Design considerations for a directed energy deposition cell

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Abstract. Setting up a robotised additive manufacturing machine requires attention to several safety aspects, including integration of different systems, a functional work area, human-machine interfaces and convenience in operation. This article presents some topics that should be considered in the design and assembly of a cell for robotised additive manufacturing. It is based on experiences from design and assembly of a cell for hybrid DED and grinding in the additive manufacturing laboratory at SINTEF Manufacturing. The cell is designed to ensure safe and stable operation of robot and build unit for additive manufacturing, and to achieve this it is constructed as a steel framework, covered with steel sheet metal and equipped with a ventilation system, laser-proof windows and a roll-up gate. A safety system was designed and integrated to ensure communication between the different elements operating in the cell and coordination of safety mechanisms.

Keywords: Directed energy deposition, Additive manufacturing, Safety design, Safety system, Laser metal deposition

1 Introduction

When working with robots in automated production settings, it is necessary to consider the safety implications in using a robot. A common solution is to place the robot inside an enclosure or cell, which enables access control while also shielding surrounding personnel and equipment from the robot activity. Another possible solution is to program a movement envelope along with load limitations, so that a robot can

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operate in an open environment without being a risk to people and its surroundings. An intermediate solution is to make a virtual barrier around the robot with photocell enclosure, which will stop the robot if the barriers are breached. The enclosure approach is often preferred whenever feasible for the work process, since it enables applying the strength of the robot in the work operation without concerns for personnel safety. A closed cell will also remove the risk of unnecessary emergency stops.

There is a substantial amount of existing publications in which a robot has been used for additive manufacturing, e.g. work done at University West in Sweden [1-3] as well as at Brandenburg University of Technology in Germany [4]. Urhal et al. gave a good presentation of possibilities using a robot for additive manufacturing [5]. However, most publications focus on the research being done with the equipment or the possibilities of the equipment, and less about the design and layout of the surrounding room required to enable safe and efficient research. There are many examples of well-designed and well-built experimental cells around the world, but few describe the design considerations behind a successful cell. This article aims to give some insight into aspects that should be considered to avoid certain pitfalls and to enable safe and efficient use of the research equipment. It presents the solutions implemented by SINTEF Manufacturing in the setup that has been installed in Trondheim with a Kuka robot and a Meltio build head. The considerations in this article will also be relevant for industrial cells, provided compliance with local working environment regulations/labour law.

The input to the design considerations came from personnel with experience both from research, manufacturing industry and oil and gas installations. Bringing this input into the design process was vital to include the necessary considerations into the design.

2 Primary design considerations

Both additive manufacturing of metals and grinding requires several safety implications to be considered due to the energy involved in the processes:

- Robot movement and force: Control of access to the area or force limitations.
- Hot work: Control of flammable materials around the process.
- Rotating machinery: Control of access to area.
- Stray powder and grinding dust: Control of access to the area, ventilation, filtration and exhaust.
- Lasers: Shielding of surrounding personnel and equipment.
- Smoke and fumes from the additive process: Ventilation and control of access to area.

For the equipment and activities at SINTEF Manufacturing, the easiest and most reliable method for mitigating these risks was to build an enclosed cell. Lasers, stray powder, grinding dust, smoke and fumes all result in the need for more protection than a load limitation approach can provide. A sensor-based enclosure could have mitigated some of the risks, but some risks would then have to be addressed by additional measures. This made a full enclosure the only solution that addressed all the main risks with one solution. Finally, an enclosed cell is simple and reliable.

