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Forensic Engineering Investigation of a Machine Guarding-Related Injury

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Abstract

OSHA regulations and industry-accepted standards are intended to be used in conjunction to help prevent worker injury. Despite the aforementioned intention, a point of operation injury occurred to an employee while he was operating a hydraulic rotary bending machine. The machine had been retrofitted with a two-hand control device that was intended to act as a means of point of operation safeguarding. A forensic engineering analysis of both the electromechanical design and programmable logic code — combined with a performance and prescriptive requirement analysis — ultimately revealed flaws in the design of the electromechanical system and software design. It also demonstrated a lack of adherence to the applicable industry-accepted standards related to machine guarding. These factors led to the point of operation injury.

Keywords

Forensic engineering, standards, machine guarding, safeguard, ANSI B11, OSHA, point of operation, normative reference, NFPA 79

Automated Machinery Hazards

Automated machinery is being used in growing numbers. While the automated machine may be used to alleviate one set of problems (e.g., repetitive motions), machinery may present a different set of hazards. There are several types of hazards related to machinery, such as electrical, noise, and burns. The largest number of injuries to operators occurs at the point of operation in the area where the machine tooling interfaces with the in-process part. As of 2021, machine guarding-related amputations and injuries remain on OSHA's top 10 list of most frequently cited issues[1]. Mechanical hazards are those that can generally be addressed by using machine guarding.

Examples of machine mechanical hazards are[2]:

- Power transmission
- Point of operation
- In-running nip points
- Rotating or reciprocating machine parts
- Flying chips, sparks, or parts

Machine Guarding Requirements

To address the issue of operator injury, OSHA requires that one or more methods of machine guarding be used to protect workers. As it relates to machine guarding, OSHA requirements are performance based — not prescriptive based. Therefore, for point of operation guarding, OSHA requires the guarding be in conformity to any appropriate standards[3], which provide the designer with prescriptive measures used to meet the performance requirements set forth by OSHA.

Voluntary Standards

The American National Standards Institute does not generate standards. Instead, it provides a framework for standards development. There are currently approximately 230 ANSI-accredited standards organizations. Examples of ANSI-accredited standards organizations are B11 Standards, Inc., National Fire Protection Association, ASTM International, and the American Society of Safety Professionals.

Machine Guarding Standards

Machine guarding standards employed within the United States include the American National Standards Institute B11 standards for machine guarding, which are generated by B11 Standards, Inc. These prescriptive-based

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standards specify methods for both the manufacturers of machines (suppliers) and the end-users (users) of machines to utilize in order to minimize the risks involving machine hazards.

The ANSI B11 *Machine Guarding Standards and Technical Reports* consist of documents pertaining to machine guarding. Essentially, these are standards that a person exercising reasonable skill and care would utilize during the design of machine guarding. They are also used by both federal and state OSHA. Additionally, they are used by the legal community in cases related to the safety of machinery[4].

In order to utilize the ANSI B11 standards, the person(s) utilizing the standards must understand their basic structure. The ANSI B11 standards are structured in the ISO type A, B, C structure (**Figure 1**). Type A standards are considered basis standards; they provide basic concepts and principles for design. Type B standards are considered generic safety standards, covering one or more safety topics for safeguards that can be applied to a variety of machinery. Type C standards contain safety requirements for specific machinery[5].

The ANSI B11 standards, like many other types of standards, contain normative references, which are additional documents (or portions of documents) that are incorporated into a standard by reference — meaning they become part of the referencing standard.

Case Study

The following case study details an investigation related to a partial amputation workplace injury involving an automated hydraulic rotary bending machine that was utilized to bend metal tubing. **Figure 2** shows the automated hydraulic rotary bending machine that was involved in the accident.

