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Full guard testing for ejection in machines, from standard requirements to accurate specification

Luca Landi

Department of Engineering, University of Perugia, Via Duranti, 63, Perugia, Italy. E-mail: luca.landi@unipg.it

Gino Zampieri

AC&E s.r.l. Via Del Perlar 37/a Verona(VR), Italy. E-mail: gino.zampieri@ac-e.com

Eros Testi

AC&E s.r.l. Via Del Perlar 37/a Verona(VR), Italy. E-mail: eros.testi@ac-e.com

Claudio Braccesi

Department of Engineering, University of Perugia, Via Duranti, 63, Perugia, Italy. E-mail: claudio.braccesi@unipg.it

Machine Directive (2006/42/CE) states the requirements for designing machine safeguards. In addition, the standard ISO 14120 and the annexes deal with the design of guards for almost all types of machinery.
Following the aim of the law and the mandatory statements, only a well-equipped laboratory can prove and validate the robustness, mechanical capability, stress, and strain state that can be reached during the ballistic impact.
Those requirements claim the necessity of finding "the weakest point on guard," which is tough to fulfill in real testing devices.
The paper presents the design of a new gas cannon device built for maximum flexibility during the test phase and able to shoot in any desired huge guards.
Examples of weak points and design errors highlighted during tests will be discussed according to the most counterproductive point requirements.
Opportunities to modify the state of the art of tests will be discussed at the end of the paper.

Keywords: machine tools guards, the safety of machinery, ejection risk, ISO 14120:2015, safety test.

1. Introduction

Requirements for the design and construction of machine guards are clearly stated in Directive 2006/42/CE (2006), also called Machine Directive (MD). All safeguards are designed to prevent access to moving parts to the operator during machining. In addition, the subset of safeguards called guards (named also "physical guards") are provided give protection against the ejection of "parts" during operation, such as chips, tools and workpiece fragments.

Discussion on relevant requirements and testing procedures were already presented in detail in other papers in ESREL 2022, such as Landi et al. (2016, 2022a, and 2022b), and will not be repeated for brevity.

The essential statement is the last paragraph of point 1.4.1, annex I, MD:

"In addition, guards must, where possible, protect against the ejection or falling of materials or objects and against emissions generated by the machinery".

This paper will discuss the state of the art of reducing ejection risk for machinery, considering general type B standard for guard design (ISO 14120:2015).

This is the type B standard representing state of the art for testing machine guards to reduce the impact hazard. Its annex B states that:

"This annex also gives basic information about the mechanical testing of guards and shows an example of a test method for guards used on

machines to minimize risks of the impact of parts or workpieces coming from inside the hazard zone. This annex applies to guard materials. The test method gives guidance for projectiles with high velocity (e.g., for ejected parts of the machinery).”

The aim is to simulate a fault condition: the ejection of broken parts of the machine, the workpiece (a part of it), or parts of a tool.

It is essential to understand the testing condition expressed in the annex.

The guard has to be tested with the following:

- the maximum foreseeable tangent spindle speed of the machine, and
- in B.2.2 ISO 14120 requires that *“the targets for the projectiles shall be the weakest and most unfavorable spots on the material sample or the guard.”*

Discussion on problems arising from fulfilling all the requirements for testing are discussed in Landi et al. (2022a and 2022b)

This paper will present the design and practical utilization of a new type of gas cannon that can perform a broader range of tests in section 2.

Using this new testing apparatus, it is possible to move in less than 20 minutes the shooting barrel as desired from approximately 300 mm to 2000 in high and as wish up to 5000 mm in length.

The technical solution finds to have an optimal reproducibility of testing such as:

- constant velocity for a given firing pressure;
- perpendicular of impact;
- reproducibility of test conditions;
- flexibility in the positioning of the shooting point

will be presented in detail.

In section 3, some tests performed using the standardized 100g projectile on huge guards up to 2000mm x 5000mm will be presented to highlight the practical description of the theoretical requirement: *weakest and most unfavorable spots.*

2. New gas cannon prototype for impact test on sample material and complete industrial machinery guards.

The prototype of the cannon was designed with reference to test methods described in the standards:

- ISO 14120-1 and
- ISO 16090-1

The prototype of the cannon was developed with the following main goals:

- flexibility of placement/positioning of tested samples/guards;
- possibility to test sample materials and complete industrial machinery guards of any size and at any point;
- maximize the range of test velocity.

