# USING GAMIFICATION TO UPSKILL WELDERS THROUGH A VIRTUAL REALITY WELDING SIMULATOR

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## ABSTRACT

This paper presents the development of a virtual reality (VR) welding simulator to support traditional welder training. It is specifically aimed at the upskilling of welders involved in the manufacturing of railway vehicles and can assist with training welders, improving turnaround time, reducing waste, and saving costs. Augmented reality (AR) welding simulators have been introduced in the industry with great success, and the usage of modelled welding equipment with AR markers makes the experience realistic and encapsulating. Developing a welding simulator using VR technology is presented as an alternative to industry-standard AR simulators to support traditional welding training.

The VR simulator is developed for metal inert gas (MIG) welding. A VIVE Tracker is combined with a physical MIG torch to immerse the welder into the virtual welding environment. Svantek vibration measurement instrumentation is used to measure the steadiness of the hand movement. The welder can adjust the virtual welding parameters, and during the welding process, the system calculates the working angle, travel speed and centre-to-weld distance (CTWD) of the weld. After completing the weld, an overall welding score is provided to quantify the quality of the welding process.

The VR Simulator was validated using differently skilled participants, and it was concluded that it could contribute to the upskilling of welders. It is an emerging technology and should be embraced by using future technology for future upskilling.

**Keywords**: Welding, Welding simulator, Virtual reality, Welding parameters, Welding defects.

## 1. INTRODUCTION

Welding, an enduring artisanal practice dating back to the 1880s, has undergone notable evolution, progressing from the rudimentary method of pouring molten metal between metal components to advanced techniques like forge and arc welding. Over time, technological advancements have propelled the adoption of contemporary welding methodologies, including metal inert gas (MIG), tungsten inert gas (TIG), arc, and spot welding, which have become the favoured processes within the industry.

The traditional apprenticeship model for welders is characterised by its time-intensive nature and substantial resource requirements. This conventional approach involves comprehensive instruction on equipment operation and technique execution, necessitating the completion of numerous welds across varied materials, sizes, and orientations for skill development. Evaluation of training welds involves meticulous examination to assess weld quality, often through destructive and non-destructive testing methods. However, the costs associated with traditional training methods prompt a need for exploration into alternative approaches.

To mitigate the financial burden of welder training, the industry has introduced welding simulators leveraging immersive technologies such as augmented reality (AR) and mixed reality (MR). While virtual reality (VR) simulators exist, their popularity lags due to challenges in seamlessly integrating real-world welding apparatus into the virtual environment.

This paper aims to create a VR welding simulator while integrating it with physical welding hardware. Several secondary objectives complement this overarching goal:

- Examine welding parameters to understand their impact on weld quality.
- Implement virtual welding functionalities within the simulator, enabling practice on training test pieces.
- Validate the simulator's effectiveness using data from accelerometers and case studies.

Training welders through traditional methods can consume significant time and resources when working with costly materials and consumables. Consequently, exploring alternative approaches to welding instruction becomes imperative.

Evaluation of virtual welding parameters and techniques can occur in real-time during welding, obviating the need for both destructive and non-destructive testing procedures to ascertain weld quality. Instead, the quality of the weld is assessed by analysing the measured parameters.

Leveraging the advancements in VR technologies within contemporary industries facilitates the creation of more efficient training environments. Integrating tangible objects from real life into virtual settings enhances the authenticity of the learning experience, thereby reducing barriers to entry for novice welders. The simulator accommodates welders with diverse backgrounds, training, and skill levels, offering them opportunities to practice various techniques, positions, and welding joints.

The paper will touch on the literature studied for this paper. Subsequently, it will delineate the development process of the VR welding simulator, elucidating the methodologies, technologies, and considerations involved in its creation. Finally, the paper will conclude by detailing the validation procedure undertaken to assess the efficacy and reliability of the simulator, along with presenting the ensuing results and findings derived from the validation process.

## 2. INTRODUCTION TO WELDING

Welding dates to around 8000 BC, employing methods like pouring molten metallic alloy between solid objects for joining. Modern welding emerged in the 19th century, notably with arc welding gaining momentum in the 1880s when Russian student Nikolai N secured the first welding patent (Cary & Helzer, 2005).

Tungsten inert gas welding (TIG), developed in the 1940s, employs a tungsten rod and inert gas for weld protection, ideal for joining ferrous materials like carbon steel, stainless steel, and aluminium alloys. Metal inert gas (MIG) welding, developed shortly after TIG, utilises a consumable electrode to initiate the arc under a shielding gas. Despite its ancient roots, welding remains prevalent in 21st-century applications, particularly fusion-based techniques requiring attention to both thermal and mechanical aspects (Oliveira, Santos & Miranda, 2020).

