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# Forensic Analysis of a CNC Lathe Window Guard Failure

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## Abstract

*An analysis of an industrial lathe accident is presented in this paper. During operation, the rotating chuck lost its grip upon the cylindrical workpiece. The detached workpiece impacted the inside of the lathe cabinet, rebounded, struck the composite viewing window, and penetrated it. While observing the machining process through the window, the machinist was struck in the chest by the workpiece. He fell backward, suffering a severe traumatic brain injury when the back of his head impacted the concrete floor. The forensic analysis incorporated an event reconstruction to include an estimate of the ejection angle, velocity, and kinetic energy of the workpiece, the impact energy capacity of the window, and a failure analysis of the window and its frame. A kinetic energy analysis was performed by destructive testing of door/window replicas and high-speed videography. Impact testing of exemplar workpieces against alternative design highly impact-resistant windows was also performed.*



## Keywords

Lathe, machine guarding, window failure, forensic engineering, hazard analysis


## Introduction

This accident occurred at a small family-owned machining job shop. To improve the shop's efficiency, the owner/lead machinist had purchased a new computer numerically controlled (CNC) lathe. The machine was equipped with a steel cabinet that captured chips and fluid during operation and discharged these waste products using a mechanical conveyor that emptied into an adjacent container. The cabinet was equipped with a sliding sheet metal door that featured a viewing window to allow observation of the process. This door and window acted as a guard. A representative of the retailer had delivered the machine, set it up, and trained the purchaser on-site in safe and efficient usage practices over the course of nearly two days just prior to the incident.

The machine measured 12 feet (ft) in length, 5 ft in width, and could turn materials up to 23.6 inches (in.) in length. During the initial job of the first day of production use, a heavy workpiece exited the CNC lathe through the window guard, impacting and severely injuring the machinist. The reason for the detachment of the cylindrical workpiece from the chuck jaws was not in dispute. The hydraulic jaws were only lightly engaged against the outer convex axial periphery of the steel workpiece — with the three jaws each engaging less than 10% of the workpiece length. The center of the 28.2 lbm (12.8 kilograms) 6-in. (15.2 millimeter) diameter steel cylinder had been rough drilled, and a boring bar was engaging the distal end of the cantilevered workpiece to machine this inner hole to its final dimension.

Given the light fixation, the boring tool cut was overly aggressive, and, during turning, the secured end of the steel cylinder opposite the boring bar was pried out of the chuck jaws. Contact impressions strongly suggested that the workpiece interacted with one or more of the chuck jaws upon detachment, which increased the magnitude of the workpiece's translational kinetic energy.

The only surviving exterior photograph of the door and window immediately post-accident is a low-resolution black and white scan (**Figure 1**). The construction of the window was a composite using two different materials. The inner pane nearest the workpiece was made of tempered common window glass (silica-soda-lime), which provided scratch resistance to the metal chips and was inert to the cutting fluid. This inner pane was separated from the outer pane by a modest air gap. The outer pane on the machinist side was made of a kinetic energy absorbing polymer; this outer pane provided the substantive impact protection. **Figure 1** shows the polymer exterior window panel

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bowed outward with a hinge-like crease in the center, and the workpiece chuck is visible at the lower center of the window. The angled red arrow in **Figure 1** is included to show that the surviving polymer window pane is slightly bigger in width and height as compared to the overlapping viewing aperture. The vertical green arrow of **Figure 1** shows the position of the workpiece chuck. The horizontal blue arrow of **Figure 1** indicates where the workpiece grazed the inner steel door window frame and dented the sheet metal. A higher quality color image of the damaged door and window assembly is shown in **Figure 2** with the door detached from the lathe enclosure. This photograph shows the door's interior side. The horizontal blue arrow shows the witness mark of the workpiece against the now-bent inner window frame, which corresponds to the arrow shown in **Figure 1**. The cylindrical workpiece grazed and damaged the steel window periphery as it struck the window substantially off window center.

## Accident Details and Initial Analysis

The lathe was powered by a 18.6 kilowatt (kW) 25-hp motor, which could drive the spindle to a maximum 3,500 rpm. The spindle was rated to hold a 62-kg (137-lb) workpiece. The three jaw chuck, which held the workpiece, was of 254 mm (10-in.) diameter and designed to safely grip a 230 mm (9-in.) diameter workpiece. The chuck was rated to 4,600 rpm. Jaws that were constructed from annealed steel were installed on the chuck at the time of the incident. A stop was machined into the jaws and documented the modest depth of workpiece fixation — ~10 mm (0.40 in.) of the overall ~90 mm (3.5-in.) length. The chuck rotated counter-clockwise when viewed from the direction of the chuck face back toward the spindle and motor.