The first version of the cannon was designed to perform impact tests with a projectile with the following characteristics:

- nominal diameter: 20mm
- weight: 100g
- Shape: As described in the reference standards

Cannon length is machined to perform the energy transfer to the projectile.

Speed, energy, pressure, and time are related by physical law.

<u>Design criticality</u>

During the design and after the equipment set up several problems occurred. The technical requirements and the geometrical 3D shape after the impact have a very strong need for ISO 14120 standard, for example the impact of projectile perpendicular to the target.

But several factors can influence the “theory” and lead to a different and unacceptable test.

As an example, it is forbidden to stabilize projectile flight by axial rotation; thus, the consequence is that the inside surface of the barrel cannot be machined to allow for typical gun barrel treatment or other machining.

Another machining along the internal parts can’t be done because the standardized projectile is a “perfect” cylinder with a shaped head along its length before the impact.

Aerodynamics turbulence must be well evaluated while working on the design of the pressure launching system to prevent Von Straul’s effects on the projectile. By the aerodynamics Navier Stokes equations, it is well known that this phenomenon led to a periodical shaking while the projectile is lifted in the air.

Barrel has a nominal internal diameter of 20mm and is fed by a pre-compressed pressure vessel (air or nitrogen).

The projectile's velocity is fine-tuned by the vessel's loading pressure, fed by a pneumatic circuit controlled by solenoid valves.

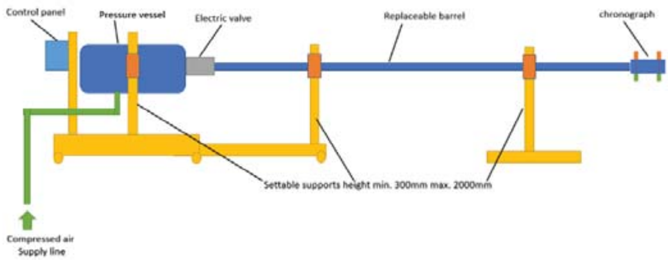

Fig. 1. Sketch of gas cannon configuration

An HMI with touch panel interface (controlled by PLC) permits vessel loading at the desired pressure. The pressure is read in real-time by a digital pressure gauge which returns the signal to PLC, and the instantaneous pressure value is displayed on the operator's HMI panel.

In its current configuration, the cannon can launch a projectile with a diameter of 20 mm and a weight of 100 g, at speeds from min 50 m/s to max 150 m/s, in straight linear flight and without rotation of the projectile in any direction.

Gas cannon position can be set in different configurations because it is installed on a movable frame with breakable wheels (see Fig. 1). The structure also includes a height adjustment by braked carriages so that the impact point can be adjusted from a minimum height of 300mm to a maximum of 2000mm.

A movable shelter (box) with sliding doors guarantees protection from possible rebounds. The shelter (box) can be positioned around the sample under the test or target point (see Fig. 2).

Fig. 2. Photograph of adjustable shelter

Speed measurement is performed by a chronograph installed at the exit of the barrel composed of an electronic system with sensors.

When the projectile leaves the barrel, it sequentially interrupts sensor signals; these signals are detected by an oscilloscope connected with a PC. The software automatically calculates the projectile's velocity (see Figure 4 for the output window of velocity calculation software).

Fig. 3. Photograph of complete configuration

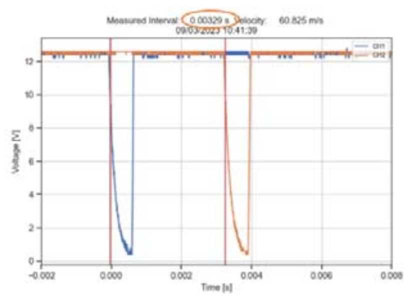

Fig. 4. Example of software measures

Figure 5 presents the sketch of the designed velocity measure by chronograph.