## 2.1 Principles of Metal Inert Gas Welding

MIG welding is a metal joining process that involves melting and fusing metals by heating them with an arc generated between the workpieces and a continuously fed electrode. This process bears similarities to TIG welding, with the notable distinction of using a continuously fed filler electrode instead of a non-consumable tungsten electrode. Additionally, MIG welding utilises shielding gas, typically argon or helium, directed through a nozzle toward the weld pool (Kou, 2021). The setup for MIG welding is illustrated in Figure 1.

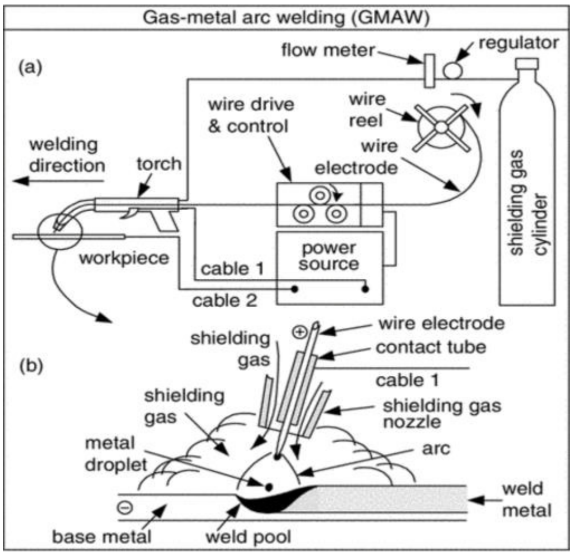


**Figure 1: Metal inert gas welding: (a) Overall process, (b) Welding area enlarged (Adopted from Kou, 2021)**

The primary distinction between MIG and TIG welding lies in the deposition rate, with MIG welding boasting a significantly higher rate. This characteristic allows MIG welding to handle thicker workpieces and achieve faster welding speeds.

## 2.2 Welding Defects and Quality Control

In comprehending the implementation of quality control in welding operations, it is essential to first address welding defects. Baughurst (2011) provides a comprehensive list of common welding defects along with preventive and corrective measures. There are eight primary geometric imperfections associated with welding setup and preparation characteristics:

Misalignment occurs when the material is not set up accurately or joined to materials of different thicknesses, as depicted in Figure 2.

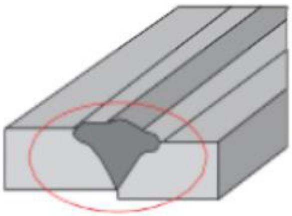


Figure 2: Misalignment (Adopted from Baughurst, 2011)

Overlap occurs when the weld metal protrudes beyond the weld toe. This is due to poor technique and can be repaired by grinding the excess weld off. This defect can be depicted in Figure 3.

Undercutting occurs when the incorrect electrode and weaving are used with a high current and high travel speed. This will leave a groove along the edge of the weld and cause improper fusion. This can be avoided by doing the proper welding preparations and can be repaired by doing a second run with a smaller electrode to fill the groove. This possible defect is depicted in Figure 3.

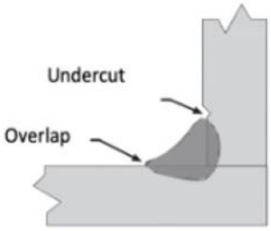


Figure 3: Overlapping and Undercutting (Adopted from Baughurst, 2011)

Concave and convex welds occur with the combination of incorrect speed and electrode current. Convex welds give rise to slag inclusions and will leave the weld with a poor stress pattern. Concave welds have insufficient throat thickness and will not be as strong. Both defects can be observed in Figure 4. These defects can be repaired by either filling the weld further using weld material or grinding back to the base material and redoing the weld.

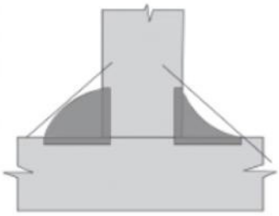


Figure 4: Concave and convex welds (Adopted from Baughurst, 2011)

Lamellar tearing occurs below a welded joint that is subjected to high-stress concentrations. It is produced by small non-metallic inclusions in the metal. The best precaution to take is to ensure that the materials are of acceptable quality.

