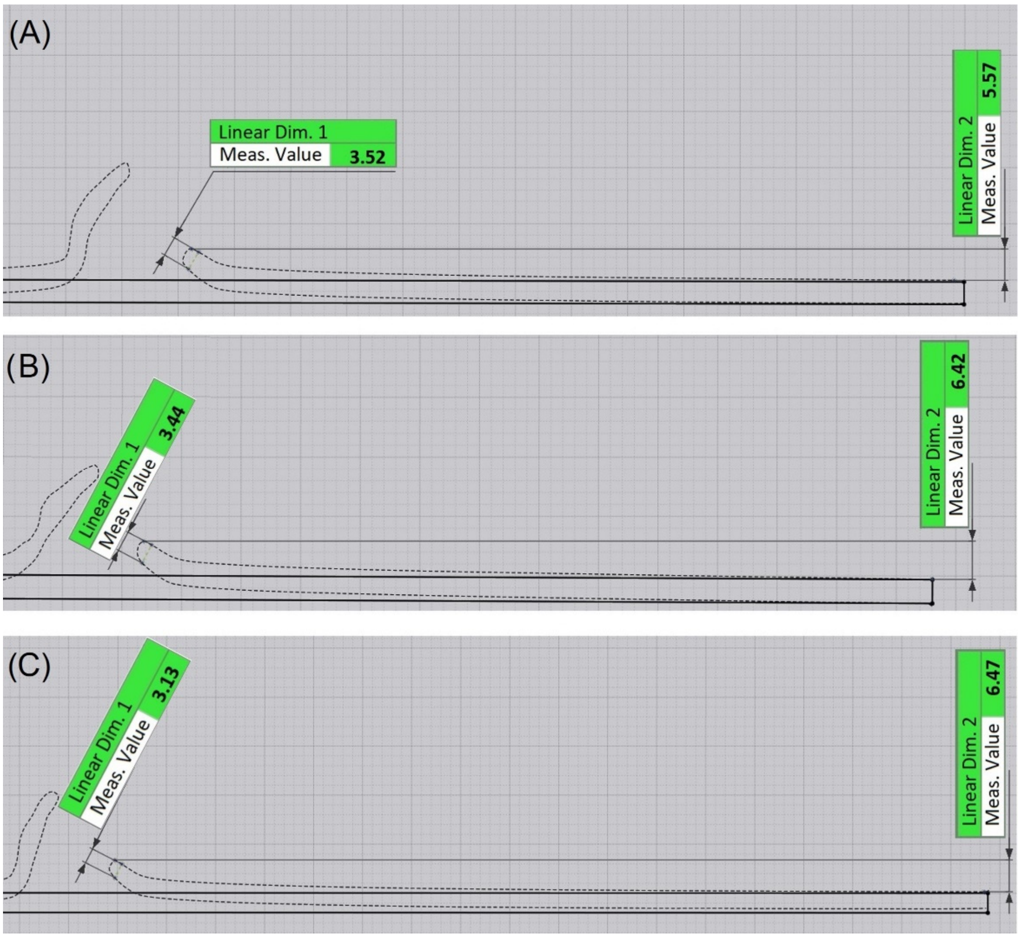

Figure 11. Deflection and reduced thickness of test panels: (**A**) test 6, 300 × 300 mm; (**B**) test 3, 300 × 300 mm; (**C**) test 5, 500 × 500 mm.

4. Discussion

Years of research and practice have demonstrated that the standardized ballistic tests for machine guards, which entail a single shot withstanding evaluation, do not provide a statistical approach to the problem of guards' safety. In fact, multiple single shots with the same test conditions lead to different results in terms of penetration resistance.

Furthermore, with the current methods, the minimum number of shots needed to evaluate the uncertainty of the results is difficult to evaluate because the test is considered "passed" when the panel presents permanent deformations without cracks or an incipient fracture visible only on one surface of the panel. References [15,16] are focused on this topic and all the uncertainties are explained in full detail. According to these articles, the authors conclude that the standardized tests are hardly reproducible and repeatable because they are affected by local impact conditions, and that three shots without any through cracking of the sheet can be considered as the minimum set to be tested for safety requirements. This achievement is not reported yet in any standard regulation and it is under discussion in different working groups of ISO TC 39/SC10. Therefore, the current standardized tests do not allow to make comparisons between different panel design solutions.

