

APPENDIX GA36d

Assessment Level 7

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Abstract

This assignment studies distortion in welded fabrications with a specific focus on Shielded Metal Arc Welding (SMAW), classified as process 111. It brings together academic and business literature to show how the heat cycles during welding cause uneven expansion and contraction, which creates residual stresses and common distortion modes such as bowing, buckling, twisting, and shrinkage. The review then narrows to SMAW-specific drivers of distortion, highlighting the influence of manual process variability, multi-pass deposition, and thermal history differences compared with more automated arc processes.

A structured methodology is proposed to define a representative case study and to specify a SMAW welding procedure suitable for analyzing distortion risk, including consumable selection, polarity, parameter ranges, pass planning and interpass control. It is explained how to use a consistent datum scheme, clear measurement locations, and clear timing of readings to get accurate measurements of distortion and, if possible, residual stress. The measurements should be able to be interpreted the same way each time. Several types of distortion mitigation are carefully looked at, including controls at the design stage, controls for the process and sequencing, and restraint/pre-setting/corrective methods. The main focus is on reducing the volume of the welded metal, balancing the forces of shrinkage, and managing restraint without creating too much residual stress. The assignment concludes with evidence-based recommendations and a critical appraisal of limitations and validity arising from the variability of published methods, reporting quality, and the context-dependent nature of welding distortion.

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1. Introduction

1.1 Context and problem statement

Due to the very localized, brief heating, uneven cooling, and contraction that fusion welding causes, welding-induced distortion is still a problem in the manufacturing industry. This causes residual stresses and large-scale changes in the shape of the parts that are being made. In structural and general fabrication work, even small out-of-plane deflections or angular changes can cause loss of dimensional tolerance, misalignment during fit-up, increased corrective operations such as mechanical straightening and rework welding, and delays to assembly. These effects are amplified in built-up fabrications where multiple welds interact and restraint conditions vary during the build sequence.

The problem is particularly relevant to Shielded Metal Arc Welding (SMAW) because it is widely used for site work, repair, and low-to-medium production fabrication where manual operation, multi-pass deposition, and frequent stop-start behavior can introduce greater variability in heat input and thermal history compared with more automated processes. Consequently, predicting and controlling distortion in SMAW-fabricated assemblies is challenging, and robust engineering guidance must integrate distortion mechanisms, procedure choices, joint design, and restraint strategy within practical workshop constraints.

1.2 Reason for selecting SMAW

Shielded Metal Arc Welding (SMAW) is chosen for this study due to its widespread use in structural fabrication and maintenance, especially in portable and outdoor settings. Its manual operation allows for significant variability in thermal history, making it ideal for exploring the impact of heat input, pass sequencing, and restraint strategies on distortion sensitivity (Xometry, n.d.).

SMAW, identified as process 111 ("manual metal arc welding") in international welding classifications, facilitates clear identification in documentation and academic studies. It also allows for the inclusion of safety and compliance considerations regarding arc-welding fumes, which are significant constraints in fabrication environments, in line with UK standards for controlling welding fume exposure (Health and Safety Executive (HSE), n.d.; TWI, n.d.).

1.3 Aim, constraints and objectives

The assignment investigates welding-induced distortion in fabricated steel components produced via Shielded Metal Arc Welding (SMAW). It examines how choices in SMAW procedures and fabrication conditions affect the type and magnitude of distortion, according to internationally recognized welding process classifications for consistency in terminology.

The limitations of this study include the fact that SMAW depends on the operator, fixturing capacity is limited, and it's hard to get accurate measurements of distortion. The objectives of the assignments are

- To identify and justify a SMAW joint configuration and preparation suitable for distortion assessment in plate fabrication, using a standards-informed approach where applicable.
- To define a controlled SMAW procedure that enables repeatable trials while capturing realistic process variability.
- To measure distortion consistently before and after welding and classify the observed distortion modes for each trial condition.
- To quantify the influence of key factors such as heat input proxy, pass sequencing, and restraint condition on distortion outcomes, using appropriate data analysis methods.
- To evaluate practical distortion mitigation options applicable to SMAW fabrication and propose procedure/fabrication recommendations supported by the findings.

2. Critical literature review

2.1 Welding distortion theory and classification

The core principle of welding distortion is the macroscopic shape change that occurs when the weld metal and adjacent heat-affected zone contract on cooling (TWI, n.d.), producing longitudinal and transverse shrinkage. When contraction is non-uniform through the thickness (or across an unsymmetrical joint), rotation and bending occur, producing angular and out-of-plane forms of distortion.