Inclusions are regularly associated with incomplete penetration, undercutting, and lack of fusion in welds. Slag inclusions reduce the cross-sectional area strength of the joint and are usually the initiation point for cracking. The defect can be repaired by grinding the weld down to the base material and re-welding.

Porosity occurs when non-metallic gasses are entrapped in the molten metal during solidification. This causes cavities and pores to be in the weld. It can be minimised through correct electrode or filler material selection, slower travel speed to allow gas to escape, and improved welding technique. This defect is depicted in Figure 5.

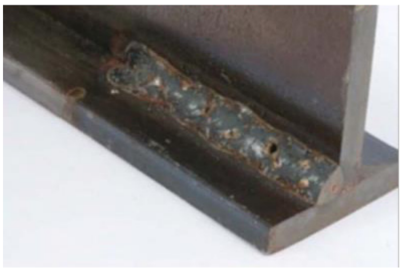


**Figure 5: Porosity in welding (Adopted from Baughurst, 2011)**

Incomplete fusion is difficult to detect and evaluate, and a visual representation is depicted in Figure 6. It occurs when the weld metal does not fully bond and penetrate to the required depth of the base material. This can cause insufficient throat thickness, which can cause failure under loading. This is caused by incorrect welding parameters of current, wire feed speed being too low, travel speed being too fast, and insufficient electrode size. The defect can be repaired by grinding the weld down to the base material and re-welding.

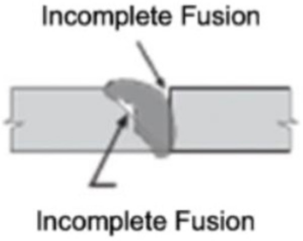


**Figure 6: Incomplete fusion (Adopted from Baughurst, 2011)**

## 3. DEVELOPMENT OF THE VR WELDING SIMULATOR

This section provides a high-level evaluation of the development procedure of the simulator. The evaluation includes how information obtained from welding training transpired into the development of a virtual welding simulator. The virtual environment architecture and the integration of the VIVE Tracker are evaluated alongside the welding procedure.

### 3.1 The Effect of Welding Parameters on Weld Quality

Welding training was obtained in MIG welding, and during the welding process, the defects in Section 2 was observed and it was noted that the quality of the weld for a butt joint was influenced by the variables depicted in Table 1.

The AWS D1.1 (2020) standard offers a chart delineating parameter settings based on material thickness, type, and filler material diameter. Employing this chart, all parameters were initially set within the recommended range for the selected material parameters, and a weld was executed. Subsequently, each parameter was individually adjusted while keeping the others within the specified range to assess their impact on the weld. Through observation of the weld and consultation with the welding supervisor, Table 1 summarises the deductions made.

**Table 1: Welding parameter influence on the quality of the weld**

| Parameter | Parameter too high | Parameter too low |
|---|---|---|
| Voltage | Will continuously fail to penetrate the base material due to the turbulent weld pool. | Results in poor arc starts and penetration. It is paired with spatter and poor tie-in at the toe of the weld. |
| Amperage | It creates poor arc starts and leads to a wide weld bead. Burn-through, spatter and poor penetration are also evident. | It is characterised by a narrow weld with poor tie-in at the toes of the weld. |
| Wire feed speed | Can cause poor arc starts, wide weld bead, spatter and burn through. | Results in a narrow bead and poor tie-in at the toe of the weld. |
| Shielding gas flow rate | Has no direct effect on the weld bead, but shielding gas will be wasted. | This will result in porosity and decrease the strength of the weld |
| Work angle | A flat shallow bead with poor tie-in at the toes of the weld will be present. | A flat shallow bead with poor tie-in at the toes of the weld will be present. |
| Travel speed | Results in a narrow bead with inadequate tie-in at the toes of the weld. Insufficient penetration and inconsistent weld beads are present. | Introduces more heat into the weld resulting in a large weld bead and poor penetration. On thinner material, it can cause burn-through. |
| Contact to work distance (CTWD) | This will result in incomplete fusion due to not enough heat to melt and fuse the base material. The inadequate heat can cause porosity and decrease the strength of the weld. | This will result in spatter and excessive heat which can cause burn-through. |

## 3.2 Creating the Virtual Welding Environment

The simulator development was facilitated by the Unity cross-platform game engine, one of the four primary platforms for VR development. Unity was primarily selected due to the access to the software, which streamlined the development process. The virtual welding simulator environment created for MIG welding included the welding machine with dials, shielding gas, a table with two test pieces, as illustrated in Figure 7.