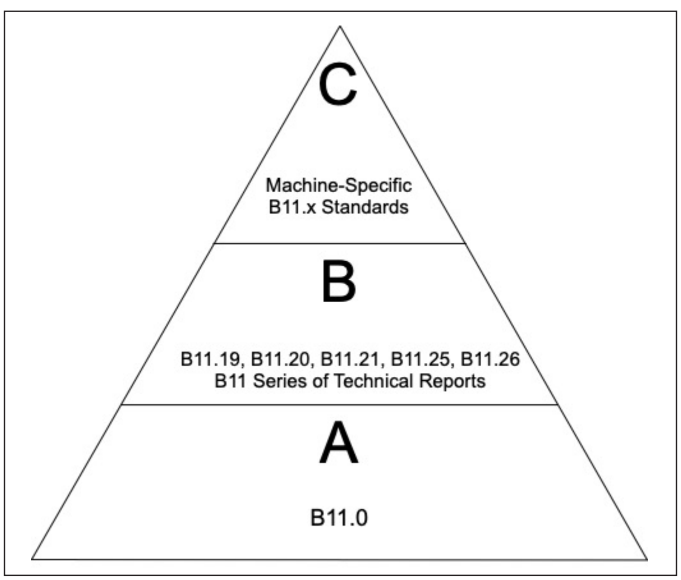

Figure 1
ISO type A, B, C structure, ANSI B11.0 Safety of Machinery[5].

Figure 2
Automated hydraulic rotary tubing bender.

Machine Tooling

The main tooling components are the mandrel, pressure die, clamp die, bend die, wiper die, and bend arm (**Figure 3**). The components are defined as follows:

- Mandrel — provides internal support for the tubing walls during the bend operation.
- Clamp die — holds the tube against the bend die.
- Bend die — the tube is rotated around the bend die during the bend operation.

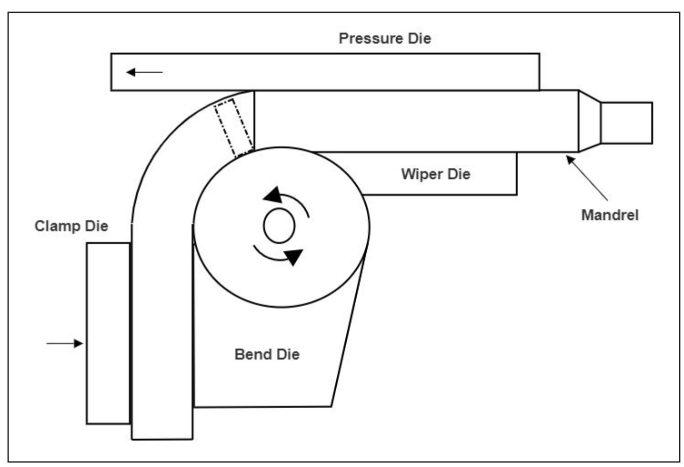

Figure 3
Tooling, ANSI B11.15[6].

- Pressure die — reduces drag and damage to the tube during bending.
- Wiper die — option tooling for use during tight bends to prevent wrinkles.
- Bend arm — rotates the bending die.

In an effort to comply with safety regulations regarding point of operation guarding set forth by OSHA[3], the manufacturing facility purchased a dual palm remote stand (**Figure 4**) from the hydraulic rotary bending machine manufacturer. Per the manufacturer's proposal, the device was intended for enhanced operator safety, and was installed/integrated into the hydraulic rotary bending machine's control system by the machine manufacturer.

Bend Cycle

The machine home position consists of the bend arm in the home position, the clamp die and pressure die open, and the mandrel in the advanced position. In the home position, the machine is ready to have a tube loaded into the point of operation. The operator slides the tube over the mandrel. The operator initiates a bend (forward) cycle by concurrently depressing and maintaining the two forward pushbuttons located on the dual palm remote stand. The clamp die would clamp the tubing, and the bend arm would rotate the bending die. During a forward cycle, the programmable logic controller would monitor the status of the field-mounted bend arm home limit switch in **Figure 5**. The limit switch actuator would be depressed by a bar that would move in concert with the bend arm.

