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# Modelling Plastic Deformation and Thermal Response in Welding using Smoothed Particle Hydrodynamics

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## Abstract

An approach for modelling plastic deformation and thermal response in a weld pool using the mesh-free Smoothed Particle Hydrodynamics (SPH) method is developed. The proposed modelling technique is illustrated by simulating a simple setup of an arc welding process. The plastic deformation and temperature distribution in the weld pool and the surrounding parent material are analysed using SPH. This work establishes the capability of SPH in gaining insight into the material deposition and its subsequent evolution, and predicting plastic deformation and heat transfer in welding processes. This can then be used to evaluate the generation of thermal stresses and the change in mechanical and metallurgical properties in the weld pool and the adjacent Heat Affected Zone (HAZ).

## Introduction

Arc welding is a complex process that involves interplay between different welding parameters and physical phenomena. The molten filler material from the welding wire is transferred to the work piece and subsequently solidifies, bonding the parent parts together. The residual stresses generated due to welding may have several harmful effects such as decrease in the resistance to cyclic loads and corrosion in hostile environments. Although these effects have been qualitatively understood for many years, there is still a lack of quantification and thus the ability to predict the phenomena. In many widely used welding processes, such as GMAW, the metal transfer, solidification, plastic deformation and temperature field play a crucial role in the residual stress distribution and the strength of the welded joint.

Numerical modelling of welding has assumed enormous significance in recent years because of the growing application of welding in capital intensive industries, e.g. marine, mining, rail, etc. The rapid temperature fluctuations, continuous phase change, and high temperature environment make it difficult to instrument and accurately measure various parameters in a weld pool experimentally. Computational modelling can immensely aid in understanding the underlying mechanisms of welding processes, assessing the relative importance of various physical processes, and predicting how different process parameters affect the mechanical and metallurgical properties of the weld.

A number of computational models have been developed to understand the interaction of filler material with parent parts [5,6,12]. The behaviour of the filler material and its interaction with the parent/base metals are governed by complex physics, including elasto-plastic solid deformation, heat transfer, phase transformation, and fluid flow. The complexity is compounded by a number of additional factors controlling the dynamics of material in the weld pool, such as electro-magnetic force, surface tension and gravity. Most approaches either ignore some of these physical processes, or consider highly simplified models of them.

Many of the limitations of the previous models can be attributed to the computational modelling framework used. The modelling approaches undertaken to date have been largely focused on grid-based techniques [8]. Conventional mesh based computational techniques, such as FEM and BEM, have limitations in simulating welding processes as they have difficulties in modelling high deformation and free surface behaviour often encountered in welding. Furthermore, the coupling of various physical processes in a multi-phase complex system often poses difficulties. In this work, we address these fundamental aspects of the mesh-based numerical modelling tools, and attempt to circumvent the difficulties associated with mesh-based computational models by adopting an alternative mesh-free approach. The primary aim of this paper is thus to develop a variant of the mesh free method called Smoothed Particle Hydrodynamics (SPH) to model material deformation and temperature distribution in a welding process.

SPH is particularly attractive for modelling welding because of its ability to naturally handle complex splashing free surface flows. Due to its mesh-free nature, this method does not require maintaining the integrity and desired shape of the elements, so it is able to handle the large scale plastic deformation involved in welding. SPH particles provide the ability to simply track history dependent properties of the material [4]. This provides a significant capability to track properties that may be of interest in welding, such as, cumulative plastic strain, damage, metal composition (including tracking multiple metals or metal composites) and trapped gas, metallic phase and microstructure, and surface oxide. Some or all of these properties can then be used to feed back into the deformation state and flow dynamics using suitable constitutive laws and rheology models. SPH based models therefore appear well equipped to overcome many of the limitations of previously used methods and to provide a clearer insight into the fundamental physics of welding processes.

Residual stresses and distortions after welding largely depend on the extent of plastic deformation and the temperature gradient in the weld pool occurred during the welding process, which in turn are governed by the weld pool geometry and processing parameters. Here we first present the SPH method as applied to solid stress analysis problems and then develop a preliminary SPH model of a simple arc welding process.

## Modelling Approach

In a weld pool, three phases usually interact with each other; a) solid phase formed by the solidification of the liquid/semi-solid metal, b) liquid/semi-solid phase material in the weld pool, and c) gas phase above the weld pool due to the plasma and shielding gas. In most applications, the shielding gas does not affect the physics of metal transfer and subsequent solidification in the weld pool, other than affecting the heat transfer. The gas phase can often be ignored in modelling by incorporating its effects using appropriate thermal boundary conditions. To simplify the modelling effort, many models in the literature assume the entire domain of analysis as a single phase system [7,11].