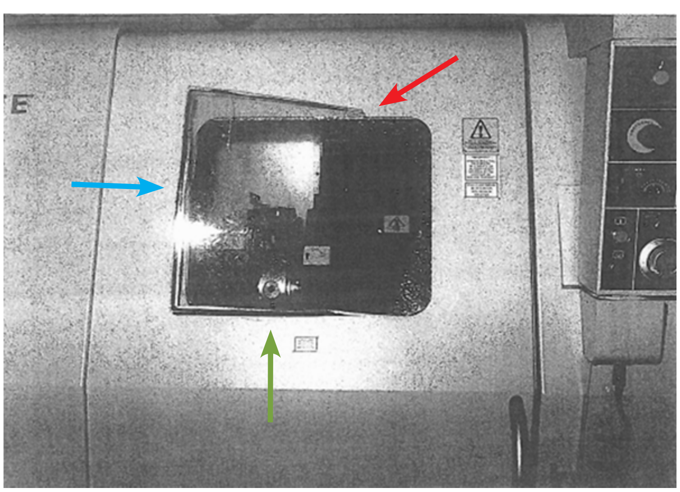

**Figure 1**
Exterior photograph of the mounted lathe door with the outward-side polymer window pane bent and folded outward.

**Figure 2**
Interior side photograph of the detached door guard showing the interior-side tempered glass fragments of the shattered inner window pane and the witness mark damage against the steel frame.

The relevant portion of the door guard consisted of two offset steel panels that framed the observation window — each sheet being 2.3 mm (0.090 in.) thick. The layered window assembly consisted of a 5.0-mm tempered glass inboard surface for abrasion and chemical resistance, then a 5.5-mm air gap, and finally a 4.5-mm polycarbonate outboard panel used for impact energy absorption. The total window thickness was 15 mm (0.59 in.). The unmounted pane measured 532 mm x 452 mm (20.9 in. x 17.8 in.). The daylight opening was reduced by 15 mm per edge through frame overlap (equal to the composite thickness). The opening also featured modestly radiused corners (see **Figures 2** and **3**). The modest edge overlap of the steel frame to the composite window suggests why the polycarbonate pane was pulled out of its frame and plastically deformed rather than being fractured and directly penetrated.

The incident occurred during the first week of unsupervised operation. The workpiece was a steel cylinder 15.2 centimeters (cm) or 6.0 in. in diameter, approximately 8.9 cm (3.5 in.) in length, with an axially drilled through hole 2.26 cm (0.891 in.) in diameter. This hole was being finish bored to its final dimension with a 0.25 mm/rev (0.010-in./rev) feed rate. The only witness to the accident was the machinist/owner who had programmed the lathe and loaded the workpiece. Due to his traumatic injuries, he was permanently incapable of being queried regarding details of the incident.

The machine code was downloaded, and the spindle speed was indicated to be at 1,945 rpm plus an additional 20% manual override (totaling 2,234 rpm). As the workpiece left the chuck, it is believed to have interacted with the rotating jaws — somewhat like an automated baseball pitching machine — as the workpiece had no linear