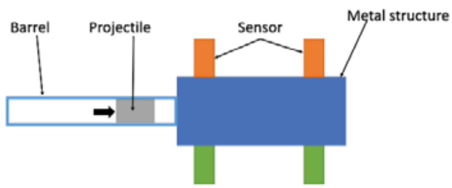

Fig. 5. Sketch of designed chronograph

The calibration table made the relationship between the projectile's velocity and the vessel's operating pressure. To create a calibration table, several launches were performed at different pressures, recording the speeds obtained for each shot. Some test results are presented in Table 1.
The entire calibration table and figure are reported partially for reasons of confidentiality.

Table 1. Sample of the gas cannon calibration test

Test number	Pression (bar)	Velocity (m/s)
T7 (projectile 14120)	2	59,34
T8 (projectile 14120)	2	60,82
T9 (projectile 14120)	2,5	67,39
T10 (projectile 16090)	2,5	67,07
T14 (projectile 14120)	3,5	78,68
T15 (projectile 14120)	3,5	78,75
T16 (projectile 14120)	5	104,64
T17 (projectile 14120)	5	104,53
T24 (projectile 14120)	7	107,92
T25 (projectile 14120)	7	107,81
T26 (projectile 14120)	7,5	111,16
T27 (projectile 14120)	7,5	111,65

As the results presented, the repeatability of the t it is very high (lower than 1% with pressures higher or equal to 2,5 bar). It is to be remember that the velocity error admitted by ISO standard for gas cannon test is 5% or less.

3. Real specification of testing

As discussed in previous works, as Landi et al. (2022a and 2022b), the weakest point condition of ISO 14120 is hard to be claimed in actual testing. The behavior of huge guards to penetration is frequently affected by local conditions such as:

- local connection between materials of different stiffness, such as metals/plastics;
- hinges and/or different types of constraints;
- local stiffness and discontinuous connection systems

The so-called corner test (e.g., impact point far from the center of the sample as for standardized material tests) was already discussed. However, only by introducing a new flexible test, it will be possible to introduce a wide variety of tests on full-scale guards.
A sketch of a typical enclosing guard for machinery is shown in Fig. 6; the real tested guard cannot be shown for confidentiality.
This front side of the full enclosing guard for huge machinery (about 5000mmx2000mm) is divided into two separate symmetrical sections connected by a safety locking system (small black square in Figure 6).
For simplicity and because of symmetry in Fig.6, only half of the guard is sketched; the other one is represented partially with dashed lines.
Every half system is connected independently to the ground by a steel beam (orange) screwed to the floor.
The two main panels (1 and 2 in the figure) are connected with two hinges (yellow in the figure), and panel 1 is also hinged to the support beam.
To reduce the structure's weight, the lower part of panel 2 (green box in the figure) is built using 2 aluminum sheets riveted to the aluminum and steel structure of the panels.
To access the machining zone, the operator must unlock the black locking system and pack each half of the enclosing guard near its supporting beam. Then, each panel can rotate on hinges with a little push.
Because of vision of the machining process is necessary for the operator, a huge vision polycarbonate window is inserted in each panel (blue boxes).
Designing an accurate test specification for a complex full enclosure guard like this is not simply because one must consider different requirements:

R1. general material test for actual size of different materials (covering possible size effect);

R2. local stiffness conditions such as corners and borders of, as an example, vision windows;
R3. fixing between parts of the guards (guard looking, hinges, and fixing of the vision windows);
R4. other local conditions due to multiple sheets of different materials

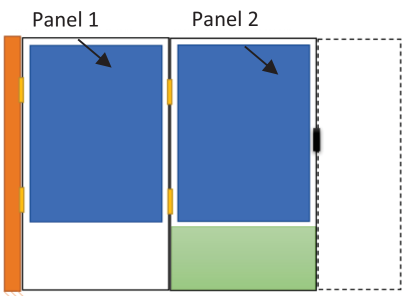

Fig. 6. Sketch of a real guard for a machine tool

Using the general 100g projectile of ISO 14120 as a penetrator, the following test was chosen to fulfill the "general weakest point and unfavorable condition" expressed as a requirement.

The test is divided considering R_xs before:

T1. test performed in the center of the smaller panel of a given material, some tests performed in the past shown that, especially for flexible materials connected with a rigid frame, smaller size is the worst condition; see Landi et al. (2017 a, 2017 b, and 2022b);
T2. tests performed on corners and borders of related materials of very different stiffness or toughness (as an order of magnitude 5 or more). In this case, as an example, more oversized vision windows have to be tested for local conditions;
T3. fixing between parts of the guards (guard looking, hinges) or local stiffness due to discontinuous constraints (e.g., rivets or fast locking);
T4. other local tests due to, as an example, coupling of different materials. Explanation and examples will be shown in paragraph 3.5.

