Influence of design parameters on the penetration resistance of machine guards

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Abstract. In the last years, different research on ballistic penetration of machine tools guards, as defined in EU Directive 2006/42/EC, were conducted in different worldwide laboratories. Even if the design of machine safety guards using the material/thickness are defined in annexes of ISO standardization, a revision of those annexes is expected in next years. Standardized tests have some limitations because they are performed using a given penetrator that impacts perpendicularly the surface of flat plates of about 500 mm x 500 mm. In this paper the influence of some design parameters will be investigated by polycarbonate sheets of 4mm thickness. The evaluation of ballistic limit for 4 mm sheets of 300 mm x 300 mm and 500 mm x 500 mm size will be presented. Moreover, the influence of constraint on ballistic limit of standardized 500 mm x 500 mm sheets will be also presented by two different constraint devices: one similar to a border hinge constraint, one to a border rigid clamping. Discussion of results will be presented with a view to review the ISO standardization annexes on ballistic penetration.

1. Introduction
The state of the art for the design and validation of safety guards for machine tools is defined by the annex B of ISO 14120 [1], that is the type B international ISO standard. This standard describes the test methodology to determine the ballistic resistance of a safety guard and consequently its suitability for machine mounting. For some types of machine tools, reference should be made to some specific annexes such as ISO 16090-1 [2], that refers to machining centres for metallic materials, ISO 19085-1 [3], for machining centres for woodworking and ISO 23125 [4] for lathes for metallic materials. The test methodology described in these standards is based on the tests conducted by Mewes [5] who has carried out numerous impact tests on steel and polycarbonate guards. The tests for the design of safety guards required by the standards are carried out through the use of a compressed air gun that supplies kinetic energy to a steel projectile, whose shape and size are defined in the annexes. The projectile impacts on a flat tested material panel of fixed dimension at the maximum foreseeable speed.

The validation of the test, and therefore the suitability of the guard, is based on an analysis of the damage reported by the panel as a result of the impact: if a through crack is experienced after the impact, the test is failed. Only bulging with plastic deformation without cracks through the whole thickness is considered as a valid result for safety.
According to the standard, a single successful test is therefore sufficient to define the safety guard in question as suitable for use on a machine tool. However, many research have been conducted and have shown that this deterministic approach is too simplistic than the real impact conditions that can occur within a machine tool as a result of uncontrolled ejection of the workpiece or machine parts. The one single shot is not sufficient to describe the overall penetration resistance of a guard, because many physical parameters can affect the guards and projectile behaviour.

Some studies have already investigated the influence of certain parameters on the withstanding capability of safety guards. Bold [6], through a series of experimental tests, has shown how a tetrahedral-shaped projectile penetrates much more easily into steel plates of 6 mm thickness and polycarbonate of 12 mm thickness than the classic standardized penetrator.

The influence of the shape of the penetrator has also been analysed in Landi et. al [7] and Steconci [8] through the execution of experimental tests on polycarbonate panels of 4 mm thickness using three penetrators of different shapes, showing that a cylindrical penetrator with flat head is less harmful than the prismatic penetrator described in [1] and the truncated-cone penetrator described in [2].

The problem of uncertainty which inevitably influences the results of current impact tests cannot be overlooked and lot of work is being done to reduce this uncertainty.

In Landi et. al [9] the dispersion of results that affects impact tests has been clearly highlighted by multiple shot at the same impact speed. These experimental tests gave contradictory results, as an example one out of three shoots completely penetrated the guard while the other two retained the projectile. These simple examples proved that the one single shot standardized test is not fully reliable at all to evaluate the withstanding capability of safety guards.

Not only the shape of the indenter, but there are many other parameters whose variation has an influence on the retention capacity of the panels. Some of these cannot be completely controlled during the tests, such as the actual angle of impact, in fact the bullet may suffer rotation effects during flight that, although slight, may affect the test results. Other parameters can be defined during setup and test preparation, such as the overlapping of the constraint or the free surface of the panel subject to impact. The effect of these has been studied in Landi et. al [10] through the realization of finite element models with polycarbonate panels of 10 mm and 12 mm thickness, in which overlap and panel opening values are varied within a defined range of values. The simulations have shown some critical points with regard to the use of panels with a smaller opening compared to the standardised opening of 450 mm x 450 mm. This is probably due to the fact that the reduction of the free impact surface reduces the material's ability to plastically deform. This negative influence on the resistance properties of the panels was further investigated and verified experimentally in Gigliotti [11] where the experimental results of ballistic impact tests carried out at the Fraunhofer institute in Berlin on 10 and 12 mm thick polycarbonate panels with an opening of 250 mm x 250 mm are reported, obtaining much lower resistance values than those required according to standards for standard panels with an opening of 450 mm x 450 mm.