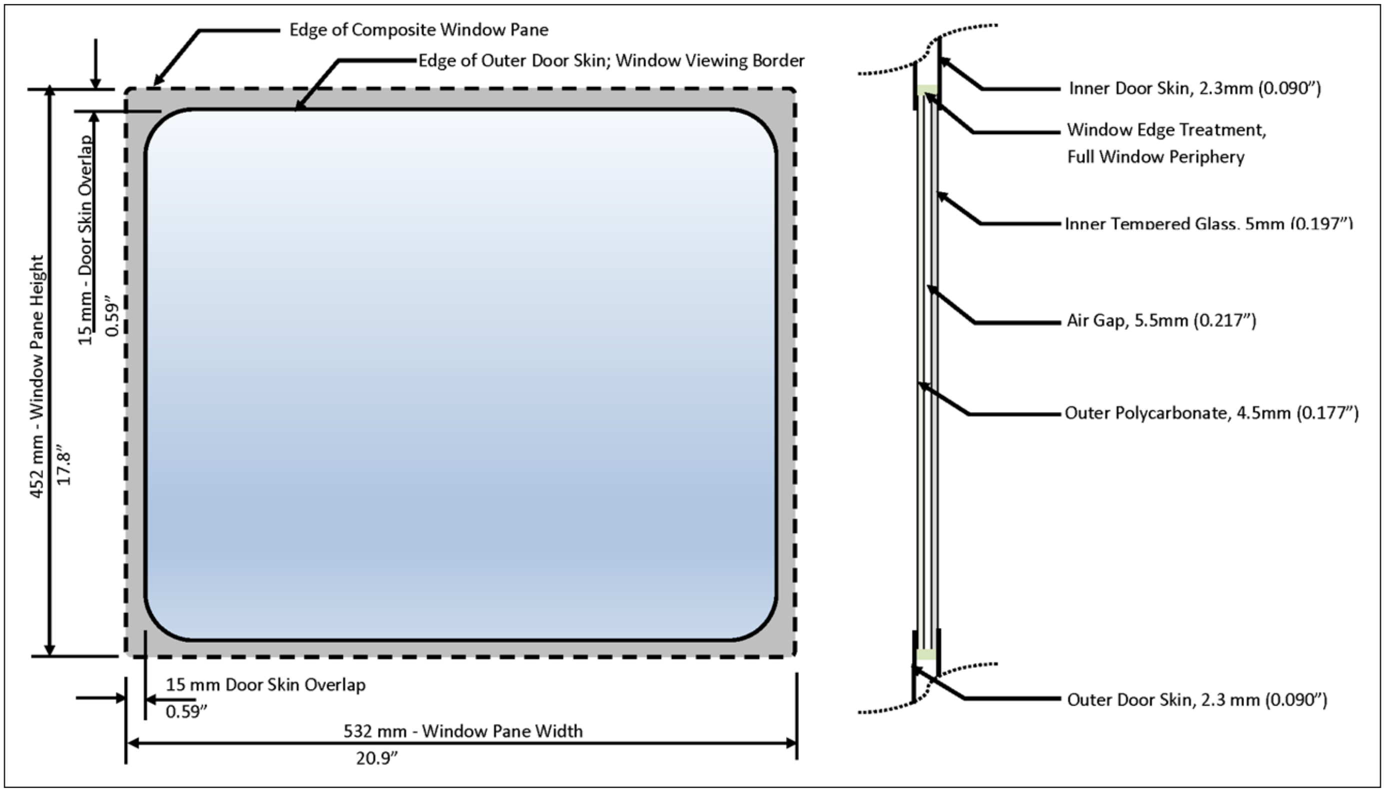


**Figure 3**
Diagram of the subject composite guard window.

velocity at the time of detachment. This added translational kinetic energy to the workpiece, which struck the interior of the glass in the plane at an angle ~30° off-perpendicular — making its flight more or less parallel to the shop floor. See the geometry of the window and door in **Figure 1** (in which the chuck is visible at the lower center of the window).

After fracture of the tempered glass inner pane and displacement of the outer polycarbonate pane, the energetic workpiece struck the operator in the chest and was redirected to the ceiling some 3.5 meters (m) — ~10 ft — above the point of the operator's chest. The workpiece superficially damaged a perforated metal ceiling panel and then fell back to the concrete floor. The operator fell and struck the back of his head against this same concrete floor, which caused substantially more severe injuries than did the workpiece impact to his chest (**Figure 4**).

It is not believed that the rotational kinetic energy consequentially increased the severity of the impact to the observation window and, hence, the operator. All energy calculations are per *Vector Mechanics for Engineers*[1].

- Angular velocity, ω = 2,234 rpm*2π/60 = 234 rad/s.
- Unbored cylinder mass, $M_o$ = π*(0.5*15.2 cm)$^2$*8.9 cm*0.0079 kg/cm$^3$ = 12.8 kg (28.2 lbm)

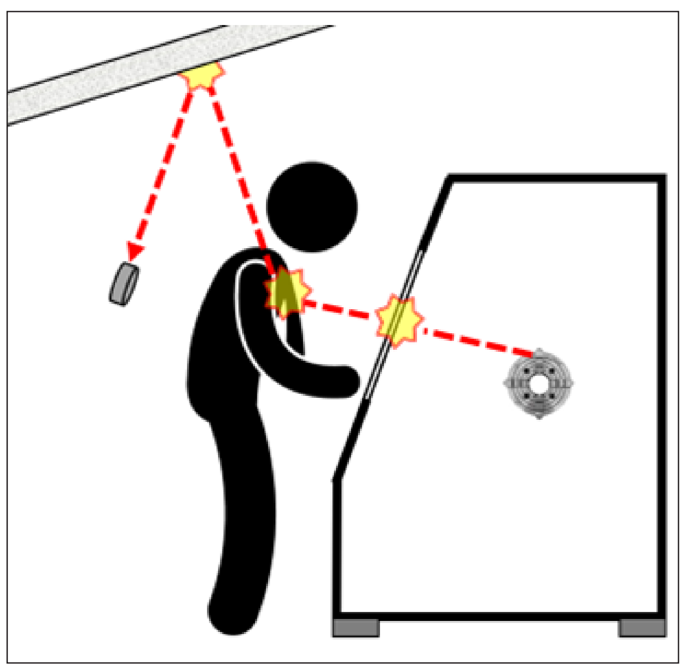

**Figure 4**
Schematic of the cylindrical workpiece path showing three separate impacts (not to scale).

- Lost through-hole mass, $M_I$ = -π*(0.5*2.26 cm)$^2$*8.9 cm*0.0079 kg/cm$^3$ = -0.28 kg (-0.62 lbm)

- Rotational moment of inertia of workpiece = I = ½($M_oR_o^2 - M_IR_I^2$) = ½[12.8 kg*(0.076 m)$^2$ – 0.28 kg*(0.013 m)$^2$] = 0.037 kg-m$^2$ (0.88 lbm-ft$^2$)

