

Demonstration of a high-performance continuous casting process for cobalt alloy ASTM F75

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Abstract. A modified horizontal high performance continuous casting configuration was investigated by the introduction of a mechanically durable and thermally insulating zirconia-based break-ring and the application of a copper-beryllium die for the casting of cobalt alloy ASTM F75 (Co: balance, Cr: 27 wt%, Mo: 5 wt%). Successful casting was demonstrated with an 8 mm diameter rod with good physical properties and a metallic phase structure and distribution consistent with the standard.

1 Introduction

The current state-of-the-art continuous alloy casting (CC) manufacturing equipment, which can output alloy weights within the range greater than 1 ton but less than 100 ton per trial run, is limited in scope by the range of castable materials owing to issues with solidification and chemical reactivity between the alloy cast and the ceramic/alloy materials which are a part of the casting die equipment. Each alloy in turn requires the setup of bespoke CC equipment with unique heating and materials selected for their alloy-specific processing properties, such as chemical resistance and heat transport.

Of particular interest is the cobalt-based alloy ASTM F75 (major elements: Co balance, Cr 27%, Mo 5%) which is widely applied in applications requiring high stiffness and wear resistance such as medical prosthetics, dental prosthetics, fuel nozzles and gas turbine vanes [1]. To cast F75 within a CC process the introduction of novel technologies are required. The use of break-ring (BR) technology comprises of a ceramic material, typically applied in a horizontal casting configuration, which displays a high thermal resistance and is placed between the crucible and casting die. It allows for a thermal break to occur whereby solidification occurs rapidly over a small and finite region around the BR material [2].

BR processes have applied Cu-Be based die material, which is chemically resistant [3] and displays a high heat resistance [4], and so can be applied for the production of a wide range of high-temperature alloys (1000 – 1800 °C range), such as steels, cobalts and nickels. The adoption of these two technologies to an existing CC process is a challenge owing to the

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required careful control of the heat transport properties in the CC setup to allow for uniform alloy solidification with no unwanted phase segregation or unwanted defects such as pores and tears in the alloy material[5].

This paper will compare the CC behaviour of F75 for an unmodified, state of the art CC process, and a modified high-performance CC process implementing BR technology and Cu-Be dies.

2 Experimental

CC was performed of alloy F75 with composition Co: balance, Cr: 28.9 wt%, Mo: 5.5 wt%, Si: 0.9 wt%; and under a state-of-the-art horizontal configuration on the Rautomead RM050 rig setup as highlighted in Figure 1A. The temperature applied was 1660 °C. Casting trials were performed with alloy rods of diameter 14 mm. Position 1 indicates the nozzle for the setup and position 2, the ceramic die components investigated, which included ZSBN (BN: 45 wt%, ZrO₂: 45 wt%, Borosilicate glass < 10 wt%) and BNP2 (AlN: 60 wt% and BN: 40 wt%). ZSBN and BNP2 are widely applied ceramic materials for thermal processing and show good physical properties and chemical resistance for CC. A modified BR configuration highlighted in Figure 1B, was also investigated for 8 mm rod diameter and applied a BR zirconia-based material chosen for its mechanical durability and thermal insulating properties and a Cu-Be die instead of a ceramic. The casting withdrawal speed was on average 2.99 m/min for all trials which were summarised in C.

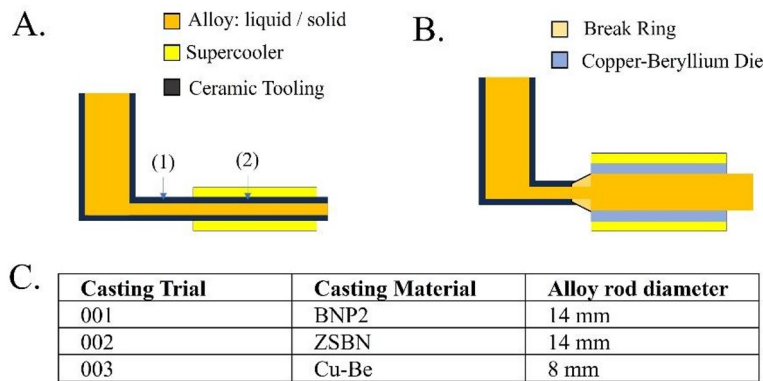


Figure 1 – Not to scale, simplified diagram of experimental horizontal CC setup of A) state-of-the-art CC process (RM050, Rautomead Ltd) and B) high-performance process with break ring and Cu-Be die. C) details of the casting trials.