This paper, together with other previous works such as [14–16,18,29], was based on a regression approach, implying the execution of multiple tests with the procedure presented in Section 2.2. This approach allows to overcome the aforementioned limitations of the standardized tests, lowering the uncertainty of results due to their dispersion.

In fact, performing six or seven impact tests starting from an impact velocity that will surely imply the full penetration of the tested panel (unsafe condition) and decreasing this velocity in the subsequent impacts to reach a non-penetrating condition, the R&I regression curve can be calculated [27], together with the ballistic limit, V_{bl}.

With this method, the ballistic limit can be predicted with a very good approximation ($R^2 > 0.99$) and the knowledge of this value allows to set a safe test velocity (V_{safe}), which in turn can be used to perform a single standardized impact test, obtaining a reliable result. Nevertheless, according to the conditions of suitability provided by the aforementioned standards, V_{bl} cannot be considered equal to the safe speed (V_{safe}).

The evaluation of the withstanding capacity of machine guards based on V_{bl} allows to investigate how different test parameters affect the test results, such as the panel size. This would be impossible using the current standardized tests.

In this paper, the influence of the panel size on the withstanding capacity to ballistic penetration was investigated with a new method based on the use of a metrology grade 3D portable laser scanner and 3D inspection software. Two panel sizes were investigated: the size of 500 × 500 mm, which was the standardized one, and 300 × 300 mm, which was the minimum panel size allowing the visual inspection of the working zone, when mounted on a real machine. The new presented technique, reported in Section 2.3, allowed to reconstruct the 3D digital models of the panels after the impact test. Then, the plastic deformation was evaluated by 3D maps representing the distribution of deviations between the deformed and undeformed panels.

Results obtained with the regression curve demonstrated that the curve for the two different panel sizes must be considered as the regression of the same experiment; in fact, as Figure 8 shows, the confidence interval of V_{bl} (level 90%) related to the size 300 × 300 mm contains the interval corresponding to the size 500 × 500 mm. The deformation analysis through 3D scanning techniques allowed to identify the reason for this result. In fact, results from the 3D digitization and inspection showed that there is an equivalent distribution of impact plastic deformation after the perforation for the two sets of vision panels and that the plastic deformation zone is limited by a threshold diameter which is almost the same for all the panel sizes. The distribution of all the experimental threshold diameters had a mean value of 303.14 mm and a standard deviation of 9.76 mm. Therefore, it was demonstrated that, given the same material, thickness, and penetrator, the plastic deformation extent was not influenced by the panel size and that there is a minimum panel size to consider when performing impact tests (300 × 300 mm in this case).

Thus, the new presented approach to evaluate the withstanding capacity of machine guards based on 3D scanners allows to define new ranges for standardized tests, overcoming the limitation of using specific sample sizes.

Furthermore, the 3D deformation analysis also allows to evaluate other deformation characteristics, such as, for example, the reduced thickness and the "permanent deflection" after the impact, as shown in this paper. This result formed the basis to evaluate the possibility of other different impact test procedures, considering different parameters or evaluating the convergence of explicit numerical simulations to a correct physical solution.

For instance, the evaluation of the deformation for impact tests with the shot target not located in the center of the panel could provide many insights to investigate different standardizations of tests. In this case, the 3D scanning technique could be used to evaluate the energy loss through the deformation analysis, knowing the elasto-plastic behavior of the material.

5. Conclusions

This paper investigated the withstanding capacity of machine guards to ballistic impacts, with the aim of analyzing the influence of the panel size on the resistance to penetration and on the plastic deformation after the shot. Ballistic tests were carried out using a standardized test rig and penetrator, but also with a new procedure in the field of safety of machinery, based on a regression approach, to limit the uncertainty of results due to their dispersion.

A new deformation analysis protocol employing 3D optical scanners and 3D inspection software was proposed and applied to determine the distribution of deformations over the panel and the reduced thickness and deflection after the impact.

Results of ballistic tests compared to theoretical ones demonstrated that, given the same material, thickness, and penetrator, the panel size does not affect the ballistic resistance of 4 mm-thick polycarbonate guards for free surfaces bigger than 250 × 250 mm, corresponding to a panel size of 300 × 300 mm. In fact, a threshold diameter representing the maximum plastic deformation extent was found for all the tested machine guards, demonstrating that for panels bigger than 300 × 300 mm, the deformation area has a mean diameter of 303.14 mm and a standard deviation of 9.76 mm.