- Rotational Kinetic Energy = 0.5*I*ω$^2$ = 0.5*0.037 kg-m$^2$ * (234 rad/s)$^2$ = 1,013 J (747 ft-lbf)

- Initial translational velocity at loss of fixation = 0

- Maximum Calculated Translational Kinetic Energy = 0.5*mv$^2$ = 0.5*(12.8 kg – 0.28 kg)*(0.127 m * 234 rad/s)$^2$ = 5,530 J (4,080 ft-lb)

As is shown, the calculated maximum translational kinetic energy of the detached workpiece from chuck jaw interaction was a multiple more than five times the calculated rotational kinetic energy. The amount of energy absorbed by the window and surrounding door was unknown.

Based upon the post-accident evidence, representatives of the machine tool manufacturer estimated that the accident workpiece impacted the window with 3,062 to 5,580 joules (J) — 2,260 to 4,118 ft-lbs — of translational kinetic energy. This was a multiple of the amount of energy absorption capacity of the window guard that they had previously calculated prior to selling the lathe — 1,450 J (1,064 ft-lb). This estimated window energy capacity assumed that a relatively low mass chuck jaw had detached and struck the window both centered and perpendicular.

Two mechanical engineers made independent estimates of the kinetic energy of the workpiece but only post-ejection. These estimates took into account the energy absorbed at impact to the machinist, travel to the workshop ceiling, and then damage to the ceiling. These two estimates — 440 J and 613 J (325 ft-lb and 450 ft-lb) — would be in addition to the energy absorbed by the window guard and door at impact. These engineers made no independent calculations regarding the impact kinetic energy absorption of the window based upon its construction, mostly in light of the offset nature of the strike that detached the window.

It was decided to estimate the workpiece to window impact energy based upon destructive testing accurately replicating the workpiece size and impact point, and then adding the estimate of the kinetic energy after exit from the window guard to estimate the overall impact kinetic energy of the workpiece against the inner window pane and frame.

## Initial Destructive Testing

A number of test door guards matching the relevant construction details of the accident door were fabricated in order to economically facilitate a series of impact tests. These construction details included the sheet metal thickness, window aperture dimensions and corner radii, tempered glass and polycarbonate thickness and area, and fasteners. The test doors were given a gray powder coat paint application for a visual match.

A series of impacts of workpieces at varying velocity was coupled with post-test analysis to estimate the subject window's generic impact resistance to the accident workpiece and trajectory at the documented impact location. After impact analysis was complete, "reasonable alternative design" door guards, featuring windows having greater impact resistance, were also tested to proof test the proposition that a more impact-resistant window guard would have adequately retained the accident workpiece and prevented the catastrophic injury.

Testing was conducted at a major contract research laboratory in a rural setting that had a large pneumatic launching device. This machine was principally used to launch euthanized chickens at prototype aircraft windshields for impact-resistance validation. The launcher consisted of a breech loading smooth bore rectangular barrel that was attached to a large air reservoir separated from the barrel by a quick-opening valve. Rectangular sabots (thrust transmitting projectile carriers) were constructed from glued up layers of expanded polystyrene to provide a seal between the workpieces and the barrel.

One difference between the testing and the accident was that no consequential rotation was imparted to the workpieces. A second difference was that solid workpieces were used without drilled through holes, making them ~2% heavier than the accident workpieces. Considering that the solid test workpieces were only modestly heavier — and also that the bored hole did not interact with the window during the accident — the geometric differences were not considered to be consequential. Each cylindrical steel workpiece was marked on the face nearest the digital image recording equipment with an "X" to indicate the workpiece center. Launches were recorded using a high-speed video camera oriented perpendicular to the projectile path and centered on the impact point. Since this testing featured 12.8 kg workpieces being launched at an initial velocity of ~30 m/s, all personnel were situated at a remote location during launch.

Two photographs of Test 1, with the first exemplar workpiece leaving the pneumatic launcher, are shown in **Figure 5**. The steel cylinder is moving in free flight from left to right horizontally and is called out with a red arrow in the top photograph. The test door is mounted on a test stand such that the projectile will only modestly impact the right edge of the window frame, accurately simulating the accident. The test door is inclined such that the relative angle of impact, ~28° from perpendicular, is identical to that documented with the accident lathe. The "X" inscribed on the right side of the projectile for frame-by-frame distance determination is also visible in the top photograph. The rectangular detail at left (blue arrow) is a "stripper," which is a barrel end trap that captures the polystyrene sabot after it and the projectile have exited in tandem from the rectangular barrel's muzzle. The four white vertical lines on the ruler centered above the stripper (four green arrows) act as a length reference to facilitate workpiece positional analysis, frame by frame, post-test. These white reference lines are 1 ft (0.30 m) apart. The background behind the test stand and the mounted door also contains a reference dimension grid with 1-ft square offsets.