If the limit switch contacts were closed, the programmable logic controller would consider the bend arm to be in the home position. If the limit switch contacts were open, the programmable logic controller would consider the bend arm to be away from the home position. At this point, the operator could remove their hands from the two forward pushbuttons. Once the forward cycle was complete, the bend arm would return to the home position, the mandrel would retract, clamp dies would open, and then the mandrel would advance to await the next cycle. The machine would then wait for the operator to initiate a forward cycle.

The Accident

The intent of the dual palm remote stand was to initiate a machine forward cycle only when each of its forward cycle pushbuttons were depressed concurrently and maintained throughout the time the point of operation hazardous conditions existed. However, the machine operator sustained a partial amputation injury to one of his hands, when the machine performed an unexpected start[5] while he was trying to correct a part placement. He was not depressing both forward cycle pushbuttons when the machine performed the unexpected start.

The Investigation

The operator was not available for interview, but it was learned by interviewing plant personnel that the operator initiated a forward bend cycle and inadvertently depressed the emergency stop pushbutton located on the dual palm remote stand while the bend arm was at a low bend angle position. The operator attempted to resolve the situation by using the reverse cycle to return the tooling to

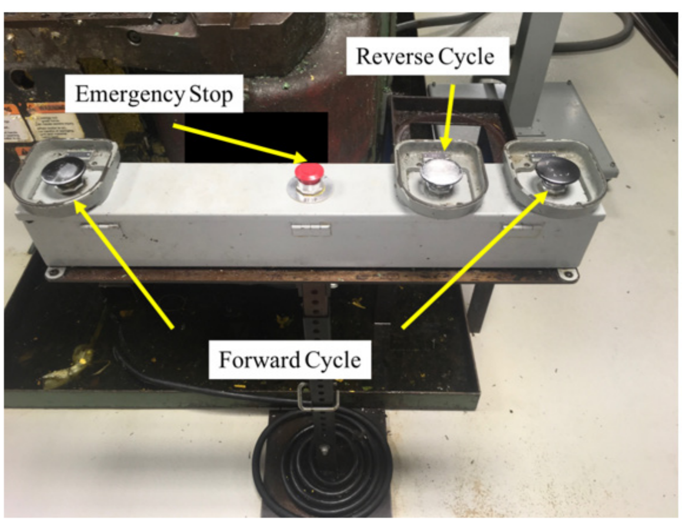

Figure 4
Dual palm remote stand.

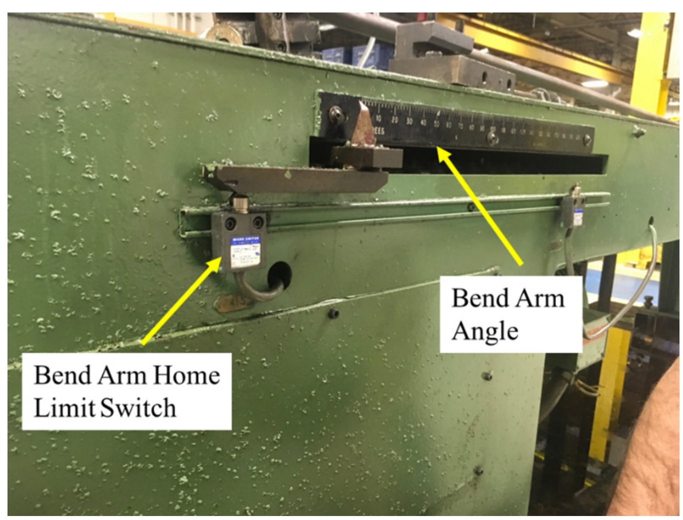

Figure 5
Limit switch.

their home positions. The tubing became dislodged when the mandrel advanced forward to its home position. The operator attempted to grab the tubing and feed it over the mandrel, when the part clamp dies closed unexpectedly — ultimately causing the injury.