In this paper a new experimental study will be presented concerning the effect that the constraint and the resulting free impact surface have on the withstanding capability of 4 mm thick polycarbonate panels. In the following paragraphs the results of tests conducted on non-standard panel dimensions of 300 mm x 300 mm (with effective opening of 250 mm x 250 mm) will be exposed and will be compared with data from tests conducted on standard panels of 500 mm x 500 mm with 25 mm of overlapping on each side (effective opening of 450 mm x 450 mm).

In addition, a study will be presented on the panel constraint system. In fact, a steel support structure has been built for these new tests, with which it is possible to create a clamped constraint on the four sides of the test guard. The results, with the same indenter used and panel tested, will be compared with those obtained from the tests described in [7], in which a support frame was used that made it possible to have hinge constraints on the four sides.
2. Standardized test and R&I ballistic limit

As briefly described in the introduction, the evaluation of the results of shooting tests of impact resistance of guards is based on a single shot at a given projectile velocity. This approach has some relevant limitations, which actually should be considered and analysed for a better design of “safer” machine guards.

Numerous studies have already discussed and analysed these limitations, see [7, 8, 9, 10, 11], highlighting how tests carried out according to the state of the art, with a deterministic approach, do not allow an exhaustive description of the resistance properties of safety guards.

It is necessary to evaluate the withstanding capability of the guard by carrying out multiple shot tests, the results of which can then be analysed using the well-known R&I equation, which, so far, is the most reliable for calculating the ballistic limit velocity of a panel of defined thickness and material.

This velocity is defined as “the minimum velocity required by a projectile to completely penetrate a target”. It must be clarified that this cannot be considered as a safety speed according to what are the conditions of suitability provided by [1] as an incipient fracture could still occur.

The R&I equation is an exponential relation between ballistic limit velocity ($V_{bl}$), impact velocity ($V_i$), residual velocity ($V_r$, velocity after impact when the target is fully penetrated), of the projectile and two dimensionless parameters called $a$ and $p$, see equation (1) below:

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

(1)

The characteristic parameters defined in equation (1) can be determined by a statistical approach based on a regression to the least squares of the data collected from the tests, see [7, 8, 11] for more information. Figure 1 shows a typical R&I curve highlighting the points used for the regression and the calculated ballistic limit.

![Figure 1. Typical R&I curve and regression points.](image-url)
This new approach for evaluating the resistance limit of safety guards, introduced in [8] and subsequently also used in [7] and [11], is particularly effective and reliable. In fact, based on the results obtained from multiple tests, it allows to consider, in the evaluation of the ballistic limit, the dispersion of the results that influences the tests themselves. As a matter of fact, two consecutive shots (performed in the same conditions of initial velocity, projectile shape, target material and thickness, etc.) may lead to different results. As shown in [9], multiple tests performed on 12 mm thick polycarbonate plates showed an evident dispersion of the results, even if the same tests are repeated.

In addition to the determination of the mean or best fit value of the ballistic limit by regression, a study of the statistical dispersion of the results will then be presented, thanks to which it is possible to construct the confidence intervals according to a defined percentage of confidence both on the ballistic limit and on the residual velocities. The method of analysis consists of fixing the parameters a and p in equation (1) equal to their mean values determined by regression to minimum squares and then evaluating the dispersion that characterizes ballistic limit velocity. For more information about the statistical analysis see Stecconi & Landi [12] and Stecconi [8].

3. Design of multiple format clamping device

The need to create a new support device for keeping the guard in position during the tests is due to various reasons. The main reason is related to the possibility of mounting two different plate sizes. The support frame used previously was in fact compatible only with standard size plates measuring 500 mm x 500 mm. Furthermore, the constraint of the previous clamping device was not symmetrical and uniform along the edge (figure 2). The upper side is characterized by a simple unilateral hinge constraint because it is not able to oppose the displacement in the opposite direction to the projectile speed. This solution has been adopted to allow the extraction of the deformed guard after the impact. Also, on the remaining three sides, the constraints can be considered as a simple hinge because this clamping device is a simple slot and it is not able to adapt to the different thicknesses of the tested guards.