In this work, we also consider a simplified single phase modelling approach. Here a reverse approach to that used in [7] is adopted, i.e. the entire system consisting of filler and parent materials is modelled as a solid phase. The filler material is modelled as a semi-solid (plastic) material with a very low modulus and the parent parts are modelled as elastic solids. An elasto-plastic analysis is performed using SPH to model the metal deposition and interaction of the deposited material with the parent materials. This is coupled with a transient thermal analysis in the weld zone that is used to model the cooling of the weld pool and heat transfer to the parent materials. This approach has the advantage that the entire analysis domain can be treated using the laws of solid material deformation and plastic flow.

The basic SPH equations used for fluid flow and heat transfer modelling are given in [4]. A variant of this SPH method is developed in [3] for simulation of forging and extrusion. In this work, we extend the same SPH formulation for modelling the welding process.

### Problem Specification and Analysis

Here we consider a groove weld, which is commonly used for joining two parts edge-to-edge. It is used in T joints, corner joints, and for other complex joints, such as joints between flat and curved surfaces. After deposition into the groove, the filler material subsequently fuses with the parent materials to form the welded joint. Figure 1 shows the geometry of the weld groove and the parent plates used in this study. We use a typical groove with depth d = 32 mm, plate thickness t = 64 mm and groove angle θ = 30°. Both filler material and parent plates are of aluminium alloy (A6061) with properties taken from [9].

For the SPH simulation, the workpiece domain was discretised into particles of resolution (spacing) 2 mm, giving a total of 5203 particles in the two-dimensional simulations. Based on the material properties, the sound speed was 5092 m/s. A coupled elasto-plastic and thermal analysis was performed using SPH to evaluate the plastic strain and temperature distributions in the filler and the parent materials. The timescale in welding (i.e. the time required for the cooling phase) varies considerably based on material properties, dimension of the workpiece and surrounding environmental (thermal boundary) conditions.

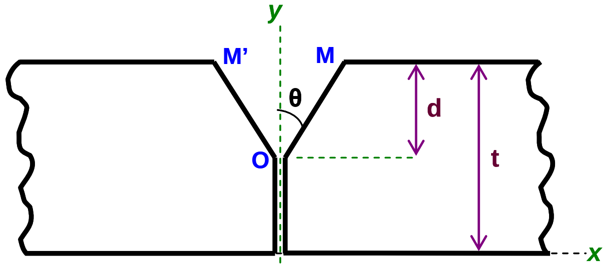

Figure 1: Schematic of the weld groove and workpiece geometry.

### Plastic Deformation

Plastic deformation plays a key role in most welding processes, as highlighted by several researchers [1,2]. Figure 1 shows the welding configuration. Figure 2 shows the flow pattern as the filler material enters and plastically deforms to fill the weld groove. When the tip of the filler material comes in contact with the groove vertex (point O), it deforms strongly resulting in a large plastic strain. High levels of plastic deformation continue along the periphery of the filler material, as it deforms against the parent plates and gradually fills the weld groove.

The level of plastic deformation clearly depends on the geometry of the groove. It first occurs near the bottom point (O) of the 'V-section' as the material flow is obstructed. As the groove is being filled, the plastic strain distribution is governed by the force exerted by the material above and the restrictions in the material flow path, which in turn is determined by the groove geometry.

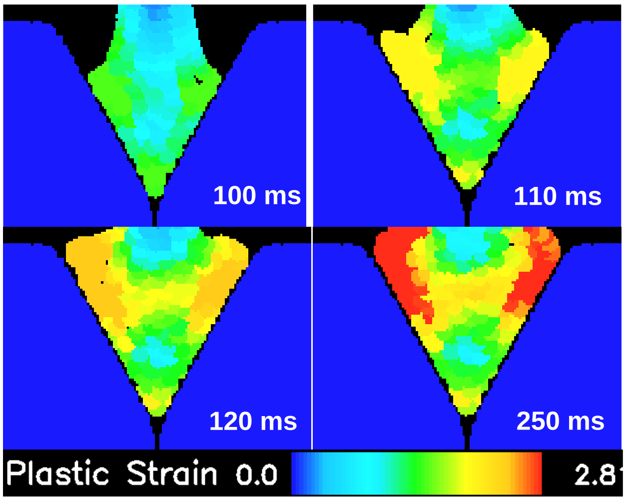

Figure 2: Filling pattern of the weld groove with filler material coloured by the level of plastic deformation.