Main types of distortion

1) Shrinkage

Longitudinal shrinkage: shortening along the weld line due to contraction parallel to the edge.

Transverse shrinkage: closing-in movement across the joint perpendicular to edge as the heated zone contracts.

2) Angular distortion

Angular distortion is rotation of the plates about the weld due to through-thickness non-uniform contraction, common in single-sided butt welds and fillet welds.

3) Bowing / bending

Longitudinal bowing occurs when weld shrinkage forces do not act through the section's neutral axis, so the component bends into a curved shape along its length.

4) Buckling

Buckling is a stability distortion mode in thin plate structures, occurring when compressive residual stresses from restrained shrinkage exceed the plate's buckling resistance.

5) Twisting

Twisting is a torsional deformation in which one end of a member rotates relative to the other, caused by asymmetric heat input, unbalanced weld placement, or non-uniform restraint during fabrication.

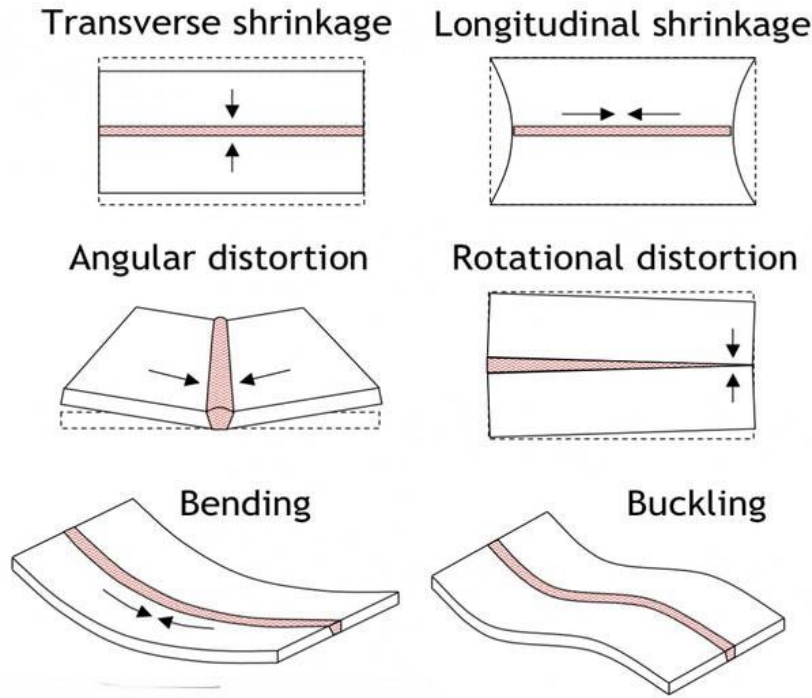


Figure 1. visualization of Various type (Kobelco Welding, 2006).

2.2 Thermo-mechanical origins

Welding distortion originates from highly localized heating and cooling. This produces non-uniform thermal expansion and contraction in the weld metal and adjacent heat-affected zone (HAZ) (Lucas, et al., n.d.). Because the temperature field is strongly non-uniform in space and time, different parts of the component attempt to expand/contract by different amounts, and the surrounding colder material restrains this free movement, generating internal stresses.

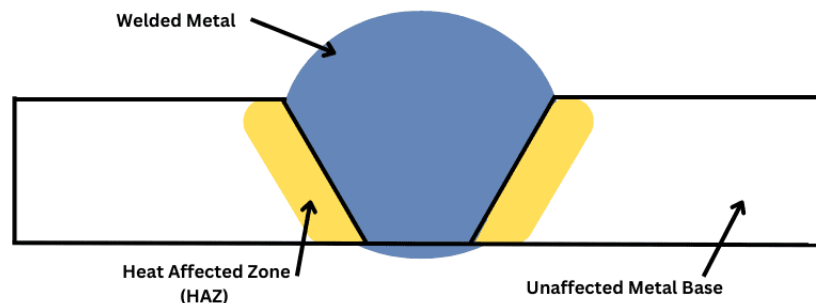


Figure 2. The HAZ is located between the unwelded and welded metal (ColdSpray.com, n.d.).