A plywood sheet was located behind the impacted test door assembly (shown at the right side of each photograph of **Figure 5** with the grain of the wood visible). This wood provided a somewhat neutral visual background for post-test photographs. A photograph of the first tested door post-impact is shown in **Figure 6**. Notice the impact damage at the right side of the steel window frame. The projectile shattered the near side tempered glass and then punctured the far side polycarbonate. In each of the four initial tests, the tempered glass and polycarbonate fractured. In none of the four initial tests did the polycarbonate window flex and peripherally detach as did the polymer window in the subject incident, which may have been a consequence of the orientation of the test projectile being different than that of the unknown impact inclination angle of the incident workpiece. Results of the first four tests conducted

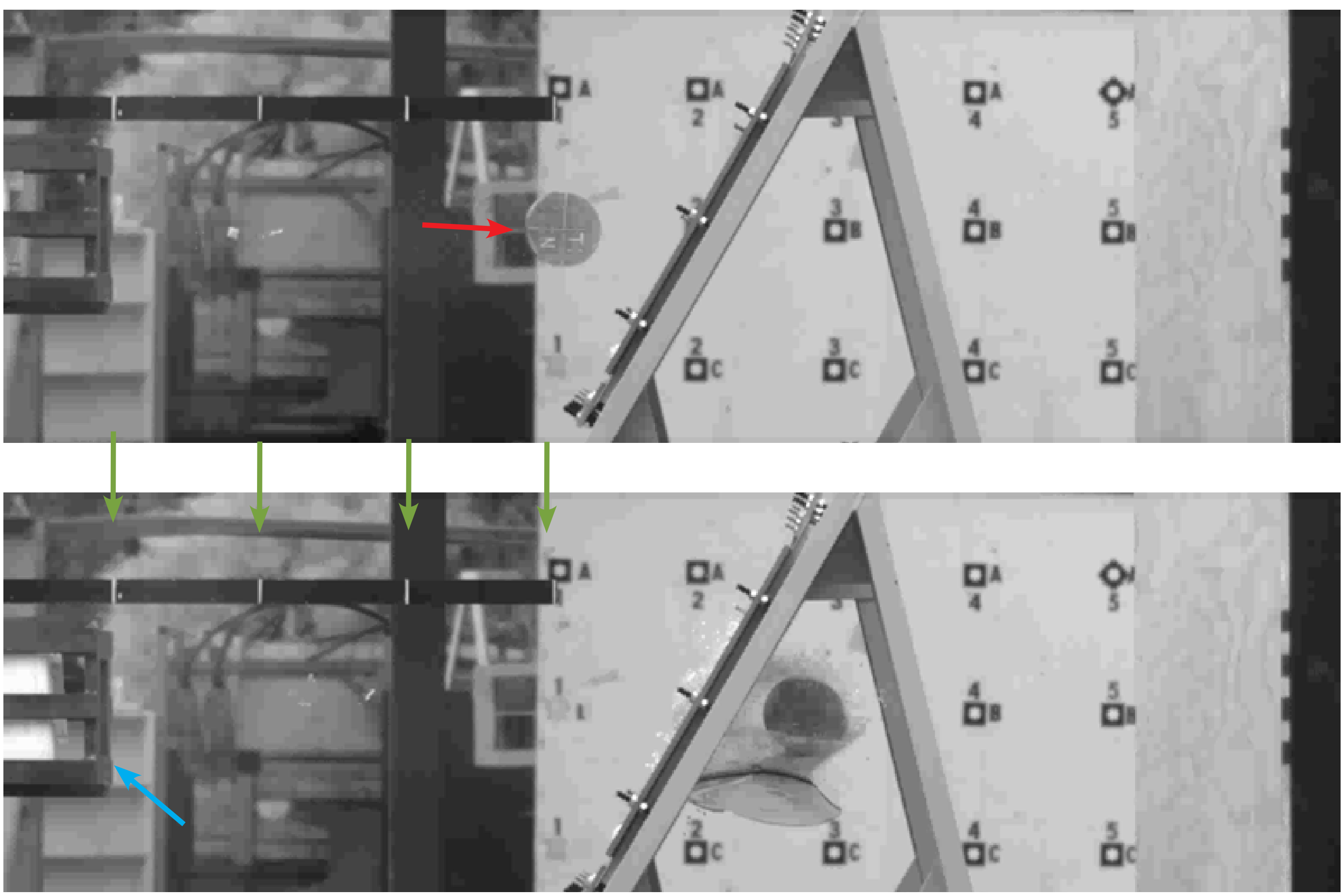

**Figure 5**
Test 1 — the projectile between the launcher and the inclined test door (top); post window penetration (bottom).

are summarized in **Figure 7**.