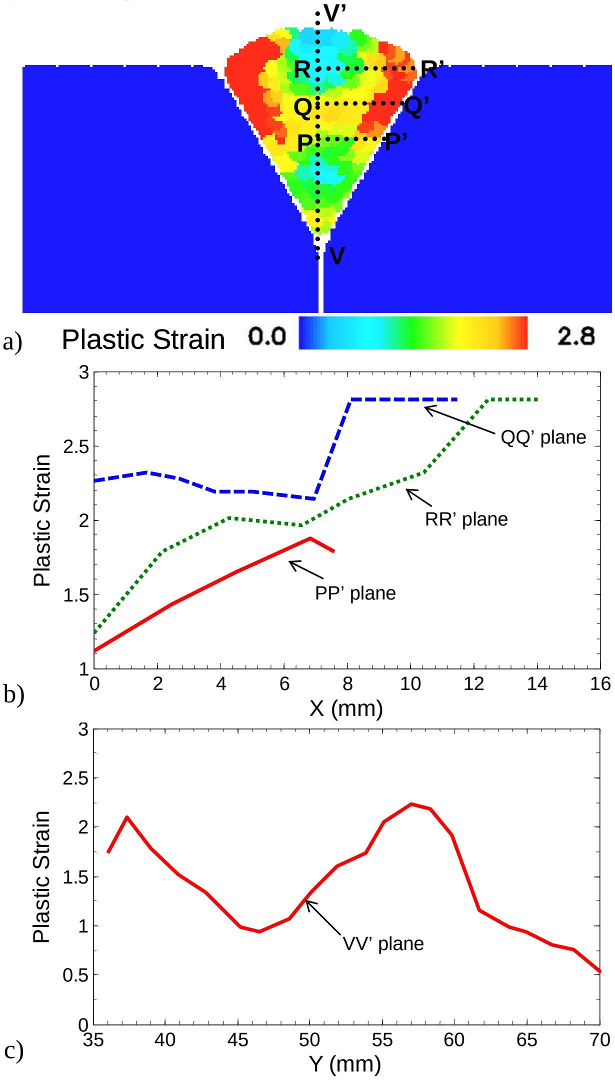

Figure 3: a) Final plastic strain distribution in the weld pool, b) Variation in plastic strain along the three horizontal planes (PP', QQ' and RR'), and c) Variation in plastic strain along the vertical mid-plane (VV').

In general, the plastic strain is higher on the surface of the filler material in contact with the parent materials. The material near this region suffers higher deformation as it is pressed onto the groove wall. The plastic strain near the contact surface increases from the lower vertex of the groove towards the upper section, i.e. from point O to M or M'. The material in the interior cannot freely deform and undergoes relatively less plastic deformation.

Figure 3a shows the final plastic strain distribution in the weld pool after the groove is filled and the plastic flow has ceased. To quantify the nature of plastic deformation, we examine the plastic strain variation along four representative planes shown in Figure 3a. Figure 3b shows the plastic strain distributions along the three horizontal planes PP', QQ' and RR' respectively, located at 16, 24 and 32 mm from the groove vertex (point O). In Figure 3b, x = 0 corresponds to the points on the mid-plane VV' (i.e. P, Q and R). Along a given horizontal plane, the plastic strain is higher near the interface with the parent material as explained before. In a small region near the interface, the plastic strain remains essentially constant. The level of plastic deformation gradually decreases as one moves towards the centreline (VV') of the filler material. Near point M or M' (indicated in Figure 1), the material forms a shoulder region and the highest plastic strain occurs here. This is because the weld groove below is already filled preventing downward flow and there is no parent material surface obstructing sidewise flow. This allows free sidewise flow of the filler material in this region, leading to a higher plastic strain.

Figure 3c shows the variation in plastic strain along the vertical mid-plane VV'. It fluctuates from point V (y = 34 mm) to V' (y = 70 mm). The plastic strain first increases slightly and then decreases to a minimum value of 0.9 (the sky blue region in the lower part of the V-groove in Figure 3a). It then increases to reach its maximum value of 2.2 (the yellow region around Q) and then decreases steadily towards the interface. The nature of this variation can be explained by the mechanism of the development of plastic strain. When the filler material fills the weld groove, the plastic deformation depends on the material flow pattern. If the material is allowed to flow sidewise, it leads to an increased plastic deformation (hence plastic strain). On the other hand, if the load from the material above restricts the flow, it leads to a lower plastic strain. The relative dominance of these two opposing effects generates alternating high-low plastic strains across the various horizontal layers.