Analysis of cast product was performed qualitatively using a digital camera, quantitatively using Electron Beam Scattering Diffraction (EBSD) (FEI Scios, EDAX Hikari EBSD detector); chemical analysis using Elemental Dispersive X-ray Spectroscopy (EDS) (FEI Scios, EDAX Octane Plus EDX) and X-ray Diffraction (XRD) (Siemens D5000); and the physical properties from tensile testing at Metlab UK Ltd, on three 8 mm diameter, F75 as cast rod samples from the high-performance CC rig at 100 mm gauge lengths.

3 Results and discussion

Two CC trial were performed of 14 mm diameter F75 rod using the standard state of the art configuration at Rautomead Ltd, Figure 1A. The trials tested two different ceramic tooling

materials ZSBN and BNP2 as both the casting die and tooling nozzle. Both casting trials failed as defined by a rod seizure within the CC machinery and its withdrawal being prevented. Attempts to continue casting such as the forcing of the rod back into the crucible furnace for remelt and a reset of the process was not possible.

Figure 2A and B highlighted optical images of the failed rod cast. The cylindrical ceramic housing had been cut away to reveal the alloy rod within and its condition. Within Figure 2A, the 14 mm diameter F75 rod was embedded within the ZSBN ceramic tooling nozzle (location (1) in Figure 1A) which had a thickness of approximately 17 mm. In Figure 2B, the rod was within a ZSBN, 2 mm thick die (location 2 in Figure 1A). In both locations the rod had debris from the ceramic tooling (nozzle and die) attached to it. This indicated a possible reaction with the ZSBN ceramic materials. Chemical reactions between the rods and the ceramic tooling materials are common causes for rod seizures owing to the accelerated reactivity at the high processing temperatures and indicated a chemical incompatibility of the setup.

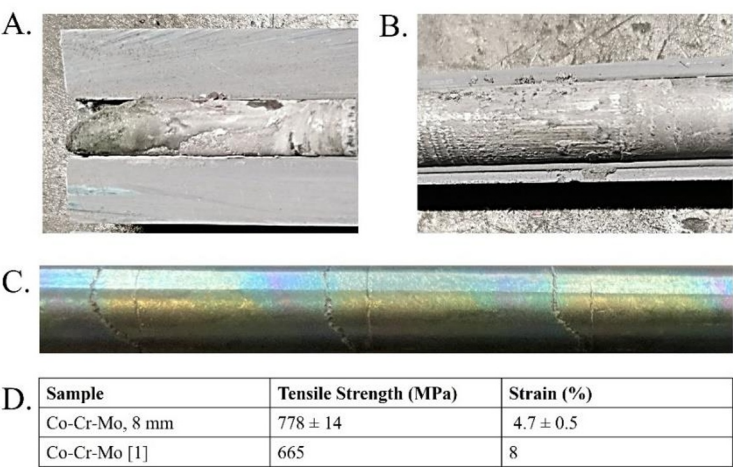


Figure 2 – Optical images depict the cast F75 (Co-Cr-Mo) for A) & B) 14 mm diameter rods from current state of the art continuous casting process, and C) an 8 mm diameter high-performance continuous casting process. D) tensile test results from 8 mm rods.

The BNP2 with F75 cast was analysed (not shown) and also indicated similar debris on the rod. The ZSBN and BNP2 results indicated a reaction likely originating with the common compound BN present in both. A Cr and BN reaction has been observed by the authors in [6] around 1100 °C, which is 360 °C cooler than the applied CC temperatures in this study. This indicated that the chemical reaction would be more accelerated when CC, however Mo showed inert behaviour with BN [6]. Co is not a likely reactant owing to the use of BN crucibles for Co intermetallic compound formation[7].