3 Secondary design considerations

Once a closed cell structure had been decided, the detailing work started. The following items had to be considered:

- Structural integrity: The structure should have sufficient strength to withstand accidental loads without risk of structural collapse, typically unintended impact by the robot or during material handling. In the design of the structure, redundancy should be taken into account, taking care to make as many members as possible redundant, meaning that their failure will not lead to a collapse of the structure. Achieving this also simplifies construction work, since less attention must be paid to the execution of the work when redundancy is achieved.
- Stiffeners/structural attachments: This obvious, but often overlooked item is included since the reinforcements required for wall-mounted supports and other structural needs should be included as early as possible in the design phase.
- Heat resistance: Due to the hot-work nature of the AM and grinding processes, the cell should be constructed of mainly non-flammable materials. Any flammable materials should be assessed for substitution.
- Ventilation: The cell should be fitted with an exhaust system to handle smoke, fumes and dust.
- Noise: Grinding is a noisy process, so noise insulation/noise reducing measures should be considered.
- Sealing: To contain dust and noise within the cell, the cell design should enable controlled sealing of surfaces so that the airflow into the cell can be controlled for maximum effect in dust containment and control. Please see Section 4.5.
- Access and material handling: Transport and handling of big and heavy components must be considered so that the cell has sufficient access and lifting aids to enable full utilisation of its potential for work on big components.
- Placement of robot and rotation table: The placement of the robot should preferably be simulated to ensure that there is sufficient room for articulation of the robot without a risk of clashes with adjacent structure.
- Internal monitoring: It is often preferred to be able to see the inside of the cell, e.g. through windows and/or camera surveillance.
- Penetrations: Size, count and location of penetrations through the cell walls for feeding power, signal and other utilities into the cell should be taken into

account. It should be assessed whether it is required to separate instrumentation cables from high-voltage cables, both in general routing and through penetrations.
- Security system: To enable safe use of the equipment in the cell, a security system should be designed and built so that the dangerous components in the cell cannot be used without having signed off the required enablers and so that an emergency stop in one part of the system stops all other processes.
- Emergency escape: Having spent a lot of energy to design a sealed, noise-insulated and structurally strong cell, it is important to have a plan so personnel cannot be trapped in the cell without a means to open it, e.g. in the case of a power failure.
- Operational procedure: An operational procedure should be written to reduce the risk of human errors when operating the equipment.

4 Implementation of design considerations

4.1 Equipment

The following equipment was installed in the hybrid cell:

- Kuka IONTEC KR 70 R2100 robot with KP2-HV500 tilt/rotation table and KR C4 control cabinet.
- Meltio Engine Robot integration package for robotised DED consisting of Meltio build head and Meltio Engine control cabinet.
- Grinding setup consisting of a 3 kW Teknomotor spindle attached to a PushCorp AFD620-2 load cell.
- High-vacuum exhaust system consisting of a Ruwac R01 R022 industrial vacuum cleaner attached to a Ruwac NA 250 wet separator.

The build head from Meltio can use both wire and powder, and utilises six lasers for melting metal, emphasising the need of placing the setup inside a cell, both for the safety of the surroundings, but also for process control.

4.2 Structural activities

The structural design of the DED cell was a steel framework with a usable area of 5000x4000 mm, constructed from 60x30 mm RHS profiles, see Figure 1. Before starting the construction work, a 3D-model of the cell framework was created, from which a set of drawings and a bill of materials was generated. Adjustments during the construction work were continuously updated in the model to ensure that the model would reflect the as-built condition.

The cell was built in-place, and fitted between the concrete floor and concrete element ceiling, total height 3100 mm. The structure consists of five ground sills bolted to the concrete floor with concrete wedge anchors, four top sills bolted to the ceiling and 3050 mm long studs welded to both sills. Stud spacing was determined according to standard sound proofing insulation from Rockwool, i.e. 1180 mm, and intermediate stiffeners were welded in between the studs creating squares of 1180x1180 mm. The structure of the individual walls was welded fully, but the wall sections were not welded together to enable disassembly or future adjustments to the cell. Full welding made the individual welds redundant, removing the need for weld inspection beyond visual inspection.