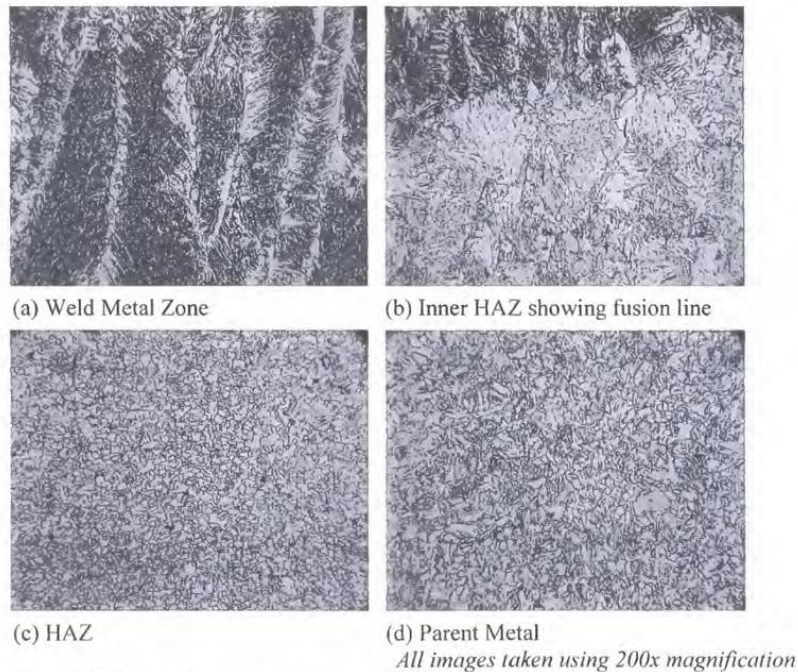


Figure 2. Images of the weld microstructure for the plate sample bead (O'Brien, 2007).

2.3 SMAW-specific drivers of distortion

The process of delivering heat and filler in short-stick, manual deposition phases has a big effect on how SMAW distortion behaves (Baghel, 2022). This makes the thermal cycle different for each pass and operator. This results in greater unpredictability and control challenges for distortion in actual fabrications compared to continuously fed wire processes.

- **Operator-driven changes in heat input:** In SMAW, altering the travel speed and arc manually affects heat input and the hot zone's size, leading to variations in shrinkage and angular rotation (WorldAutoSteel, n.d.). Even with constant current and voltage, these changes can produce distortion distribution.
- **Stop-start thermal cycling from electrode changes:** SMAW involves frequent electrode replacement, leading to repeated arc starts and stops, which can result in non-uniform contraction along the weld line and cause longitudinal bowing and twist, especially in long seams (Xiris Automation Inc., n.d.).
- **Multi-pass deposition and reheat effects:** SMAW is often used for multi-pass welding on moderate to thick sections. Each additional pass reheats the material that was already welded, changing the local stress/strain history and possibly

causing angular distortion if the pass layout is not balanced (Shridhar, et al., 2025).

- **Weld bead volume and shrinkage:** When larger electrodes and bead volumes are used, more molten metal will later contract, increasing shrinkage forces and related distortion if sequence and restraint are not maintained (Xiris Automation Inc., n.d.).
- **Lower deposition rate and longer arc-on time:** Compared to GMAW, SMAW has lower deposition rates and more downtime due to electrode changes, leading to increased total time at elevated temperatures and a potential for uneven heating during fabrication (IJREAM, n.d.).
- **Slag system and interpass cleaning practice:** Slag layers and interpass cleaning in SMAW impact interpass timing and local cooling rates, altering the effective thermal cycle and affecting contraction distribution across the joint thickness (Shridhar, et al., 2025).

2.4 Dilution and weld bead geometry

Dilution is often defined as the amount of base material (or previously deposited weld metal) that melts and mixes into the weld deposit, which changes the composition of the weld metal. It is also true that dilution is affected by welding parameters and technique because these change the penetration and bead geometry (e.g., weld width/depth/height), which are directly related to how much substrate melts. Published research indicates that dilution can vary considerably, even with equivalent calculated heat input, based on whether the heat input is modified by altering welding current or welding speed. This illustrates that "heat input" alone may not exclusively dictate dilution or bead morphology.

2.5 Distortion mitigation approaches

Distortion control is typically addressed in three layers:

- (i) Reduce the amount and leverage of shrinkage forces,
- (ii) Balance shrinkage forces through joint/weld layout and sequencing
- (iii) Manage restraint and presetting while avoiding excessive residual stress.

