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# Proving the viability of manufacturing of multi-layer steel/vanadium alloy/steel composite tubes by numerical simulations and experiment

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## HIGHLIGHTS

- Possibility of manufacturing of multilayer material vanadium alloy/steel layers was considered.
- The influence of parameters of co-extrusion was studied by numerical simulations.
- The process conditions suitable for producing a good quality product were identified.
- Experimental verification was conducted using industrial equipment.

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## ABSTRACT

Vanadium alloys are promising structural materials for fuel cladding tubes for fast-neutron reactors. However, high solubility of oxygen and nitrogen in vanadium alloys at operating temperatures of 700 °C limits their application. In this work, we present a novel composite structure consisting of vanadium alloy V-4Ti-4Cr (provides high long-term strength of the material) and stainless steel Fe-0.2C-13Cr (as a corrosion resistant protective layer). It is produced by co-extrusion of these materials forming a three-layered tube. Finite element simulations were utilised to explore the influence of the various co-extrusion parameters on manufacturability of multi-layered tubes. Experimental verification of the numerical modelling was performed using co-extrusion with the process parameters suggested by the numerical simulations. Scanning electron microscopy and microhardness measurements revealed a defect-free diffusion layer at the interfaces between both materials indicating a good quality bonding for these co-extrusion conditions.

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## 1. Introduction

Modern nuclear power engineering require the creation of new structural materials that have high heat resistance, radiation and corrosion resistance, which enable the creation of new highly efficient power plants with ultra-high operating parameters.

While the earlier studies on the fast reactors have been mainly focused on the reactor core design concepts and their performance, one of the critical issues is the performance of the fuel cladding material because of the high neutron fluence and temperature. The fuel cladding material and other critical elements of the core for fast neutron reactors operating in a closed nuclear fuel cycle is expected to undergo severe irradiation-induced deformation, such as irradiation creep and swelling with thermal creep, due to its high neutron fluence (up to 180–200 dpa with maximum fuel burnup up to 20% of heavy atoms) as well as high temperature operating condition (600–750 °C).

However, the materials currently used have limitations on a number of characteristics and do not allow the fullest possible

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realization of the possibilities of new generation power plants.

One of the most promising structural materials for fuel cladding tubes for fast neutron reactors operating in a closed nuclear fuel cycle are vanadium alloys of the V-(5–10)Ti-(4–6)Cr (weight %) series. These alloys have various advantages (over austenitic and ferritic-martensitic steels) such as high short-term and long-term strength at temperatures up to 750 °C and significant radiation resistance [1–3]. Flem et al. [1] showed that the tensile strength of V–4Cr–4Ti alloy of about 400 MPa is relatively insensitive to temperature in the 600–750 °C range. This value is in good agreement with those obtained by Rowcliffe et al. [2] on unirradiated and irradiated alloy V–4Cr–4Ti.

However, high solubility of oxygen and nitrogen in vanadium at operating temperatures of about 700 °C limits their application for fuel cladding tubes due to possible corrosion in a liquid-metal coolant [3–5].

One way to overcome this limitation of vanadium alloys, which undergoes embrittlement upon interaction with oxygen and nitrogen, is to create a multi-layer composite with corrosion-resistant sheaths serving as protective layers. Specifically, the surface of a vanadium alloy can be protected by corrosion-resistant ferritic chromium steels. Nikulin et al. [6] justified the selection of ferritic chromium steels as a favourable choice by arguing that vanadium alloys of the V–Cr–Ti system and ferritic steel can produce a diffusion layer and form a continuous series of solid solutions. Furthermore, these materials have comparable physical and mechanical properties and therefore are suitable for fabricating bimetallic composites through industrial metal forming techniques such as rolling or extrusion. The growing interest in novel composite materials for nuclear fuel claddings for fast reactors with significant radiation resistance at high temperatures paired with good corrosion resistance has been the motivation for current research reported in this work.

The viability of co-extrusion as a way to produce multilayered composites was previously demonstrated for other materials [8]. Bimetallic materials often give rise to an economical benefit in terms of reduced manufacturing cost. One of the main technological challenges for producing such materials remains the optimisation of the processing parameters to obtain void-free deformation bonding between the constituents of the multilayered composite. Successful manufacturing of bimetal tubes by co-extrusion was demonstrated using experimental and numerical methods [9–12].