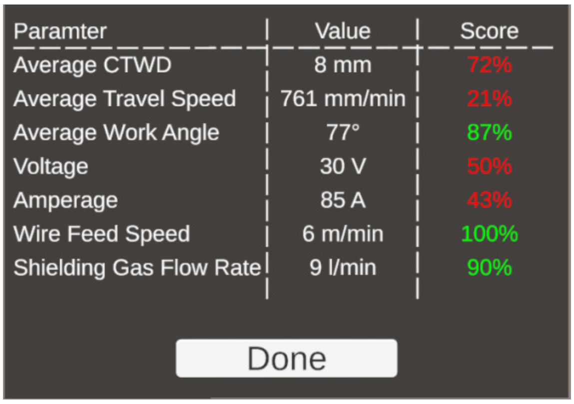
**Figure 7: Welding simulator environment**

To enhance immersion within the simulator, it was decided to integrate an authentic MIG torch. Subsequently, the MIG torch was 3D scanned and imported into the simulator scene. The 3D scanned model is depicted in Figure 8. The challenge of tracking the MIG torch was resolved by employing a HTC VIVE Tracker, as illustrated in Figure 8. The VIVE Tracker featured five input pins to expand system functionality. A push button was integrated into the system, connecting it to pin two and four, with pin four serving as the "trigger" button input from a VR controller.


CTWD | 0 mm
Travel Speed | 0 mm/min
Work Angle | 0°

**Figure 8: (a) 3D scanned model of the MIG torch;(b) MIG torch integrated with the VIVE Tracker**

All parameters monitored throughout the welding process contribute to the size and quality of the weld bead, providing users with a visual representation of the ongoing process. Upon completion of the weld, users encountered a scorecard detailing their performance in terms of seven parameters (average CTWD, average travel speed, average work angle, voltage, amperage, wire feed speed and shielding gas flow rate). The value for each parameter is shown and scored in a red/green colour code, which provided guidance on areas for improvement. This concept is illustrated in Figure 9.



| Paramter | Value | Score |
|---|---|---|
| Average CTWD | 8 mm | 72% |
| Average Travel Speed | 761 mm/min | 21% |
| Average Work Angle | 77° | 87% |
| Voltage | 30 V | 50% |
| Amperage | 85 A | 43% |
| Wire Feed Speed | 6 m/min | 100% |
| Shielding Gas Flow Rate | 9 l/min | 90% |

**Figure 9: Scorecard**

### 3.3 Validating the Welding Simulator

For the validation of the simulator, three participants were chosen:

Participant 1: Coded or experienced welder.
Participant 2: Self-taught welder.
Participant 3: Participant with no experience in welding.

All three participants consented to the research and understood the confidentiality of the data that was generated. The weld to be performed was a 100mm long butt weld on 6mm S355JR steel. A four-step procedure was followed to validate the welding simulator:

*Step 1: Perform pre-simulation weld:*

All three participants were requested to perform the butt weld using a MIG welding machine. The participants had to set all parameters themselves without guidance, but with supervision to ensure safety. After setting the parameters, they proceeded to weld on the test piece. The test piece was labelled with a number corresponding to the abovementioned participants.

*Step 2: Obtain welding training using the welding simulator:*

After the three participants completed step 1, they were trained on the welding simulator in the VR laboratory: During this step, they performed the same butt welding in a virtual environment with guidance through a user interface. An accelerometer was placed on the tip of the MIG torch to measure the stability of the torch tip during practice. The participants could practise until they felt comfortable with the experience.

*Step 3: Perform post-simulation weld:*

After welding simulation training was complete, the participants again reperformed the physical butt weld as outlined in Step 1.

*Step 4: Perform mechanical tests on weld pieces:*

In the fourth step, the mechanical properties of the pre- and post-simulation butt weld test pieces are tested and the results are compared. Visual examination of test specimens was conducted to identify welding imperfections. Two sets of test pieces for each participant were then prepared for tensile testing, to determine the weld strength: a set from the initial welding phase (step 1) and the post-simulation welding phase (step 3). Following the guidelines outlined in the AWS D1.1 standard, three dog bone samples were extracted from each test specimens. Water jet cutting was used due to its precise nature and the absence of heat, thus mitigating any potential distortion of the testpiece and the weld. Each dog bone sample was tensile tested and the UTS findings obtained were meticulously recorded and utilized to quantify the degree of improvement achieved by each participant.