The data from impact Tests 1 – 4 are plotted in **Figure 8**, which also gives a least-squares curve fit of the data determined by the Excel software. The equation in the inset gives the calculated linear relationship between the workpiece impact kinetic energy and the workpiece exit kinetic energy. As the data set is small (limited to four empirical data points), no $R^2$ goodness of fit value has been provided.


**Figure 6**
Test 1 — photograph of the door from the inclined impact side, post-test, showing impact damage similar to that shown in **Figure 2**.

Using the developed equation $KE_{EXIT} = 0.600^* KE_{IMPACT} - 146$ J and the estimated range of workpiece post-guard penetration kinetic energy (440 J to 613 J), the estimates for workpiece impact kinetic energy are 977 to 1,265 J. This range of estimated workpiece impact severity is significantly less than the estimates of the machine tool manufacturer's engineers: 3,062 to 5,580 J. Further, the testing-based estimate of window guard energy capacity using the most severe of the two impact estimates (1,265 J) gives an estimated window energy absorption of 652 J. This is also less than the analysis of the manufacturer's designers, which was a 1,450 J capacity, albeit using a different impact scenario. Any estimated window guard energy capacity developed by this destructive testing necessarily overstates the capacity of the transparent window panes alone compared to impacts against both the window and the steel frame.

## Relevant Viewing Portal Construction Standards

As this door was sold within the domestic market, U.S. laws and regulations were applicable. However, no federal governmental safety regulation existed at the time of sale for energy absorption of the window/door combination. Two American National Standards Institute (ANSI) standards were applicable, though not governing. The first, ANSI B11.19-2003, "Performance Criteria for Safeguarding,"[2] states under Paragraph 7.1 Design and Construction:

| Test | Mass kb / lbs | V-Impact m/s / ft/s | V-Exit m/s / ft/s | KE-Impact J / ft-lbs | KE-Exit J / ft-lbs | Absorbed KE J / ft-lbs |
|---|---|---|---|---|---|---|
| T1 | 12.8 / 28.2 | 29.8 / 97.8 | 22.6 / 74.2 | 5686 / 4194 | 3270 / 2412 | 2416 / 1782 |
| T2 | 12.8 / 28.1 | 21.3 / 69.9 | 15.7 / 51.5 | 2901 / 2140 | 1576 / 1162 | 1325 / 978 |
| T3 | 12.8 / 28.1 | 15.8 / 51.8 | 12.0 / 39.2 | 1596 / 1177 | 921 / 679 | 675 / 498 |
| T4 | 12.8 / 28.1 | 15.0 / 49.1 | 9.9 / 32.6 | 1442 / 1064 | 628 / 463 | 814 / 601 |

**Figure 7**
Initial impact testing.

- 7.1.1. Material used in the construction of guards shall be of such design and strength as to protect individuals from identified hazards.

A second standard, ANSI B11.22-2002, "Safety Requirements for Turning Centers and Automatic, Numerically Controlled Turning Machines,"[3] contains the following text relative to the subject CNC lathe guard:

- 6.23 Ejected Parts or Fluids

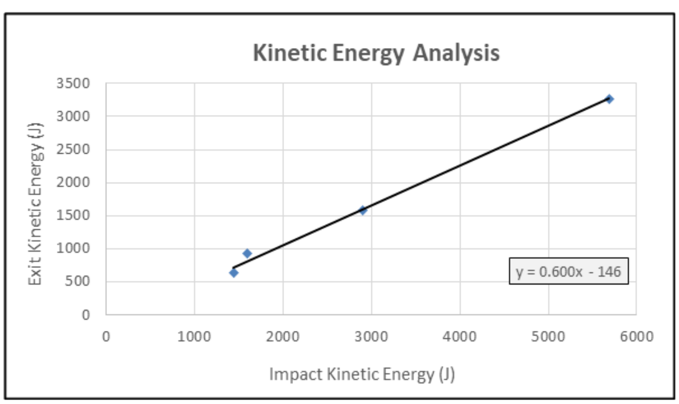


**Figure 8**
Tests 1 – 4 plotted along with a linear curve-fit relationship.

> Persons shall be protected against ejected parts by shields of sufficient strength (including means of fixing to the machine/floor) to contain these parts… These could include things such as broken tools, work material, machine parts and coolant.

- 6.24 Viewing Windows
  When safety guards are equipped with viewing windows, which are also intended to contain ejected parts, consideration shall be given to the selection of materials and the method of their installation.

While these two ANSI standards were informative, they were but aspirational in that neither detailed a protocol for the validation of the minimum level of impact resistance.