2.5.1 Design-stage approaches (TWI Ltd, n.d.)

- **Minimize weld metal volume:** Keep weld size to the required throat/strength because larger deposited volume increases shrinkage and distortion.
- **Place welds close to the neutral axis:** Reducing the “lever arm” of shrinkage forces lowers bending and angular distortion.
- **Balance welds about the neutral axis:** Use opposing welds (e.g., double-sided fillets where feasible) so shrinkage forces counteract rather than accumulate.

2.5.2 Procedure and sequencing approaches (TWI Ltd., n.d.)

- **Balanced welding sequence:** Alternate sides and/or distribute passes to prevent angular distortion from building up during multi-pass welding.
- **Segmented welding:** Segmented welding involves using short runs arranged in a specific pattern instead of longer continuous welds, which helps minimize heat accumulation and progressive distortion.
- **Weld toward free ends / manage welding direction:** Sequencing and direction are selected to reduce restraint-driven accumulation of distortion in long seams.
- **Reduce overall heat input/time at temperature:** Fewer passes and shorter welding time reduce cumulative shrinkage effects and distortion risk.

2.5.3 Restraint, presetting, and corrective approaches (TWI Ltd., n.d.)

- **Jigs, fixtures, clamps, and strongbacks:** Restraint can hold geometry during welding, but it can increase residual stress and cracking risk if applied excessively or to susceptible materials.
- **Pre-setting/pre-bending (pre-springing):** Intentionally offset parts before welding so expected shrinkage pulls them into tolerance; the required preset typically needs representative trials.
- **Back-to-back assembly/mirrored welding:** Welding paired components in a symmetric arrangement can balance shrinkage forces and reduce distortion.

3. Methodology

3.1 Case study

The case study is a typical welded piece that is meant to show measurable distortion while still being true to SMAW practice and typical workshop limitations. Specimen selection should be driven by distortion sensitivity (thin-to-moderate thickness plates are more prone to bending/buckling than very thick sections), joint accessibility for manual welding, and the ability to define repeatable boundary/restraint conditions so that any observed distortion can be meaningfully attributed to welding shrinkage effects rather than uncontrolled setup variation.

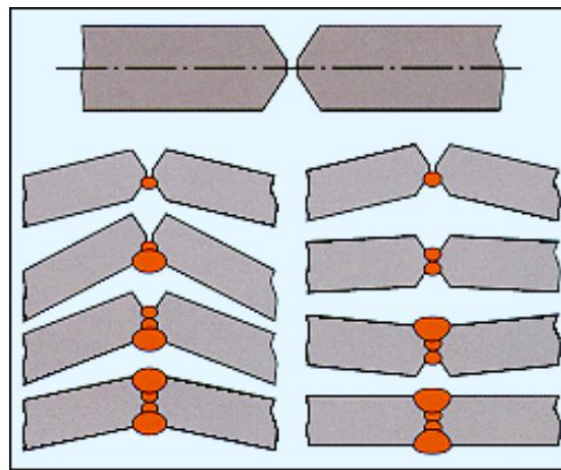


Figure 3. Reducing angular distortion through balanced welding (Lucas, et al., n.d.).

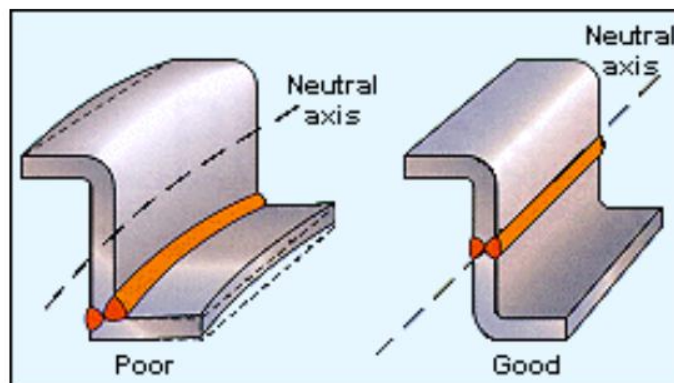


Figure 4. The welds can be positioned around the neutral axis to minimize distortion (Lucas, et al., n.d.).