Manufacturer's Evaluation

A field service technician from the machine manufacturer performed a separate investigation of the incident. Subsequently, a service report was written. The report indicated that there were three scenarios that would result in an unexpected start. The report indicated that the personal injury was simply the result of a mis-adjustment of the bend arm home limit switch in **Figure 6**. Subsequent to the injury, an updated version of the programmable logic controller software was implemented that was intended to address this issue.

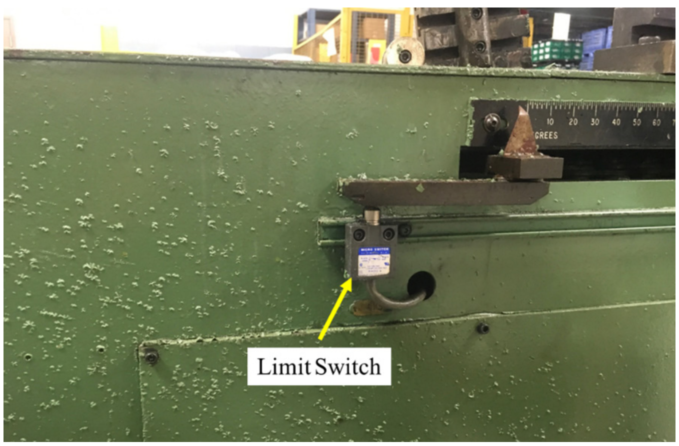

Figure 6
Limit switch alleged to be misadjusted.

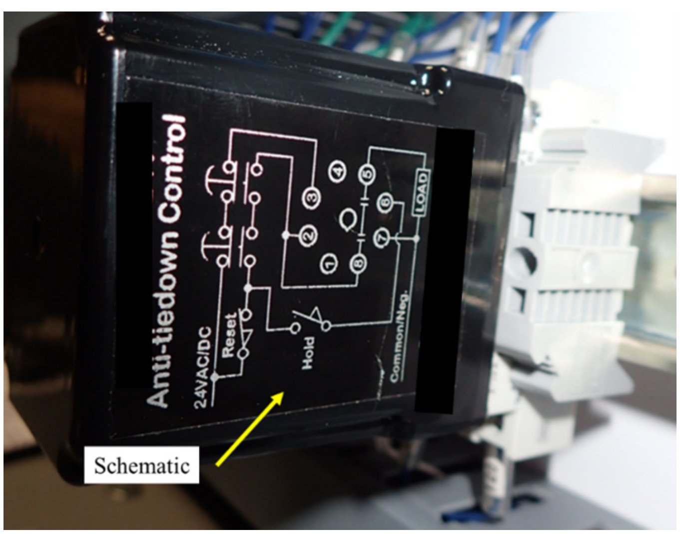

Figure 7
Anti tie-down module.

Forensic Engineer's Evaluation

As a part of the analysis of the failure, the wiring of the system and suitability of the PLC device/PLC code were evaluated. Through analysis of the PLC code, it was determined that the PLC code contained an error where — under certain conditions — an unexpected start could occur.

Figure 7 shows the anti-tiedown safety interface module (SIM) that was used to interface the two forward cycle pushbuttons with the control system. The two pushbuttons were wired into the SIM. According to the manufacturer's documentation (**Figure 8**), the output contacts of the SIM were supposed to be hard-wired to a load, which represents the hazardous machine motions. However, in this instance, the SIM contacts were wired directly to a PLC input.

In this instance, wiring the SIM contacts into the PLC was a design error because the machine was controlled via an off-the-shelf PLC that is not intended for safety-related functions. It should be noted that there are PLCs that are designed for safety-related functions[7,8].

When a machine guarding injury occurs, the goal of the forensic engineer is to determine how and why the injury happened by analyzing the system design. This can involve, in part, machine design, machine controls design, and machine guarding design. After the analysis is complete, the design choices are compared to the applicable standards for machine control and guarding to determine if the design met or exceeded requirements set forth in the applicable standards.