## Thermal Response

The filler material was initially at 927 °C and the workpiece (parent plates) was at room temperature (27 °C) for the coupled elasto-plastic and thermal analysis. Both convective and radiative boundary conditions were applied on the free surfaces of the workpiece. The typical heat transfer coefficients for arc welding conditions were used in this work [5]. The convection coefficient was assumed to be 50 W/m$^2$.K and the emissivity of the surfaces was taken to be 0.04 W/m$^2$.K$^4$.

Figure 4 shows the temperature distribution in the weld pool and the surrounding material as the workpiece is being cooled. Heat is transferred from the hot semi-solid filler material to the surrounding parent material and flows towards the boundaries where it is lost by convection and radiation. For this weld groove geometry, the cooling begins at the bottom vertex of the groove (point O in Figure 1). The region around point O is exposed to the maximum area of the adjacent low temperature parent material (i.e. higher area to volume ratio), resulting in a higher rate of heat loss. The temperature rapidly decreases from the vertex towards the shoulder region (MM' in Figure 1) of the weld. With time, the filler material gradually cools maintaining approximately uniform temperature distribution across various horizontal layers. The temperature variation of the neighbouring parent material plays an important role in controlling the change in microstructure and residual stress generation. The rapid heating of the surrounding region and its subsequent gradual cooling, as observed in Figure 4, conform to the expected thermal response for a typical weld zone [5,10].

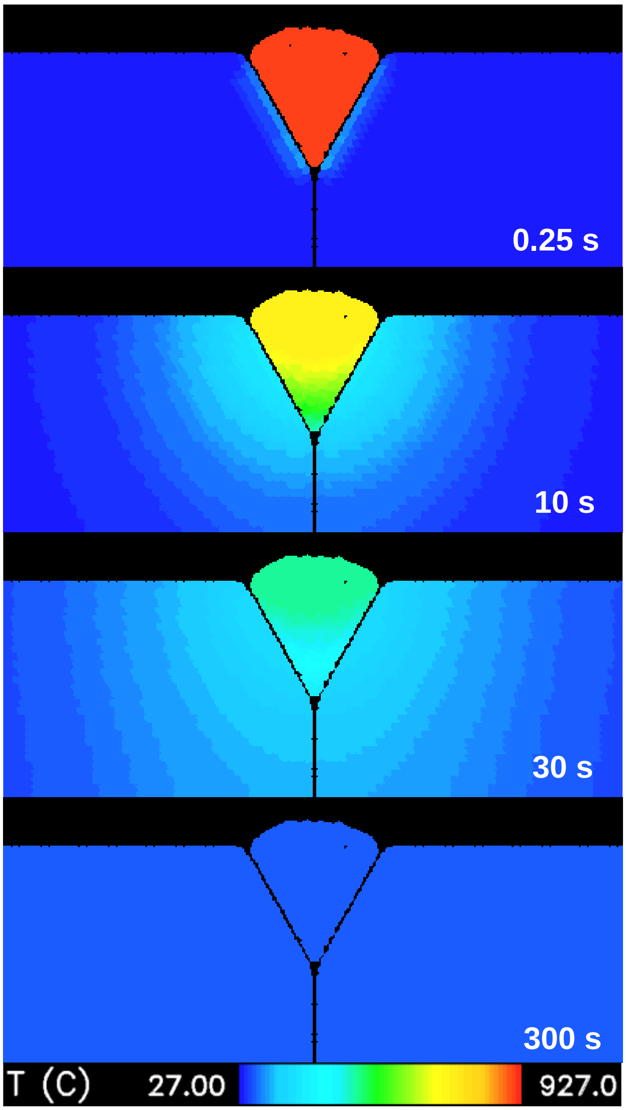

Figure 4: Heat transfer in the weld pool and the surrounding parent material during the cooling phase.

Figure 5 shows the temperature distribution at different times along a horizontal plane through the middle of the filler material (at a height of 16 mm from groove vertex O). The temperature distributions are symmetric, as one should expect from the problem geometry and the initial/boundary conditions. The weld pool cools gradually with the heat conducting to the surrounding parent material. Over longer times, both the filler and parent materials attain a uniform temperature (e.g. 65 °C at 300 s).

As the weld pool cools, the temperature in the filler material does not have considerable spatial variation (across different horizontal layers) because of relatively high thermal conductivity of the aluminium alloy. This is desirable as a higher temperature gradient in the weld pool can result in residual thermal stresses producing distortions in the weld. Also, the filler material is cooled and the surrounding parent material is initially heated non-uniformly with time, see Figure 5. This will lead to different levels of thermal strains (hence the stresses) and micro-structural transformations in the HAZ.