This study represents a contribution to enhance the test procedures for machine guard resistance using new optical digital methods and 3D scanning instruments. The new proposed approach will allow to evaluate all the 3D deformations of the panels and this possibility can form the basis to investigate different impact tests and different standardization annexes. The results of this paper allow to set proper new ranges for standardized tests, overcoming the limitation of using specific sample sizes and shooting perfectly into the center of the vision panel.

Author Contributions: L.L., S.L., G.M. and M.C.V. contributed to conceptualization, methodology, software, validation, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, supervision, project administration, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Cassa di Risparmio di Terni e Narni Foundation—year 2019—Project "Economia, società e salute del territorio ternano: l'Università e sviluppo sostenibile".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: Authors warmly acknowledge Ing. Fabio Pera Dit-INAIL for providing gas cannon for testing.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Valigi, M.C.; Papini, S. Analysis of chattering phenomenon in industrial S6-high rolling mill. *Diagnostyka* **2013**, *14*, 3–8.
2. Moedden, H. Probabilities in safety of machinery—Risk reduction effects by combination of full enclosure and fault detection in the process. In Proceedings of the Risk, Reliability and Safety: Innovating Theory and Practice—Proceedings of the 26th European Safety and Reliability Conference, ESREL 2016, Glasgow, UK, 25–29 September 2017; p. 319.
3. Aldaihani, M.M. Scheduling methodologies for a flexible manufacturing cell with non-identical parallel machines and a robot. *Int. J. Ind. Syst. Eng.* **2015**, *21*, 499–514. [CrossRef]
4. Chan, D.Y.; Bedworth, D.D. Design of a scheduling system for flexible manufacturing cells. *Int. J. Prod. Res.* **1990**, *28*, 2037–2049. [CrossRef]
5. Trump, T.; Etherton, J.; Jensen, R. Machine Guards Can Protect Workers!—I. Ergonomics and Lathe Safety. *Natl. Saf. News* **1983**, *128*, 33–37.
6. UNI. *Safety of Machinery Guards: General Requirements for the Design and Construction of Fixed and Movable Guards*; UNI EN ISO 14120; UNI: Milan, Italy, 2015.
7. Iqbal, M.A.; Senthil, K.; Bhargava, P.; Gupta, N.K. The characterization and ballistic evaluation of mild steel. *Int. J. Impact Eng.* **2015**, *78*, 98–113. [CrossRef]
8. Khan, M.K.; Iqbal, M.A.; Gupta, N.K. A Numerical Study of Ballistic Resistance of a Single Layer Ceramic Target. In *Lecture Notes in Mechanical Engineering*; Springer: Singapore, 2022; pp. 235–247. [CrossRef]
9. Khan, M.K.; Iqbal, M.A. Damage and ballistic evaluation of ceramic-metal composite target against cylindrical projectile. *Eng. Fail. Anal.* **2022**, *131*, 105903. [CrossRef]
10. Khan, M.K.; Iqbal, M.A.; Bratov, V.; Morozov, N.F.; Gupta, N.K. Ballistic resistance of ceramic metallic target for varying layer thicknesses. *Mater. Phys. Mech.* **2021**, *47*, 159–169. [CrossRef]