In Fig. 7, test points for the specified conditions are marked with labels such as Tx_y, where x refers to the state, and y refers to the test point (for example, T1_2 test for the center of a panel, test number 2).

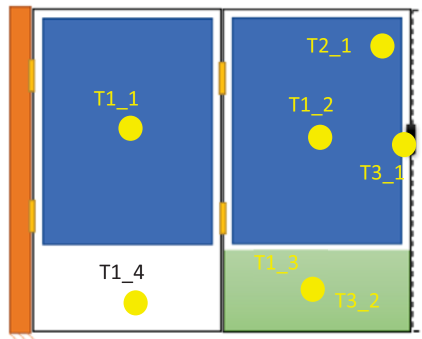

Fig. 7. Test point specification

3.1. *Test on the center (T1)*

In Fig. 8, the typical behavior of a passed test (no thought crack) for the center of the panel in a vision window is presented; primary data for acquisition and results are in Table 2.

In center test for guards, the results are expected to be similar to the one for the material test of ISO 14120 annex B.

In this case, the real global fixing performance of the panel is also tested.

Suppose panels smaller than 500mmx500mm are tested. In that case, different results can be expected that the one widely known for standardized material tests, Landi et al. (2022c), where the window size opening is 450mmx450mm with a frame overlapping of 25 mm on each side.

Table 2. Data for test T1_2

Characteristic	Value
Speed (m/s)	77,8
Acquisition frequency (HZ)	12000
Material and thickness (mm)	Polycarbonate 5mm
Result	PASSED

Fig. 8. Centre test on vision panel; test result is expected to align with the material test for large panels.

3.2. *Test on the corner and borders (T2)*

In Fig. 9, the typical behavior of a failed test for the panel's border in a vast vision window is presented.

Data for acquisition and results are in Table 3.

Table 3. Data for test T2_1

Characteristic	Value
Speed (m/s)	78
Acquisition frequency (HZ)	10000
Material and thickness (mm)	Polycarbonate 5mm
Result	FAILED FIXING

In this case, the material can adsorb the impact as in the previous test, but the fixing cannot retain the vision windows because of the impact-induced vibration.

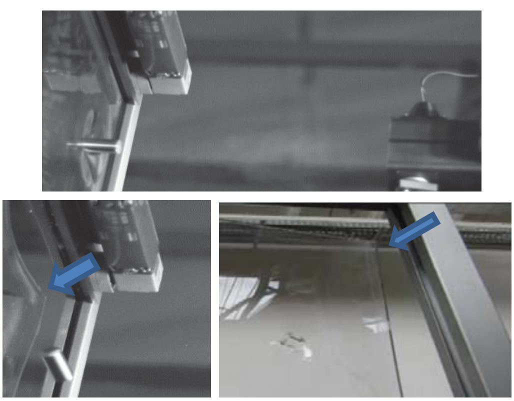

Fig. 9. Corner test on vision window; the bigger one is critical for fixing.

In Fig. 9, the blue arrow focuses on the loosen corner of the vision window.

3.3 Test on the guard locking and local stiffness (T3)

In Fig. 10, the typical guard locking test is presented. In this case, there is a particular risk to be taken into account. If the guard locking is released after an impact (near the locking to induce a locking mechanism break) and the impact opens the guard, the projectile can be projected out of the machining zone.

Table 4. Data for test T3_1

Characteristic	Value
Speed (m/s)	81
Acquisition frequency (HZ)	1000
Material and thickness (mm)	Aluminum and locking system
Result	PASSED

Fig. 10. Locking system test, the locking is not visible inside the machining zone.

3.4 Local fixing (T3)

In Fig. 7, the internal to the machining area aluminum panel (green) riveted to the main board 2 was shown. There are two for every guard section, one inside the machining zone and one towards the operator's position.

During the test T1_3 (center of the panel), the heads of the rivets fixing the aluminum sheet on the machining side were broken by vibration. However, the sheet was not perforated, so the test passed.