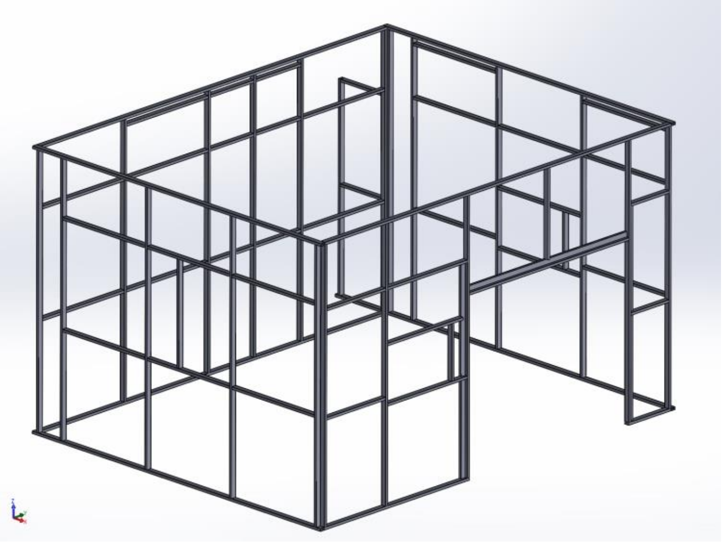


Figure 1: 3D model of cell showing the as-built structural arrangement.

The interior of the framework was covered with 1 mm steel plates, cut to fit the stud spacing and welded to the framework from the outside to provide smooth interior walls and simplify cleaning inside the cell. The walls were insulated with two layers of 30 mm fire-retardant mineral wool noise insulation slab with staggered joints. The exterior of the framework was covered with the same 1 mm steel sheet metal, but the external sheets were installed using self-tapping screws to enable disassembly. The sheets were washed/degreased before installation. Joints between the sheets as well as gaps towards the floor and ceiling were sealed with MS polymer sealant that gives a good combination of flexibility, adhesion and fire-retardant properties. The interior and exterior walls of the cell were painted white using a solvent-based primer followed by a water-based acrylic topcoat with low smoke release in the case of heat damage or fire.

Two laser-proof windows were glued in place using the same sealant. The windows had been ordered specific for the wavelength of the lasers used in the Meltio build head. Protective glass plates were installed on both sides of both windows to avoid damaging the laser-proof window. An insulated roll-up gate was installed to enable access control to the cell and manual opening handles were installed both inside and outside the cell to enable opening the gate in case of the gate opener failing to operate.

4.3 Safety system

A safety system was designed and installed. The safety system provides communication between the built-in safety triggers in the robot and the additive manufacturing unit as well as additional safety enablers.

The enablers include:

- Acknowledgement button for selecting build unit or grinding equipment, located outside the cell at the wall of the safety system cabinet.
- Acknowledgement button for verifying that the gate is closed and that no personnel are inside the cell. Feedback from a magnet detector installed on the gate blocks the gate closing acknowledgement until the gate is closed, and trips this part of the system when the gate is open.

Without activating the enablers, the dangerous parts of the system are disabled. E.g. the lasers of the build head cannot start before the acknowledgement button for the gate closing has been pushed. Another example would be the robot, which cannot be operated in automatic mode while the gate is open, only in manual/training mode with the controller enabler active.

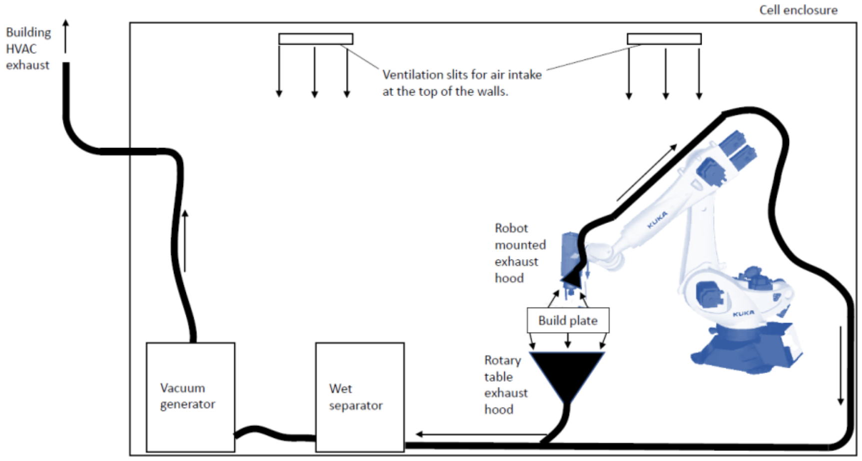
In addition to these comes emergency stop buttons, both on the Meltio engine located outside the cell, on the robot controller, which is mobile and can be used both outside and inside the cell, and there are also additional emergency stop buttons installed both inside and outside the gate as part of the safety system. Pushing one of the emergency stop buttons stops all activities, both additive, grinding and robot movement.