A third F75 trial was performed using BR technology and Cu-Be casting die (**Figure 1B**). Under this configuration a casting of 8 mm F75 was performed successfully without rod seizures and until the alloy melting crucible had emptied. The condition of the rod was highlighted in **Figure 2C** and indicated a metallic surface free from debris. Periodic lines (vertical in image) on the rod outer surface (witness marks) were present and were characteristic of a break-ring CC configuration which has two marks induced during the withdrawal processes[8].

The physical parameters were tested from tensile investigations of the 8 mm rods cast under the high-performance process (**Figure 2D**). The sample performed to the

recommended ASTM F75 tensile strength, however its elongation was less at $4.7 \pm 0.5 \%$ instead of 8% [1].

The F75 crystallographic structure was characterised using XRD as highlighted in **Figure 3A**. The XRD pattern agreed with expected F75 phases from its phase diagram (**Figure 3B**, [9]), which include γ -Co face-centred cubic (fcc) phase; a ϵ -M(CoCrMo)₂₃C₆ hexagonal close packed (hcp) phase, and a σ phase (Co-Cr) [10]. The prominent diffraction lines were observed for γ -phase at the orientations (111) [11], (220) [11], and possibly a (200) around 62° angle (shifted from the 51° position[7]); the ϵ -phase at (10 $\bar{1}$ 0), (10 $\bar{1}$ 1), (11 $\bar{2}$ 0) [11]; and the σ phase at (330) around the 44° angle[12] [10], which overlapped with the γ phase and around the 83° angle[11].

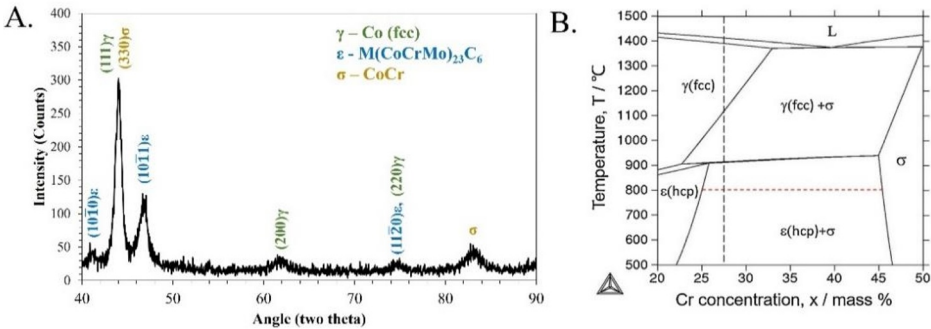


Figure 3 –A) XRD pattern of F75 (Co-Cr-Mo), 8 mm diameter rod, continuously cast using high-performance process. B) calculated phase diagram of ASTM F75 with 6% Mo[9].

The grain structure and composition of the successfully cast rod from the high-performance process were analysed using EBSD. A rod sample was cross-sectioned and analysed along casting direction. **Figure 4A**, showed the inverse pole figure and indicated the orientation of the expected prevalent main phases γ -fcc and ϵ -hcp superimposed on one another. The texture was mainly along the fcc (101), (001) and hcp (2 $\bar{1}$ $\bar{1}$ 0) and (0001) directions. The phase structure map in **Figure 4B** highlighted the locations of the ϵ -hcp and γ -fcc phases, which indicated the ϵ surrounded by the matrix of the γ . The ϵ -phase decomposes from the γ -phase depending on the heat treatment holding duration, where prolonged heat treatments, such as 86.4 kilo-seconds at 1073 K can result in an almost entire ϵ -phase structure[13]. The cast results indicated that the CC condition produced some ϵ -phase but with the γ -fcc dominating, as witnessed in other as-cast F75[14].