![Figure 2. Typical constraint on the old clamping device.](image)

The pre-set characteristics for the design of the new clamping device are:
- multiple formats,
- reduction of setup times,
- constraint system adaptable to different thicknesses of the guards,
- closure system that does not come loose during the impact,
- full visibility of the impact area during the penetration (see b on figure 4).
The model concept was first realized on a 3D CAD platform. A modular system was adopted to allow a quick change of the plate format. The structure was completely made of steel to guarantee the necessary strength and rigidity. The main clamping device for standard-sized is composed of two elements consisting of two frames with an internal opening of 450 mm x 450 mm (by regulation) in order to allow an overlapping along the edge of 25 mm. One of the two frames is 10 mm thick with an L-profile and is equipped with the necessary elements for fixing it in the test apparatus. On the side edge that is exposed to the camera, an opening has been made in the central part to leave the view free on the impact area (figure 3). The locking system provides manually unscrewing screws to allow quick installation without the use of tools (see a on figure 4). The thickness of the second frame is thinner (5 mm). The guard must be inserted between the two frames which are coupled adapting to the thickness of the plate. There are also two small supports on the lower part to keep the guard in position during the tightening phase (see c on figure 5).

A second module is designed for the smaller plate size 300 mm x 300 mm. It consists of a square steel plate with a thickness of 10 mm and dimensions of 500 mm x 500 mm. This should be placed on the main frame in the same position where the standard size plate would be placed (see d on figure 5). In the centre of the plate there is a square opening measuring 250 mm x 250 mm to allow 25 mm overlapping around the edge. The system is constrained by a second steel element with the same square central opening of 250 mm x 250 mm. The guard is held in position by two supports when tightening the four manual unscrewing screws.

The new designed clamping device is characterized by a homogeneous clamped constraint along the entire edge of the panel.
4. Testing

In the following paragraph the comparison between the results of the impact tests described in [8] and the new one performed with the new clamping device will be presented.

In both cases 4 mm thick polycarbonate panels with dimensions 500 mm x 500 mm were used. The projectile used during the tests is the standardized one from 14120 [1]. Shape and dimension of the penetrator are shown in figure 6 and table 1. The mechanical properties of the steel projectile are the following:

- Tensile strength of $560 \text{ Nmm}^{-2}$
- Yield strength $\leq R_{0.2} \leq 690 \text{ Nmm}^{-2}$
- Elongation rupture $A=20\%$

![Figure 6. Standardized projectile shape according to ISO 14120.](image)
Table 1. Standardized projectile mass and dimensions according to ISO 14120.

| Mass [kg] | Diameter [mm] | Impact area (a x a) [mm x mm] |
|----------|--------------|-----------------------------|
| 0.100    | 20           | 10 x 10                     |

The experimental results from [8] and the corresponding best fit values of the parameters of the R&I equation are reported in tables 2 and 3. The total residual (e_r) is also reported.

Table 2. Test results [8].

| Shot | V_i [m/s] | V_r [m/s] | ΔE [J] |
|------|-----------|-----------|--------|
| 1    | 92.19     | 54.81     | 274.77 |
| 2    | 85.10     | 44.75     | 261.96 |
| 3    | 84.21     | 42.52     | 264.12 |
| 4    | 81.97     | 29.28     | 293.10 |
| 5    | 77.74     | 27.67     | 263.85 |
| 6    | 76.14     | N.P.*     | 289.86 |

*not penetrated

Table 3. Best fit parameters for R&I equation [8].

| Parameter | Value |
|-----------|-------|
| a         | 1.00  |
| p         | 1.91  |
| V_{bl} in m/s | 72.66 |
| e_r       | 58.42 |

Table 4 shows the results of the tests executed with the new redesigned clamping device; the best fit values of the R&I curve and the total residual (e_r) are shown in table 5.