4.4 Material handling

There have been no structural material handling arrangements in the cell, beyond a gate that is wide enough to accommodate a small forklift, but this also means that there is more than sufficient room for the more commonly used hand pallet trucks. To handle heavy lifts, a wheeled engine hoist has been procured.

4.5 *Ventilation and exhaust*

The cell was planned to be used for additive manufacturing with both powder and wire, in addition to grinding experiments. This would mean that smoke and fumes from the welding operation would have to be extracted and removed, in addition to dust from metal powder and abrasives.



Robot model courtesy of: https://robodk.com/blog/wp-content/uploads/2018/07/KUKA-Robot-Machining.png

Figure 2: Schematic illustration of the exhaust system inside the cell.

The best solution for this was found to be a high-vacuum wet separation system from Ruwac in combination with the building HVAC system. The ventilation and exhaust system is shown schematically in Figure 2, where the goal is to utilise high-vacuum to remove the majority of fumes and dust locally from the AM or grinding area followed by particle removal from the extracted air by running it through a wet separator, before the industrial vacuum cleaner that drives the exhaust system transfers the clean, but humid and warm air to the building low-vacuum HVAC system that then evacuates the air from the cell and the building.

To enable local extraction from the build table, a fume hood will be attached to the robot with a backpack to route the air extraction hose along the robot without limiting the robot's freedom of movement, while an exhaust hood will be fitted to the stationary parts of the rotary table where most of the AM work takes place.

The air-intake design of the cell was done in accordance with the guidelines from ISO/ASTM 52931 [6], with the exhaust system creating a slight under-pressure inside the cell by extraction at the build table, combined with vents placed at the top of the walls. This design creates a downwards air stream which knocks down powder and dust towards the floor in the case of dust and powder not being extracted by the vacuum system. Avoiding circulation of particles is important for operator safety, since airborne dust can be difficult to detect.

4.6 Installation and integration

The placement of the robot and tilt/rotation table was simulated and optimised to allow full range of robot motion. The cell was originally planned with 2.4 m ceiling height, but after the simulation, this was increased to 3.1 m. The robot was installed on a pedestal, which was shimmed for levelling and bolted to the concrete floor with glue bolts before the robot was installed. The rotation table was also shimmed and installed with concrete wedge anchors. The shimming is not strictly necessary, but having both the robot and table level simplifies transformations between world and base coordinate systems, reducing the risk of operator mistakes while also limiting wear in the robot joints.

Figure 3: Finished layout inside the cell. The left image shows robot and tilt/rotation table, note build head hanging on tool-changer on the wall. The image to the right shows the Ruwac high-vacuum exhaust system, note ventilation slits close to the ceiling.

5 Concluding remarks

To enable safe and efficient operation of robotised additive manufacturing and grinding, an enclosed cell is a recommended way to secure both personnel and operating conditions. There are several considerations that should be made in the design of a cell, and it is important that they are assessed so that a satisfying compromise between cost, effort, safety and productivity can be achieved. It will always be either difficult or too expensive to design and build the perfect cell, but assessing the different considerations enables a conscious choice of priorities, so that the best possible compromise can be reached.

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