In the manufacturing of bi-material products by co-extrusion, it is crucial to obtain good quality bonding between the constituent materials and to minimize the occurrence of voids at the interfaces, which may cause fracture. Some of the important parameters that influence the strength of the interface of the co-extruded materials are extrusion ratio, die angle, the coefficient of friction between the billet and the die as well as the ratio of the flow stress of both materials [13–15].

Despite the existing experience in manufacturing of bi- and multi-metallic items for a variety of materials, manufacturing of multilayer parts has been tried mostly for sheet materials. The experience of multilayer tube manufacturing in general is scarce, while multilayer vanadium-based tubes have never been produced to date. A multilayer composite tubular material presented in this work is therefore a novelty. Manufacturing of such multimetallic tubes requires a tailored selection of processing parameters which are not known today. Determining suitable co-extrusion parameters experimentally for a specific set of materials is a time consuming and challenging task. Therefore, the use of numerical techniques such as Finite Element Method (FEM) for pre-selecting the processing parameters has gained popularity. A number of commercially available software such as ABAQUS, ANSYS, DEFORM, QForm and others have been successfully utilised to study extrusion of multi-material parts [16–18], but, as mentioned above, the experience with such simulations is still fairly limited.

In this work, we focus on determining the process parameters for co-extrusion of steel/vanadium alloy/steel tube utilising the QForm FEM software package taking into account the availability of the industrial extrusion equipment. The software was designed specifically to perform metal forming simulations. It uses a hybrid approach which combines the advantages of the Voronoi Cells and the Finite-Element Method. The advantages include a provision for automatic re-meshing and advanced algorithms for solving coupled mechanical and thermal problems. The main purpose of simulations of the co-extrusion process was to determine appropriate processing parameters, which can be used in industry-scale co-extrusion manufacturing of thin-walled tubes where high-quality bonding between different materials is at a premium. The results of the simulations were then validated experimentally using the proposed extrusion parameters. In addition, interface bonding between the stainless steel and the vanadium alloy were investigated using scanning electron microscopy and microhardness measurements, along with the chemical analysis of the composite at the interface and its vicinity.

## 2. Numerical simulation procedure

Previous investigations by several research groups have shown that extrusion of multi-material products requires optimisation of several factors mentioned in the Introduction, including the semi-die angle, the coefficient of friction between the work-piece and the die, the extrusion ratio, the work-piece temperature, etc. [9–17]. FEM simulations are an effective tool for narrowing down the parameter space to values suitable for industrial production, thus reducing the number of experiments required and accelerating the development of new products. In the present work, the FEM code QForm7 was employed for simulation of extrusion of a three-layer tube based on the vanadium alloy V-4Ti-4Cr sheathed at its inner and outer surfaces with Fe-0.2C-13Cr stainless steel.

The simulations were set up as a 2D axisymmetric general forming problem coupled with a thermal problem, and also as a 3D model where only a quarter of the sample and the die were simulated. The geometry of the die and the initial geometry of the tubes and their assembly are shown in Fig. 1. In the simulated co-extrusion process, the initial diameter of the work-piece was reduced from $A_0 = 110$ mm down to $A_f = 65$ mm, which corresponds to an extrusion ratio of 1.7. The die and the punch were all treated as non-deformable rigid bodies.

In order to simulate the material behaviour of the vanadium alloy V-4Ti-4Cr and the Fe-0.2C-13Cr stainless steel, experimental stress-strain curves of both materials obtained under uniaxial tension were imported into the database of QForm7 as flow stress curves, see Fig. 2. The tensile tests of steel and vanadium alloy specimens at elevated temperatures were specially carried out using the Gleeble 3800.

This information was compiled using our original tensile testing results and other published data describing the mechanical behaviour of the vanadium alloy and the stainless steel considered. These data include the results obtained by Nikulin et al. [6] for three-layer material based on the vanadium alloy and the corrosion-resistant steel; high temperature tensile properties and deformation behaviour of V-4Cr-4Ti was studied by Rowcliffe et al. [19].

The work-piece temperature was varied between 900 °C and 1000 °C. This temperature range is only slightly below a typical temperature for extrusion of steel and was identified as a suitable regime for the simultaneous extrusion of both materials. Since the

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