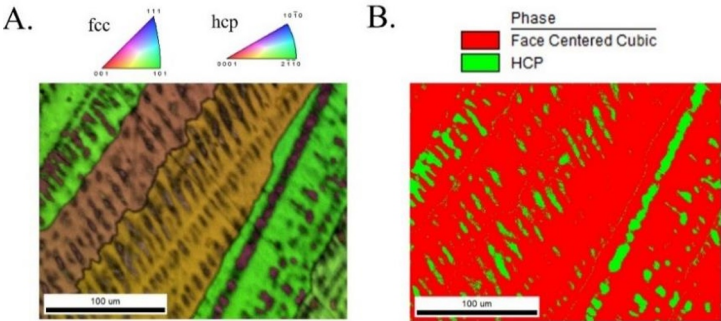


Figure 4 - EBSD analysis of F75 (Co-Cr-Mo),8 mm diameter rod, continuously cast using high-performance process showing A) Inverse Pole Figure with γ -fcc and ε -hcp superimposed, and B) Phase map.

The elemental composition by weight percent was summarised in **Figure 5A** from a point scan of a featureless region and showed to be within expected guidelines for ASTM F75 [1]. An elemental map was performed and the major elements were illustrated in **Figure 5B-E** for Co, Cr, Mo and Si, respectively. They were distributed as expected with Co forming the γ matrix and Cr distributed uniformly along secondary carbide precipitates. The Mo revealed precipitates of size diameter $9 \pm 0.9 \mu\text{m}$ along with a dendritic structure which was also demonstrated in the EBSD scan (**Figure 4B**) by the ε -hcp phase. Si, which was applied to the alloy for hardness and wear resistance, was present throughout and as small precipitates of size $4 \pm 0.4 \mu\text{m}$. The results indicated that the solidification conditions did not induce an elemental segregation outside of the expected metallurgical behaviour for F75.

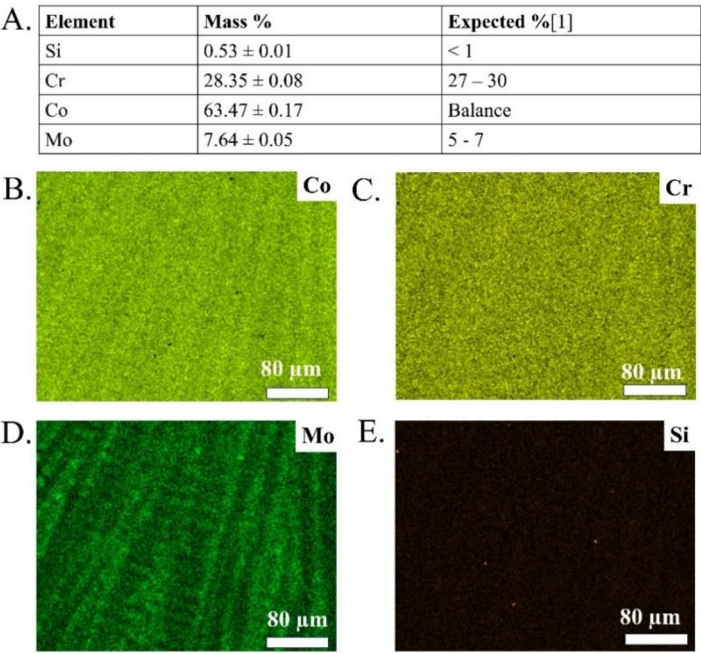


Figure 5 – EDS of F75 (Co-Cr-Mo), 8 mm diameter rod, continuously cast using high-performance process, showing A) the mass % from point scan of a featureless region; and A) to D) elements Co, Cr, Mo and Si, respectively.

4 Conclusions

Investigations into the cast-ability of cobalt alloy F75 with a modified horizontal continuous casting configuration revealed an ability to produce an 8 mm alloy rod with no observable adverse chemical reactions owing to the introduction of a chemically resistant Cu-Be alloy die.

The physical properties of the rod were consistent in terms of strength with the ASTM F75 standard and the distribution of metallic phases and elements were consistent with the standard.

The work highlighted the potential to form alloys within the 1 to 100 ton output weight range and initiated further investigations into different sized diameter rods, casting orientations, and other alloy families.

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