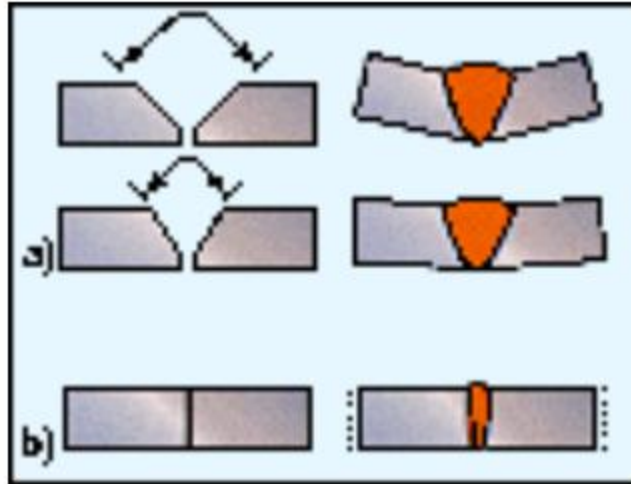


Figure 5. Lowering angular distortion and lateral shrinkage by: **a) decreasing the volume of weld metal; b) applying a single-pass weld** (Lucas, et al., n.d.).

Base material grade, plate thickness, overall geometry, and assembly condition should all be specifically specified in the specimen definition before welding. A recognized joint-preparation standard should be used to set joint preparation and fit-up targets when appropriate (International Organization for Standardization, 2013). ISO 9692-1 covers joint preparation recommendations for steels for manual metal arc welding and includes preparations for full penetration butt welds and fillet welds, enabling you to define groove type, root gap, and related preparation parameters in a standardized manner.

3.2 Welding procedure specification (SMAW)

Shielded Metal Arc Welding, which is called process 111 (manual metal arc welding) in ISO process nomenclature, is at the center of the welding procedure specification (WPS) (Standardization, 2022). This is done to make sure that all the terms used are consistent and that the method can be tracked. The WPS should state the base material group and thickness range, joint type and preparation, and the welding position(s) to be considered, because these factors directly influence bead shape, number of passes, and thermal input distribution that drives distortion.

Specification of joint preparation and fit-up needs should be based on a well-known joint-preparation framework. For example, ISO 9692-1 applies to steels and covers joint preparation for both full penetration butt welds and fillet welds for manual

metal arc welding (International Organization for Standardization, 2003). This lets you define the type of preparation and key dimensions, for example, groove form when needed. The WPS should then define consumable electrode classification and diameter, electrical characteristics and polarity, parameter ranges (current and arc voltage range where recorded), and travel technique, since these control heat input per unit length and therefore shrinkage forces.

3.3 Distortion and residual stress measurement strategy

The purpose of a measurement strategy is to (O'Brien, 2007),

- (i) create a geometric baseline that is constant,
- (ii) measure rotation and displacement caused by welding in a repeatable manner, and
- (iii) When appropriate, characterize residual stress using established techniques. A stable reference frame is chosen on the component as the first step in a clear datum scheme.

For distortion measurement, the strategy must outline the specific modes of distortion, like angular change, longitudinal/transverse shrinkage, and out-of-plane deflection, etc.; the measurement locations; and the instruments to be utilized (Kumar, et al., 2025). Common measurement options for welded plates include straightedge/dial gauge methods for localized deflection, as well as advanced techniques like CMM or 3D scanning for comprehensive out-of-plane deformation mapping, chosen based on accuracy, access, and repeatability requirements.

3.4 Ethics, risk assessment, and H&S

For health risks, welding fume is treated as a primary hazard because arc welding generates airborne contaminants that must be controlled; UK HSE guidance emphasizes controlling exposure by avoiding/reducing fume, using local exhaust ventilation (LEV) to capture fume at the source, and supplementing with suitable respiratory protective equipment (RPE) where LEV alone is not adequate or not

reasonably practicable (Health and Safety Executive, n.d.). Risk assessment should also consider “others nearby” in the welding area and the need for effective general/mechanical ventilation where appropriate, as highlighted by HSE.

Hot work risks are addressed through fire prevention measures such as removing combustibles from the work area, recognizing that sparks and molten metal can travel and ignite materials, and maintaining a fire watch during and after welding where required. Electrical safety is important because arc welding uses live electrical circuits. HSE stresses checking the condition of equipment like cables, connectors, and insulation and taking extra care when working in wet or damp areas or inside metal structures, which are higher-risk areas for electric shock. They also say that open-circuit voltage limiting devices can lower the risk of electric shock for MMA and SMAW. Finally, PPE requirements are treated as essential controls supporting the hierarchy of risk reduction for arc welding activities.

4. Limitations and validity

This assignment is limited by its reliance on secondary sources rather than primary experimental data, meaning conclusions depend on how completely and transparently other authors report welding variables, boundary conditions, and measurement methods. Without a controlled test program, it is not possible to quantify distortion magnitudes for a specific fabrication with known confidence bounds, so the work focuses on analyzing mechanisms, trends, and mitigation logic rather than producing universally predictive numbers.