Table 4. Test result using new clamping device.

| Shot | V_i [m/s] | V_r [m/s] | ΔE [J] |
|------|-----------|-----------|--------|
| 1    | 91.00     | 50.59     | 284.57 |
| 2    | 87.12     | 47.83     | 263.52 |
| 3    | 85.36     | 39.80     | 283.40 |
| 4    | 83.22     | 35.57     | 281.32 |
| 5    | 79.58     | 20.01     | 294.85 |
| 6    | 61.50     | N.P.*     | 189.11 |

*not penetrated
Table 5. Best fit parameters for R&I equation and mean square error

| Parameter | Value |
|-----------|-------|
| a         | 0.791 |
| p         | 3.10  |
| V$_{bl}$ in m/s | 78.84 |
| c$_r$     | 12.01 |

Figure 7 shows the best fit curves obtained from the tests carried out with the old and the new frame, the experimental data used to determine the best fit parameters and the confidence intervals on the ballistic limit. In the following figures 99% confidence intervals will be used.

Comparing the R&I curves shown in figure 7 and the relative confidence intervals on the ballistic limit, it is evident that the type of constraint significantly influences the results and consequently the retention capacity of the panel.

Specifically, with the new clamping device the panel shows a higher energy absorption capacity with a higher ballistic limit. Moreover, since the confidence intervals on the ballistic limit are completely separated from each other, we can also say with statistical evidence that the two models are not related and that the new clamping device (blue curve on figure 7) guarantees a greater withstanding capability. The better constraint system that characterizes the new device showed a lower dispersion of results. In fact, the previous system is characterized by a greater randomness of the tests directly related to the system of constraint that allows the plate to move more "freely" during the impact.

In energy terms, as shown in figure 8, we can observe that the part of energy lost by the projectile, and absorbed by the guard, during the impact is on average higher using the new clamping device (283...
than the old support frame (271 J). This can be explained by the fact that the constraint of the new frame is almost comparable to a perfect clamped constraint which allows the panel to absorb more energy during the impact. This effect is evident from the traces visible along the edges of the plate in the area of the constraint due to permanent deformation (see figure 9).

Figure 8. Boxplot comparison of energy loss between new and old clamping device.

Figure 9. Deformation traces left on the panel after the test.
In order to investigate the effect of the free surface of the panel on the penetration resistance, a series of tests were carried out on 4 mm thick polycarbonate guards with non-standard dimensions of 300 mm x 300 mm. The test results are shown in table 6, the relative best fit parameters of the R&I equation and total residual are reported in table 7.

**Table 6. Test results 300 mm x 300 mm plates.**

| Shot | \( V_i \) [m/s] | \( V_r \) [m/s] | \( \Delta E \) [J] |
|------|----------------|----------------|------------------|
| 1    | 89.76          | 53.79          | 258.15           |
| 2    | 87.15          | 43.83          | 283.71           |
| 3    | 54.96          | 35.31          | 298.56           |
| 4    | 82.56          | 37.78          | 269.45           |
| 5    | 81.18          | 32.36          | 277.11           |
| 6    | 78.68          | 14.57          | 298.94           |
| 7    | 61.84          | N.P.*          | 177.79           |

*not penetrated

**Table 7. Best fit parameters for R&I equation and mean square error for 300 mm x 300 mm plates.**

| Parameter | Value |
|-----------|-------|
| \( a \)   | 0.789 |
| \( p \)   | 3.10  |
| \( V_{bl} \) in m/s | 78.38 |
| \( e_r \) | 60.22 |

Comparing these results with the results previously seen on standard size panels (table 4), we can see that there is no substantial variation between the two different plate sizes, in fact the curves of R&I are practically superimposed on each other and the ballistic limit velocity for both cases is about 78 m/s (figure 10).
Figure 10. Comparison of R&I curves between 500 mm x 500 mm and 300 mm x 300 mm plates.

As a further proof, the energy lost by the projectile after the impact is maintained on average at the same value, as we can see from figure 11. The ballistic resistance of the 4 mm thick polycarbonate is therefore not affected by the effect of the panel size in the range of values considered. For machinery guards, vision panels smaller than 300 mm x 300 mm are not expected.

Figure 11. Boxplot comparison of energy loss between 500 mm x 500 mm and 300 mm x 300 mm plates.
5. Conclusion
In this paper the influence of constraint and size of the opening on ballistic penetration of transparent panels of small thickness has been presented.