## 4. RESULTS AND DISCUSSION

The tensile test results for each participant (pre-training and post-training) were obtained for each participant. Three dog bone samples were cut out of each welding test plate and the average tensile strengths were calculated. Although many factors can influence the quality of a weld, it was assumed that the training from the welding simulator would be quantified by the increase or decrease in pre- and post-training welds. The results of the UTS tests are shown in Figure 10.

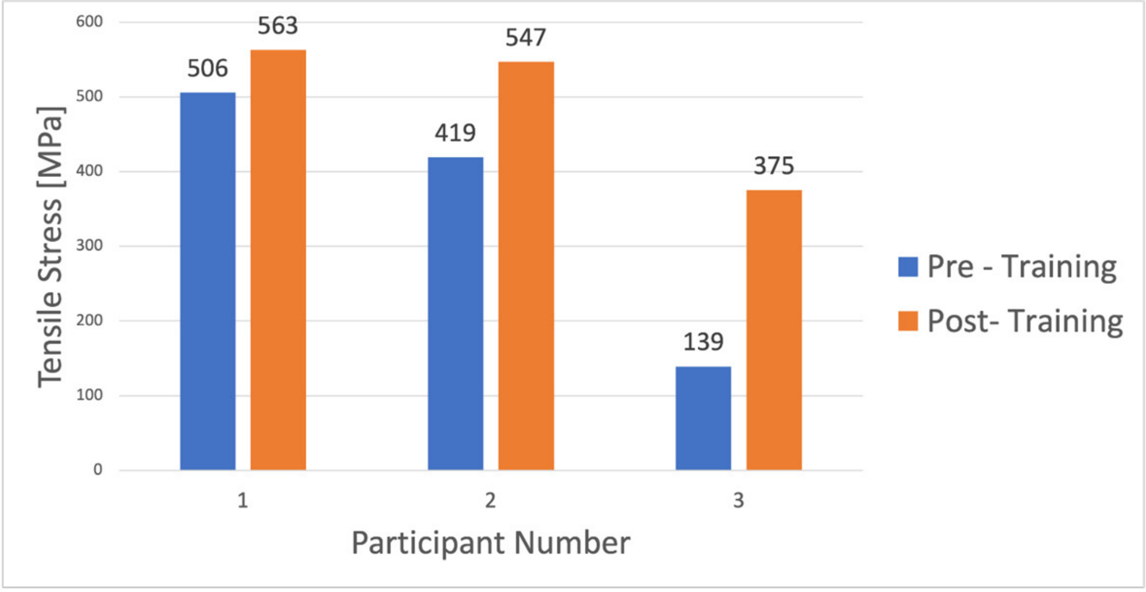


**Figure 10: Tensile test results**

Each of the three participants underwent approximately 20 minutes of training with the welding simulator, and the results from Figure 10 show notable improvements in the tensile strength of the welds for all three participants. Participant 1 achieved an 11% increase, Participant 2 a 30% improvement, and Participant 3 a substantial 170% improvement in their welding capabilities.

The accelerometer data was used to determine the stability of the torch tip. The RMS graphs were calculated from the data. The stability increase can be seen from Participant '3's first attempt at the simulator(Figure 11) to his last attempt(Figure 12).