11. UNI. *Machine Tools Safety: Machining Centers, Milling Machines, Transfer Machines—Part 1: Safety Requirements*; UNI EN ISO 16090-1; UNI: Milan, Italy, 2017.
12. UNI. *Woodworking Machines: Common Requirements—Part 1*; UNI EN ISO 19085-1; UNI: Milan, Italy, 2017.
13. UNI. *Machines Tools Safety: Turning Machines*; UNI EN ISO 23125; UNI: Milan, Italy, 2015.
14. Stecconi, A.; Landi, L. Finite element analysis for impact tests on polycarbonate safety guards: Comparison with experimental data and statistical dispersion of ballistic limit. *ASCE-ASME J. Risk Uncertain. Eng. Syst. Part B Mech. Eng.* **2020**, *6*, 041004. [CrossRef]
15. Landi, L.; Mödden, H.; Pera, F.; Uhlmann, E.; Meister, F. Probabilities in safety of machinery—risk reduction through fixed and moveable guards by standardized impact tests, part 1: Applications and consideration of random effects. In Proceedings of the Safety and Reliability—Theory and Applications—Proceedings of the 27th European Safety and Reliability Conference, ESREL 2017, Portoroz, Slovenia, 7 June 2017; pp. 2155–2164.
16. Landi, L.; Uhlmann, E.; Meister, F.; Pera, F.; Mödden, H. Probabilities in safety of machinery—risk reduction through fixed and moveable guards by standardized impact tests, part 2: Possible improvements with FE impact simulations. In Proceedings of the Safety and Reliability—Theory and Applications—Proceedings of the 27th European Safety and Reliability Conference, ESREL 2017, Portoroz, Slovenia, 7 June 2017; pp. 1967–1975.
17. Uhlmann, E.P.M.; Hörl, R.; Bergström, N.; Thom, S.; Wittwer, P. Experimental investigation of the kink effect by impact tests on polycarbonate sheets. In Proceedings of the 31st European Safety and Reliability Conference, Angers, France, 19–23 September 2021; pp. 1253–1261.
18. Landi, L.; Uhlmann, E.; Hörl, R.; Thom, S.; Gigliotti, G.; Stecconi, A. Evaluation of Testing Uncertainties for the Impact Resistance of Machine Guards. *ASME J. Risk Uncertain. Part B* **2022**, *8*, 021203. [CrossRef]
19. Valigi, M.C.; Logozzo, S.; Rinchi, M.; Galletti, L. New prototype of blade for planetary concrete mixers and wear analysis with a new method [Neuer Schaufel-Prototyp für Planetenmischer und Verschleißanalyse mit neuem Verfahren]. *Betonwerk Fert.-Tech./Concr. Plant Precast. Technol.* **2018**, *84*, 18–25.
20. Valigi, M.C.; Logozzo, S.; Gasperini, I. Study of wear of planetary concrete mixer blades using a 3D optical scanner. In Proceedings of the ASME International Mechanical Engineering Congress and Exposition, (IMECE), Houston, TX, USA, 13–19 November 2015.
21. Affatato, S.; Valigi, M.C.; Logozzo, S. Knee wear assessment: 3D scanners used as a consolidated procedure. *Materials* **2020**, *13*, 2349. [CrossRef]
22. Valigi, M.C.; Logozzo, S.; Affatato, S. In vitro 3D Wear Characterization of Knee Joint Prostheses. *Mech. Mach. Sci.* **2019**, *73*, 3855–3863. [CrossRef]
23. Affatato, S.; Ruggiero, A.; Logozzo, S.; Valigi, M.C. Roughness digital characterization and influence on wear of retrieved knee components. *Appl. Sci.* **2021**, *11*, 11224. [CrossRef]
24. Logozzo, S.; Valigi, M.C.; Malvezzi, M. Modelling the human touch: A basic study for haptic technology. *Tribol. Int.* **2022**, *166*, 107352. [CrossRef]
25. Logozzo, S.; Valigi, M.C. Wear Assessment and Reduction for Sustainability: Some Applications. *Mech. Mach. Sci.* **2022**, *108*, 395–402. [CrossRef]
26. Valigi, M.C.; Logozzo, S.; Meli, E.; Rindi, A. New instrumented trolleys and a procedure for automatic 3D optical inspection of railways. *Sensors* **2020**, *20*, 2927. [CrossRef] [PubMed]
27. Recht, R.F.; Ipson, T.W. Ballistic perforation dynamics. *J. Appl. Mech. Trans. ASME* **1960**, *30*, 384–390. [CrossRef]
28. Landi, L.; Stecconi, A.; Pera, F.; Del Prete, E.; Ratti, C. Influence of the penetrator shape on safety evaluation of machine tools guards. In Proceedings of the 29th European Safety and Reliability Conference, ESREL 2019, Hannover, Germany, 22–26 September 2020; pp. 2936–2943.
29. Landi, L.; Vittori, M.; Stecconi, A.; Valigi, M.C. Influence of design parameters on the penetration resistance of machine guards. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Genova, Italy, 2–5 September 2021. [CrossRef]