The Type C standard applicable to hydraulic rotary bending machines is ANSI B11.15.[6] ANSI B11.15 contains a flow chart that outlines the responsibilities for addressing machine-related risks. Main risk reduction responsibilities are shared between the supplier and user. The operator needs to comply with safety training and safety procedures. The flow chart contained in ANSI B11.15 further details

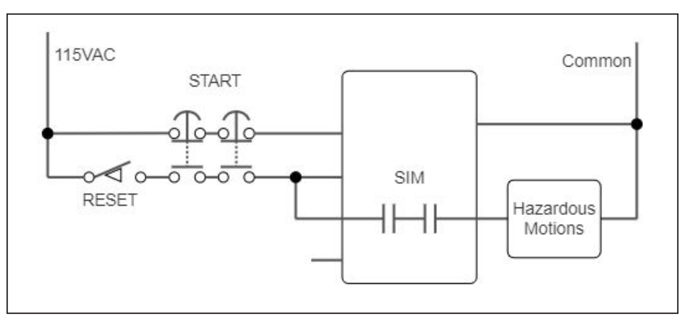

Figure 8
Anti tie-down module schematic.

the applicable ANSI B11 standard(s) for specific tasks.

Machine Safeguarding Device

As stated earlier, the dual palm remote stand (as shown in **Figure 4**) was intended as the safeguarding device, which is one of the methods of safeguarding listed in ANSI B11.15.

Under normal operations, to initiate a machine forward cycle, the operator would depress both forward cycle pushbuttons concurrently and maintain them throughout the time the hazardous conditions exist. As it relates to the hydraulic tubing bender, the hazardous motions ceased when the clamp die clamped the tubing. Once the clamp die clamped the tubing, operators could remove their hands from the pushbuttons because it was then considered safe. ANSI B11.TR6 contains description and information related to two-hand control[9].

Comparison to Applicable Standards

ANSI B11.15 was the Type C standard applicable to Pipe, Tube, and Shape Bending Machines[6]. According to ANSI B11.15, two hand controls are a prescribed method for safeguarding. While a SIM designed specifically for two hand controls was used, it was wired into a PLC input that was not consistent with the SIM instructions and applicable standards, which required the final switching device be a hardwired electromechanical device[8]. There is an exception for PLCs that are listed for safety-related functions; however, the PLC used was not listed for such functions[8].

Discussion

Operator safety must be considered when machinery is utilized. When involving point of operation guarding, the performance-based clauses contained within OSHA require that guarding be done to any appropriate standards. The ANSI B11 series is an example of applicable standards. However, when the safeguarding device is not integrated properly into the machine control system, there is still a risk of operator injury. During the course of a forensic investigation relating to machine guarding, it is important to analyze the machine operation and control and compare those decisions to the applicable standards.

As implemented, the dual palm remote stand and associated components did not meet the requirements set forth by the applicable B11 standards nor the SIM instructions. The intent of hardwiring the SIM contacts to the hazardous machine motion actuators is to prevent operation of the actuators until the SIM contacts are in the closed position. At the time of the incident, the operator was not depressing the forward cycle pushbuttons; therefore, the SIM contacts where in the open position. Had the SIM been wired correctly, the contacts being in the open position would have blocked the start signal from the PLC (due to the programming error) to the actuators. Ultimately, this would have prevented the unexpected start and injury to the operator.

Conclusion

Based on the forensic investigation, it was determined that although it was appropriate to use a safeguarding device in lieu of fixed guarding, the safeguarding device was not properly integrated into the machine's control system. This, combined with a PLC programming error, resulted in an unexpected start and subsequent machine operator injury. Had the machine safeguarding device been properly integrated into the machine control system, the PLC programming error would not have been allowed to initiate the unexpected start, and the machine operator would not have sustained the injury.

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