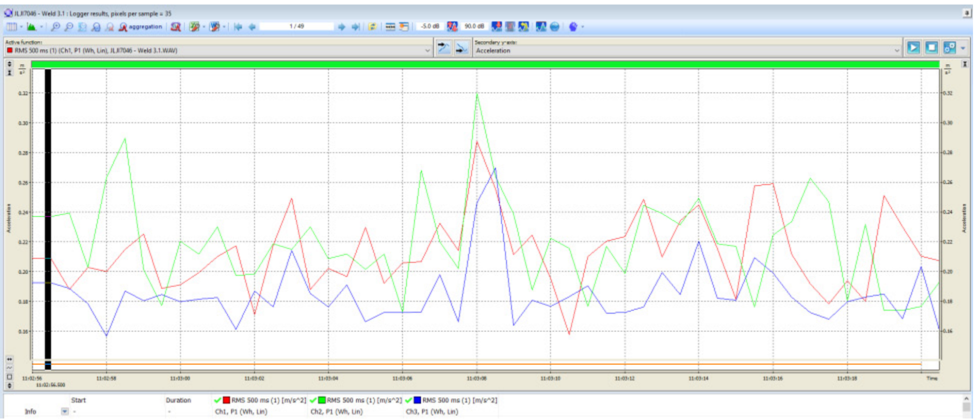


**Figure 11: Participant 3, First Attempt**

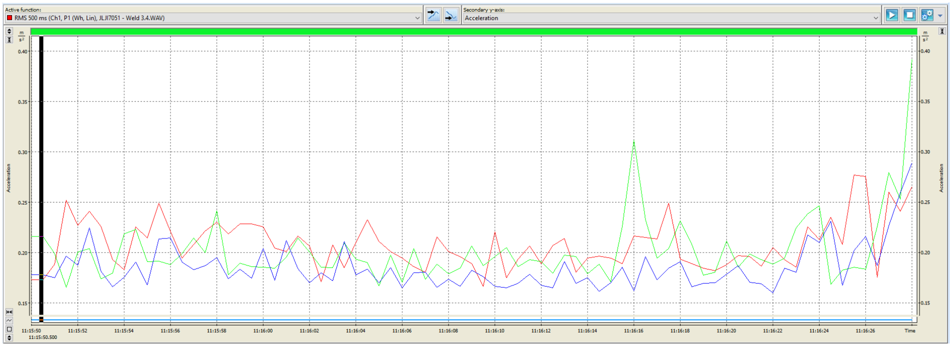


**Figure 12: Participant 3, Final attempt**

A more consistent torch tip can be observed with less sharp change in directions along the length of the weld. This observation was consistent with the exported VIVE Tracker data, which exhibited similar trends, thus validating the accuracy of the VIVE Tracker on the MIG torch.

The quality of the welding of all three participants improved, as evidenced by visual inspection and tensile testing. Particularly noteworthy was the significant improvement demonstrated by participant 3, indicating the promising effectiveness of the simulator especially for the training of participants with no welding experience. The exported data from the simulator proved instrumental in identifying areas for improvement in welding techniques, further validating the simulator's efficacy in skill enhancement.

Furthermore, the validation of the VIVE Tracker was concurrently conducted, revealing congruent data patterns between accelerometer data analysis and the exported Tracker data. This alignment reinforces the reliability and validity of the Tracker's performance within the simulator.

# 5. CONCLUSIONS

The primary goal of the paper was to create a welding simulator utilising virtual reality technology and subsequently conduct a validation process to assess its effectiveness.

The simulator's development drew upon both received training and an extensive literature review. It featured a MIG welder equipped with a 3D-scanned MIG torch, lending authenticity to the simulation. To augment immersion, a real-life MIG torch was seamlessly integrated with a Tracker. The simulator environment incorporated dials enabling users to adjust welding parameters such as voltage, current, wire feed speed, and shielding gas flow rate.

The welding process was governed by the parameters set using the dials, in conjunction with variables such as travel speed, work angle, and CTWD. These variables collectively influenced the size and quality of the weld bead. As the welder moves along the weld, dynamically altering parameters cause fluctuations in the size of the weld bead.

The concluding phase of the project involved validating the simulator's efficacy. The three participants selected for validation had diverse welding backgrounds: one was a trained welder with extensive experience, the second was self-taught, and the third had no prior welding experience.

The validation process commenced with the participants executing a butt weld on 6mm S355JR steel. Subsequently, they underwent training in the simulator until achieving a satisfactory score and feeling proficient in the welding procedure. Training sessions also incorporated the use of an accelerometer mounted onto the tip of the MIG torch to assess the stability of each participant's torch handling. The accelerometer data served a dual purpose of validating the accuracy of the exported Tracker data. Following the training phase, participants made a second attempt at the butt weld.

Three dog bone samples were cut with water jet from each welded joint and subjected to a tensile test. A comparison was made between the average UTS values before and after training. All three participants exhibited improvements, of 11%, 30%, and 170%, respectively.

The findings indicated a noticeable improvement in the welding capabilities of all participants, thereby validating the effectiveness of a VR welding simulator.

Suggestions for further work:

- Enhance MIG welder capabilities to cover various joint types for comprehensive training, while also improving realism by simulating authentic weld pool, arc, and sparks, and implementing an auto-darkening screen.
- Improve MIG torch tracking in the virtual environment to prevent interference with objects and implement a penalty point system to discourage improper welding practices.
- Develop a real-life training environment for rail car manufacturing scenarios, advancing the simulator to include additional welding processes and providing a user-friendly interface for process selection.
- Extend validation test duration over multiple days with more participants, allowing for longer training periods and multiple post-training welding attempts to ensure process consistency.

## 6. FUNDING

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