The rivets head's strength was insufficient to retain the sheet, and some rivets were ejected (T3_2). However, because the second aluminum sheet was not affected by the impact, the operator side is still safe (test passed).

Even if there is no risk for the operator, this test shows the importance of testing discontinuous fixing such as rivets. In this case the test was performed with speed lower than the others, but the clips were ejected anywhere.

Table 5. Data for test T3_2, T1_3

Characteristic	Value
Speed (m/s)	51,3
Acquisition frequency (HZ)	10000
Material and thickness (mm)	Aluminum 2mm
Result	PASSED

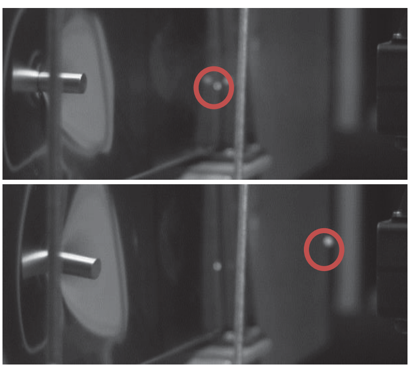

Fig. 11. Local fixing –rivet's heads in red circles

Table 5 presents data for the test; in Fig. 11, rivets ejected into the machining area are shown in two different time frames (the bottom figure is about 80 milliseconds later than the first).

3.5 Coupling of different materials (T4)

Another crucial local condition has been evaluated: coupling material of different stiffness/behavior and blocked deflection of deformable materials.

In some vast guards, coupling different materials is used for cost reduction and/or other design intents. For example, polycarbonate sheets have excellent penetration behavior but are expensive, hardly formable in curved shapes, and hardy paintable.

So, in many machinery guards, polycarbonate sheets in the machining area are coupled locally with ABS (or other lower resistance but high formability materials) outside. The designer intends to divide the withstanding capability function provided by polycarbonate from the visual aspect.

Usually, the deformation of polycarbonate sheets directly impacted by a standardized projectile is wider than the ABS (as an example), whose strength is lower concerning polycarbonate. Moreover, ABS acts to penetrate like a more rigid material and break into parts suddenly with sharp corners.

In Fig. 12, an ABS external grid broken by the impact of the polycarbonate sheet elastically deflected by the impact is shown. The polycarbonate sheet can retain the projectile, but during its deflection, polycarbonate strike on the grid. As a result, parts of the broken ABS grid are ejected toward the operator position (test failed).

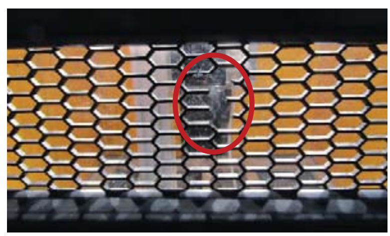

Fig. 12. ABS grid break for secondary strike

In Fig. 13, a polycarbonate sheet is broken by its deflection directly on rivets used to joint another external part of the guard.

In this case, the polycarbonate sheet deflects and leans directly on three aluminum rivets used for the external connection of other guard parts. The deflection of polycarbonate is blocked by rivets that act like a tree point punctual constraint.

The polycarbonate is broken, but the test is passed because the outer part of the guard is not perforated. The machine needs restoring before being used again, as for the examination in paragraph 3.4.

Fig. 13 Polycarbonate fracture due to ABS grid break for secondary strike

As one can see, in this case, the polycarbonate, probably due to very high local pressure on rivets, acts like a rigid material. All these local conditions shall be considered during the design of guards to avoid the local weakness of guards to penetration.

Conclusions

In this paper, the authors presented some possible interpretations of the *weakest and most unfavorable spots* for the standardized testing of real machine tool guards.

Tests performed in the past in typical fixed-position gas cannons showed that some of the requirements stated in type B standards must be clarified and improved to reduce ejection risk.

The examples presented in this paper were possible thanks to the newly designed gas cannon presented in this paper. Those examples were never given and discussed in a paper and are a relevant "practical contribution" to improve the state of the art of standardization. Furthermore, those first examples will help determine future standardization works and real critical aspects for complete guard testing as required by ISO 14120.

The impracticability of the worst-case analysis (e.g., only sometimes the center of the guard is the weakest point, where is the weakest point?) added to the necessity for a precise and repeatable standardized annex for testing must be completed.

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