The spatial variation of temperature at any instant produces differential expansions and generates residual thermal stress, which accumulates over time. To provide a more quantitative assessment of the temperature variation, we study the temperature profiles along the same three representative horizontal planes used for monitoring the plastic strain (shown in Figure 3a).

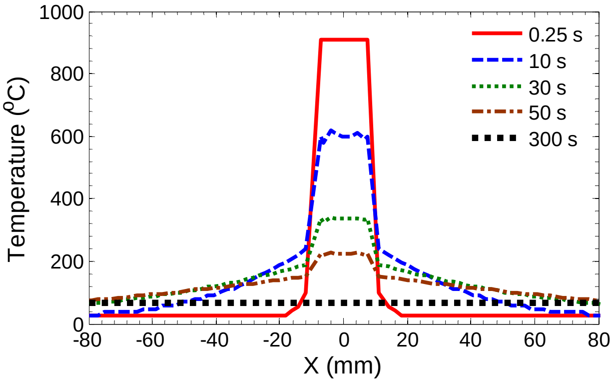

Figure 5: Variation in the temperature profile with time along the horizontal plane through the middle of the filler material (through point Q).

Figure 6 shows the temperature distributions along the horizontal planes (PP', QQ' and RR') at 25 s. The nature of the temperature variation is similar along all the three planes. Each profile includes a relatively uniform zone extending from 9-18 mm, which represents the temperature in the filler material. This is followed by a sharp drop in temperature, indicating the high temperature gradient existing in the interface between the filler and parent materials. Thereafter, the temperatures become nearly the same irrespective of the planes, as evident by the near coincidence of the three curves in Figure 6. This shows that although a local temperature gradient exists in the filler material, the temperature distributions along different horizontal planes in the parent material remain essentially the same at any time. This means that for this specific welding configuration the thermal strains will not cause significant distortions of the welded joint perpendicular to the thickness of the plates (i.e. in the horizontal direction).

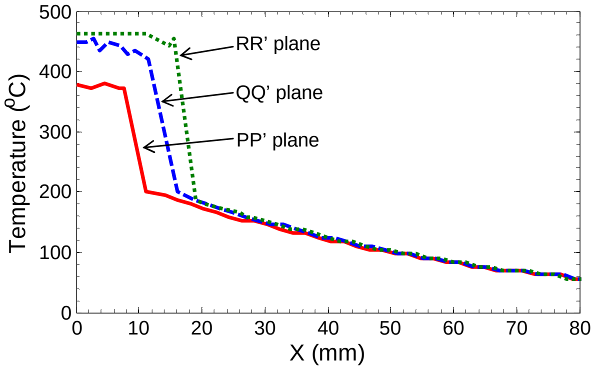

Figure 6: Temperature distributions along the three horizontal planes (PP', QQ' and RR' in Figure 3a).

## Discussion and Conclusions

In this paper, we have shown that SPH can be successfully used to model simple arc welding configurations. The SPH solutions are sensible and demonstrate the physical phenomena that occur in a typical arc welding process. The SPH predictions of plastic deformation pattern and the resulting complex variation in plastic strain in the weld pool conform to the physically expected behaviour experienced in welding. The filling and deformation patterns are found to depend on the restrictions in the material flow and the geometry of the weld groove.

The heat transfer characteristics in the weld pool and the parent materials are well captured using SPH. The temperatures and the rate of cooling/heating in the filler and parent materials depend on the weld groove geometry. As such, SPH based models confirm the non-uniform cooling rate and the temperature field in a workpiece, which are exhibited in real life welding processes.

The temperature distribution and the rate of cooling/heating can be used to predict the change in micro-structure and mechanical properties in the weld pool and the Heat Affected Zone around. The SPH thermal solution can also be used to evaluate the residual stress-strain state and the extent of distortion in a weldment.

For welding applications, SPH has the advantages of being able to follow very high deformations (beyond what is possible with the FEM and FV methods) and to keep track of the specific history of each part of the metal allowing fine scale control over the constitutive model (e.g. rheology/plasticity), and potentially direct prediction of many types of flow and microstructure related defects, such as dross formation and porosity.

This work can be extended to incorporate other underlying physical processes that play critical roles in welding. The development of adequate models to simulate welding will lead to improved welding processes capable of reducing residual and thermal stresses, and distortion in weldments and welded structures. The improved welding models will also be useful to provide input for determining design and process parameters that will produce optimum weld quality and joint properties. This will reduce failure of welded structures and extend operating life of critical industrial components.

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