

# Mapping the elasto-plastic properties of a Cu-CuAl functionally-graded alloy using the Virtual Fields Method

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**Abstract.** This paper presents a numerical analysis and experimental validation of the behaviour of a Cu-CuAl functionally graded material (FGM). In the inverse identification, the Virtual Fields Method (VFM) was used to extract material parameters from full-field deformation measurements obtained by Digital Image Correlation (DIC). The FGMs were fabricated by Wire and Arc Additive Manufacturing (WAAM), using gas tungsten arc welding (GTAW) and inert metal gas (MIG) welding as heat sources. This study evidenced the feasibility of using WAAM in the production of FGMs. The material parameter identification was carried out based on simulation first, as verification, then on experimental data. The present research paves the way for manufacturing and analysing Cu-CuAl FGMs using the WAAM process.

## Introduction

The significance of materials to society has undergone a transformational progression throughout the course of history [1]. In current societal challenges, the importance of material innovation for economic and environmental sustainability has been recognised [2]. Advanced composite materials possess unique properties that enhance the performance, durability, and efficiency of engineered products. Moreover, they can be tailored to meet specific application-oriented requirements, enabling the creation of innovative and customised products [3].

Functionally graded materials (FGMs) are advanced structures embedding a smooth variation of properties. In contrast with conventional composite materials, their design mitigates delamination or stress concentration at interfaces and is characterised by a gradient pattern of properties across the volume of the bulk material [4]. Driven by advanced computational and manufacturing techniques, FGMs can be created with outstanding mechanical behaviour [5]. This approach mimics natural biological tissues that are favourable to produce gradient patterns considering the diversity of chemical, structural and geometric variations [7]. Bone, teeth, wood and bamboo have already inspired FGMs. Remarkable outcomes have already been attained, for instance, in mitigating stress concentration or enhancing fracture toughness.

Additive manufacturing (AM) is a revolutionary technology for producing 3D parts. Some AM processes have been used to obtain FGM parts in a single step, which is an advantage over more traditional manufacturing processes [8]. More recently, FGM metal parts have been manufactured by Wire and Arc Additive Manufacturing (WAAM) to look for a manufacturing method that will reduce material costs [9]. The WAAM twin-wire process has already been successfully applied with various material combinations, such as Fe-Al, Fe-Ni, Ti-Al, Ni-Ti, inconel625-stainless steel and others.

In response to the widespread adoption of full-field measurement techniques, such as digital image correlation (DIC) [10], material parameter identification methods have been proposed. Among different methods, the VFM can efficiently extract parameters of materials from deformation maps [11]. Nevertheless, a suitable test configuration needs to be defined first [12]. Then, for heterogeneous properties, a suitable parameterization needs to be formulated. This is the object of this research.

## Numerical Simulation

A finite element analysis of the experimental test method was developed to create synthetic data to verify the VFM code and to explore the design space for a suitable test configuration. To describe the material behaviour, a bilinear isotropic hardening plastic model was selected. This elasto-plastic model was built in Ansys Parametric Design Language (APDL). To simulate the heterogeneous elastic constants two distinct regions were designed in the model. In the transition zone of the two materials, a linear variation of the elastic properties was considered. The numerical data was used to validate the identification procedure. In this analysis, sensitivity-based virtual fields were selected for the VFM. For the elastic constants, the deformation values of the elements were exported and analysed in a MATLAB software VFM in order to identify the stiffness coefficients. Then the results were identified and converted to Young's modulus,  $E$  [GPa] and Poisson's ratio,  $\nu$  [m/m].

## Experimental Work

The samples were produced through the WAAM process using an inert metal gas (MIG) welding power source PRO MIG 3200 from Kempy and a gas tungsten arc welding (GTAW) power source CITOTIG 315 AC/DC from Oerlikon. The welding parameters, travel speed, wire feed speed, gas flow rate, voltage, electrical current and interpass temperature were defined depending on the material and type of welding used. The FGMs were produced through layers deposited on layers. These layers were deposited on top of an ASTM a36 steel substrate. After some layers were deposited and cooled, the sample was machined. This machining allows obtaining a sample with a uniform appearance for applying a speckle pattern. The wall produced was cut transversally and placed in resin to carry out some characterization tests of the material. Throughout this research, several FGM specimens were studied to improve the manufacturing efficiency and accuracy of the current process. In this study, overcoming specific challenges, such as porosity, defects, cracks, and delamination of the layers, was necessary.

Finally, the specimens were tested on an electro-mechanical test machine. A set up system for the DIC, such as cameras, light source and acquisition software (MatchID), was necessary to acquire image of the specimen during the loading.

## Conclusion

This study presents a numerical analysis and experimental validation of the behaviour of a Cu-CuAl functionally graded material (FGM). The paper presents the material parameter identification based on simulation first, as verification, then on experimental data. This work reports some initial test results and provides an outlook for the future challenges in this topic.

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