The subject CNC lathe was also sold in western Europe. In this market, specific regulatory requirements existed for impact energy resistance of viewing windows. Specifically, regulation EN 12415, "Safety Of Machine Tools - Small Numerically Controlled Turning Machines And Turning Centres," 2001 edition[4], was applicable. *Note: The EN 12415 standard has since been withdrawn and replaced by the ISO 23125:2010 standard, "Machine Tools-Safety-Turning Machines[5]." This ISO standard had not been written at the time of the lathe's manufacture (2006) or the accident (2007). Further, the initial 2010 edition has been superseded by the 2015 revision[6]. The energy requirements are very nearly identical between the ISO standard and the EN standard upon which it was based.*

Table B.2 of EN 12415 is entitled, "Resistance Classes of Windows." For the subject lathe, the diameter of the chuck exceeded 250 mm by 4 mm, making it a "C" class machine. The peripheral speed developed at the rated 3,500 rpm was 46.5 m/s; this placed it in the C2 class as the peripheral velocity exceeded 40 m/s. A window guard for this machine size was required to resist a 2.5 kg impactor at 63 m/s, an impact of 4,960 J (3,658 ft-lbs). The relevant table from the EN 12415 standard is reprinted in **Figure 9**. The tests are conducted using a cylindrical hardened steel projectile with a pyramidal leading endform that has been truncated, giving it a square and flat impact surface. In **Figure 9**, the dimension "a" represents the side length of the square.

Note that the table giving resistance classes for the various windows for machine tools is unchanged except for the borderline between B and C class guard windows between the EN 12415 standard and the ISO 23125 standard of 2010, which replaced it. The ISO standard expanded the B class window category "from 130 up to 250 mm" turning diameter maximum to "from 130 mm up to <260 mm." The subject workpiece chuck, being 10 in. in diameter, would require a C2-class window under the EN standard, but only a B2-class window under the superseding ISO standard.

A 2.5 kg impactor is substantially lighter than was the 12.8 kg accident workpiece. However, the case-specific destructive initial destructive testing strongly suggested that the window pane sold in the unregulated American market would not be able to withstand the required 4,960 J impact of a 2.5 kg impactor as the window was defeated by three impacts of lesser energy — the least of

| Turning Diameter (mm) | | Circumferential Velocity | Projectile Size ϕ x a | Projectile Mass | Impact Velocity | Impact Energy | Resistance Class |
|---|---|---|---|---|---|---|---|
| From | Up To | v (m/s) | (mm x mm) | (kg) | v (ms/s) | (J) | |
| | 130 | 25<br>40<br>63 | 30 x 19 | 0.625 | 32<br>50<br>80 | 320<br>781<br>2000 | A1<br>A2<br>A3 |
| 130 | 250 | 40<br>50<br>63 | 40 x 25 | 1.25 | 50<br>63<br>80 | 1562<br>2480<br>4000 | B1<br>B2<br>B3 |
| 250 | | 40<br>50<br>63 | 50 x 30 | 2.5 | 50<br>63<br>80 | 3124<br>4960<br>8000 | C1<br>C2<br>C3 |

**Figure 9**
Impact resistance classes per European Standard EN 12415 as of 2006[4].

which was 1,442 J. Note also that in each of the initial tests, some portion of the impact energy was absorbed by the window frame, rather than the tempered glass and polycarbonate panes alone.

The unregulated American market lathe window used a 4.5-mm-thick polycarbonate window pane for energy absorption. The regulated European market lathe window used a 12-mm-thick polycarbonate window pane for energy absorption. The EN 12415 standard, along with the superseding ISO 23125 standard, provided a table of polycarbonate window thicknesses for which 6 mm is the listed minimum (**Figure 10**). Note that for the C2 class window, 10 mm of polycarbonate was minimal, while for the B2 class window, 8 mm sufficed.

The development of the EN 12415 and the successor ISO 23125 standards were based upon the seminal work of Mewes and Trapp[7] who used a pneumatic gun similar to that used in the current study to launch a standard projectile at a number of different guard materials, including polycarbonate, several sheet steel alloys, and the aluminum alloy AlMg3. Inspection of **Figure 10** shows that both kinetic energy and projectile mass are relevant to polycarbonate window penetration performance; a projectile of greater mass and — hence greater cross sectional area — requires more kinetic energy to penetrate a given polycarbonate window. For example, a 6-mm polycarbonate window will pass the B1 requirement as it can absorb a 1562 J impact by a 1.25 kg standard projectile, but that same window cannot absorb a lesser 781 J impact by a 0.625 kg standard projectile. Similar comparisons can be made for the 8-mm polycarbonate window (B2 at 2480 J = Pass; A3 at 2000 J = Fail) and the 10 mm polycarbonate window (C2 at 4960 J Pass; B3 at 4000 J = Fail).

The previous work by Mewes cannot be used to directly analyze the subject accident and window capacity, as no 4.5 mm polycarbonate window is listed, and the accident workpiece at 12.8 kg was somewhat more than five times as massive as the largest standard projectile used by Mewes. Further, these validation tests did not have the impactor graze the window frame.