Internal validity: Internal validity is limited because the definitions of distortion modes and metrics, heat input calculations, and the way that restraint, tack strategy, and welding sequence are used are not always the same. These confounding factors complicate attributing outcomes to single variables, such as current or travel speed, due to the co-variation of multiple variables in practical welding and case studies.

External validity: External validity in distortion behavior is limited due to factors such as component stiffness, thickness, joint type, weld size, and material properties. Recommendations should be conditional rather than absolute, as process capability

varies with welder skill, fixturing, and environmental conditions, implying that effective controls may not achieve the same distortion reduction in different settings.

Operator variability: SMAW introduces an additional limitation. When changing the arc length, travel speed, electrode angle, and weaving by hand, it is possible for the thermal cycle and bead geometry to change significantly. This means that even a well-written WPS might not produce the same heat input or shrinkage behavior for different operators or over long weld lengths. This variability reduces repeatability and is a key reason why published parameter windows may not be directly transferable without local trials.

Measurement and reporting limits also affect validity. Many sources do not provide full datum definitions, measurement uncertainty, repeat counts, or timing of measurements, all of which materially influence distortion results. Where modelling results are cited, predicted distortion is sensitive to assumptions about heat source representation, material properties at elevated temperature, and boundary restraint modelling; without validation data, modelling outputs should be treated as indicative patterns rather than definitive values.

To improve validity despite these problems, the assignment focuses on reliable sources like standards bodies, peer-reviewed journals, and well-known technical institutes. Check claims against three different sources before using them as guidance. Finally, clearly label conclusions based on the quality and consistency of the evidence.

5. Recommendations

Based on the finding Following steps is recommended for reducing distortion in SMAW welding process (Lucas, et al., n.d.).

- **Control weld size:** Specify target fillet size/throat and enforce it with gauges and visual checkpoints, because excess weld metal increases shrinkage forces and drives distortion.
- **Use balanced welding sequences:** plan the weld order to balance shrinkage forces, and document the sequence clearly in the WPS.

- **Use segmented welding for long seams:** apply skip welding/back-step style segmentation to reduce progressive heat build-up and to distribute shrinkage more evenly along the fabrication.
- **Minimize heat input consistent with quality:** maintain adequate travel speed, avoid unnecessarily wide weaving, and avoid excessive pass count by selecting a practical electrode size and pass plan, because higher cumulative heat generally increases distortion risk.
- **Design/fit-up to reduce distortion leverage:** place welds as close to the neutral axis as practical, and design joints to minimize weld volume while still meeting strength and access needs.
- **Apply restraint intelligently:** use jigs, clamps, and strongbacks to hold geometry, but recognize the trade-off that heavy restraint can increase residual stress and cracking risk; include a release strategy (sequence of unclamping) where applicable.
- **Use pre-setting where repeatable distortion is expected:** if a fabrication repeatedly distorts in a known direction, introduce controlled pre-bending/pre-setting so weld shrinkage pulls the assembly into tolerance.
- **Standardize inspection and measurement practice:** Define a consistent datum scheme and check points for distortion monitoring (before welding, after welding, and after cooling/unclamping) so corrective actions are based on comparable measurements.
- **Strengthen documentation and competence controls for SMAW:** Record key variables and ensure welders follow the same technique, since SMAW is operator-sensitive and variability can drive inconsistent distortion outcomes.

6. Conclusion

Welding distortion is mainly caused by uneven heating and cooling, which causes uneven contraction (shrinkage) and residual stress fields that show up as changes in the dimensions of the parts that are welded. Within this framework, SMAW (process 111) is particularly relevant because manual operation and multi-pass deposition can introduce variability in heat input and thermal history, making distortion behavior more sensitive to procedure control and fabrication practice.

This assignment established that distortion can be understood and managed by linking distortion types (e.g., shrinkage, angular distortion, bowing, buckling, and twisting) to their thermo-mechanical origins and then targeting the controllable contributors—weld size, weld placement relative to stiffness/neutral axis, welding sequence, and restraint strategy. The reviewed mitigation approaches indicate that the most consistently supported controls are minimizing weld metal volume, balancing shrinkage through sequencing, and applying restraint or pre-setting in a planned way while recognizing the residual-stress trade-off.

Finally, the work is bounded by the limitations of secondary-source evidence and variation in how distortion is defined and measured across references; therefore, recommendations should be applied as conditional engineering guidance and validated against the constraints of a specific fabrication context.

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