Transparent safety guards of machines, made to offer the full visibility of the work area to persons, are typically made by polycarbonate sheets whose thickness is between 4 mm and 16 mm.

Following previous test, made on 10 mm and 12 mm polycarbonate sheets and projectile mass of 2.5 kg, these new one was conducted to investigate the design parameter relevance on 4 mm thickness with a standardized penetrator of 0.1 kg.

The influence of constraint (clamped or hinge borders) and size on ballistic penetration was studied through the well-known Recht & Ipson curves.

Based on curves on figure 10 no evidence of dependence from size can be claimed by authors. This result is different from the one obtained for thicker panels where smaller windows of 300 mm x 300 mm resulted in a noticeable decrease of withstanding capability of the panels.

In the case of 4 mm thickness the greater part of the permanent deformation of the panels after the penetration is limited approximately to a circle of 150 mm – 200 mm of diameter so we concluded that openings wider than 200 mm x 200 mm has no influence of plastic deformation (energy dissipation).

For the influence of constraint, a new very stiff clamping device was designed to perform the tests.

This device proved to be excellent to clamp also the smaller panels and, based on curves on figure 7, a visible energy plastic deformation/dissipation was experienced near the borders.

It is to conclude that, for future standardization works on safety guards for machines, referring to results on 12 mm – 10 mm and 4 mm sheets for standardized size and smaller no general approach can be claimed such as: smaller is worst or opposite approach.

Also, for constraint design it is not possible to claim general finding because of the different characteristic of standardized penetrator (size and mass) combined to wide variation of thickness and size.

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References
[1] UNI EN ISO 14120°2015° Safety of Machinery Guards: General Requirements for the Design and Construction of Fixed and Movable Guards°BSI Standard Publication
[2] UNI EN ISO 16090-1°2017°Machine Tools Safety: Machining Centers, Milling Machines, Transfer Machines – Part 1: Safety Requirements°BSI Standard Publication
[3] UNI EN ISO 19085-1°2017°Woodworking Machines: Common Requirements – Part 1°BSI Standard Publication
[4] UNI EN ISO 23125°2015°Machines Tools Safety: Turning Machines°BSI Standard Publication
[5] Mewes D, Trapp R P°2000°Impact Resistance of Material Guards on Cutting Machine Tools – Requirements in Future European Safety Standards°International Journal of Occupational Safety and Ergonomics°Vol. 6°no 4°507-520.
[6] Bold J°2004°Trennende Schutzeinrichtungen für Werkzeugmaschinen zur Hochgeschwindigkeitsbearbeitung (Separating protective devices for machine tools for high-speed machining)°Fraunhofer IRB Publishing Company
[7] Landi L, Stecconi A, Pera F, Del Prete E, Ratti C°2019° Influence of the Penetrator Shape on Safety Evaluation of Machine Tools Guards°Conference Paper, Proceedings of the 29th European Safety and Reliability Conference (ESREL)
[8] Stecconi A°2018°Valutazione della Dispersione Statistica delle Prove di Penetrazione per i Ripari delle Macchine Utensili°Master Degree of Mechanical Engineering°University of Perugia (text in italian)
[9] Landi L, Moedden H, Pera F, Uhlman, Meister F°2017°Probabilities in Safety of Machinery-risk Reduction Through Fixed and Movable Guards by Standardized Impact Test. Part 1: Applications and Consideration of Random Effects°Conference Paper, Proceedings of the 27th European Safety and Reliability Conference (ESREL)°pp 1013-LL-rev2

[10] Landi L, Moedden H, Pera F, Uhlman, Meister F°2017°Probabilities in Safety of Machinery-risk Reduction Through Fixed and Movable Guards by Standardized Impact Test. Part 2: Possible Improvements with FE Impact Simulations°Conference Paper, Proceedings of the 27th European Safety and Reliability Conference (ESREL)°pp 995

[11] Gigliotti G°2018°Investigation on Ageing of Polycarbonate Sheets Exposed to Cutting Fluids for Assisted Design of Machine Tools Safety Guards°Master Degree of Mechanical Engineering°University of Perugia

[12] Stecconi A, Landi L°2020°FE Analysis for Impact Tests on Polycarbonate Safety Guards: Comparison with Experimental Data and Statistical Dispersion of Ballistic Limit°Journal of Risk and Uncertainty in Engineering Systems Part B: Mechanical Engineering