The substantial increase in absorbed kinetic energy of the test windows in this study, as a result of increased projectile velocity (tests T4 → T1), strongly suggests that the window frame was a significant absorber of impact energy. This is supported by earlier work of Mewes[8], which showed the relative insensitivity of polycarbonate energy absorption to impact velocity. This can be attributed to the brittle nature of polycarbonate, which, while energy absorbing, does not deform in a similar fashion to low carbon steel for which the balance of the door/window guard was manufactured. Thus, the substantial increase in window guard energy absorption with increasing workpiece impact velocity can be attributed to the steel construction of the window frame rather than the polycarbonate glazing that was penetrated. One further relevant observation is that when Mewes conducted his testing, he used a 25-mm (1-in.) frame to viewing panel overlap, rather than the 15-mm (0.6-in.) overlap design of the accident lathe window.

## Alternative Design Validation Testing

Two additional tests were performed to validate alternative design windows given two different workpiece impact scenarios. Test 5 used a 12-mm polycarbonate window replicating the construction of the window that was sold on the European market. The frame engagement of this test window was also extended from 15 mm to 25 mm to diminish the probability of a peripheral

| PC Thickness (mm) | Impact Resistance Classes of Machine Tool Safety Windows Energy Capacity Requirements (J) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | A1 320 | A2 781 | A3 2000 | B1 1562 | B2 2480 | B3 4000 | C1 3124 | C2 4960 | C3 8000 |
| 6 | • | - | - | • | - | - | - | - | - |
| 8 | • | • | - | • | • | - | • | - | - |
| 10 | • | • | • | • | • | - | • | • | - |
| 12 | • | • | • | • | • | • | • | • | - |
| 15 | • | • | • | • | • | • | • | • | • |
| 19 | • | • | • | • | • | • | • | • | • |

• Passes requirements of the applicable impact class - Insufficient to satisfy requirement of the applicable impact class

**Figure 10**
Impact resistance classes per European Standard EN 12415 as of 2006[4].

pullout. Test 5 was conducted to determine if this window design would have adequately retained the workpiece in the subject accident. The workpiece was launched at a velocity of 15.0 m/s (49.1 ft/s) to achieve an impact kinetic energy of 1,439 J (1,061 ft-lb), more than 10% greater than the larger of the two estimates of impact kinetic energy provided by the plaintiff's engineers (1,265 J = 933 ft-lb). At impact, the tempered glass shattered, but the polycarbonate window held — and the workpiece was retained.

Test 6 was of a hypothetical "maximum protection" window designed to see if a redesigned window could retain the subject workpiece given an impact energy in excess of the highest impact energy estimated for the subject accident by any party. This alternative design used thicker steel for the exterior door panel and a lattice work of steel across the viewing pane. Lattice work subdivides the daylight opening of the window into a grid and is called "muntin bars" in glazier jargon. In this case, the muntin bars were intended to absorb impact energy in tandem with the polycarbonate window. The Test 6 workpiece (weighing 12.8 kg) was launched at a velocity of 30.7 m/s (49.1 fps), which developed over four times the kinetic energy estimated for the subject accident. The test was successful in that the door and window were heavily damaged, but the workpiece was retained.

Photographs of Tests 5 and 6 are presented in **Figures 11** and **12**. In **Figure 11**, the workpiece is highlighted with


**Figure 11**
Test 5 – European market CNC lathe window using 12-mm polycarbonate pane.


**Figure 12**
Test 6 – "Maximum Protection" CNC lathe window using muntin bars at exterior surface.

| Test | Mass kb / lbs | V-Impact m/s / ft/s | V-Exit | KE-Impact J / ft-lbs | KE-Exit | Comments |
|---|---|---|---|---|---|---|
| T5 | 12.8 / 28.1 | 15.0 / 49.1 | 0 | 1439 / 1061 | 0 | 12 mm polycarbonate |
| T6 | 12.8 / 28.2 | 30.7 / 100.6 | 0 | 6033 / 4450 | 0 | 12 mm polycarbonate + 4.2 mm steel construction + window muntin bars |

**Figure 13**
Validation impact testing.

a green arrow showing rebound. In this test (and this test only), the workpiece missed the frame edge and interacted only with the window proper, ensuring that no energy was dissipated by frame deformation. The test details of Tests 5 and 6 are recorded in **Figure 13**.

## Results and Conclusions

It has frequently been observed in mechanical design that adequate component strength is necessary but otherwise uninteresting. That is, a factor of safety in excess of a consensus standard and justifiably adequate level does not provide any incremental safety benefit, and "more strong than strong enough" is not any more beneficial than is "strong enough" in a practical sense.

For the analyzed accident, inadequate window guard strength was incorporated into the studied U.S. domestic market CNC lathe, and this inadequate window strength was a cause of the injury incurred by the operator. Had the stronger European market window utilizing 12-mm-thick polycarbonate been used instead of the weaker domestic market 4.5-mm polycarbonate window, then the accident would still have caused the door/window guard assembly to be severely damaged and in need of replacement. However, that is likely all that would have happened — no operator injury would have been incurred.

## Acknowledgements

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