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Thermal Stability and Heat Treatment of Biomedical Co–28Cr–6Mo Alloy for Knee Implant Applications

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This study investigates the effect of heat treatment on cast Co–28Cr–6Mo biomedical alloy used for the production of knee implants. The alloy is widely used due to its excellent corrosion resistance, wear resistance, and mechanical properties. However, these properties can be further optimized by appropriate heat treatment. The thermal stability of the alloy was evaluated through hardness measurements and microstructural characterization. The highest hardness was achieved after annealing at 800 °C, which was associated with an increased fraction of the ε-phase with HCP crystal structure. In contrast, solution annealing followed by aging resulted in a microstructure dominated by the γ-phase with FCC structure and the precipitation of fine $M_{23}C_6$ carbides. Although both heat-treatment routes increased hardness by approximately 30 % compared to the as-cast condition, they operated through different strengthening mechanisms. The results indicate that the solution-treated and aged condition may provide a favorable combination of strength and ductility, making it a promising option for orthopedic implant applications.

Keywords: Knee implant, Microstructure, Heat treatment, Thermal stability

1 Introduction

A wide range of biomaterials is used in medicine, all of which must satisfy strict requirements for long-term performance in the human body. Among metallic biomaterials, the most commonly used are stainless steels, titanium alloys, and Co–28Cr–6Mo alloy [1]. Owing to its excellent biocompatibility, corrosion resistance, mechanical strength, and wear resistance, Co–28Cr–6Mo is widely employed in orthopedic applications, particularly for knee implants [2-5]. These components are most commonly manufactured by investment casting, which provides excellent dimensional accuracy and high surface quality [2, 6, 7].

The as-cast Co–28Cr–6Mo alloy is characterized by a typical dendritic microstructure composed of two solid-solution phases. The primary phase is the γ-phase with a face-centered cubic (FCC) crystal structure, which is stable at elevated temperatures and is retained during solidification as a result of the relatively rapid cooling of the casting. The second phase is the ε-phase with a hexagonal close-packed (HCP) crystal structure, which is thermodynamically stable below approximately 800 °C according to the Co–Cr phase diagram. In addition to these matrix phases, minor amounts of M23C6 carbides or the tetragonal σ-phase may also be present [4, 8, 9].

The mechanical properties of Co–28Cr–6Mo alloys, which must satisfy the requirements of EN ISO 5832-4 for biomedical applications, are strongly influenced by the phase composition and the morphology of the dendritic microstructure. These characteristics can be modified through appropriate heat-treatment procedures, enabling optimization of the alloy's performance for orthopedic applications. Various heat-treatment regimes for Co–28Cr–6Mo alloys have been reported in the literature, with the most common approach being a combination of solution annealing and subsequent aging [10-13]. Sedlaček et al. [11] investigated the effect of solution annealing at 1200 °C for 2 h followed by aging at 900 °C for different durations (1–12 h) on the hardness of Co–28Cr–6Mo alloy. Their results showed that prolonged aging promotes more extensive precipitation of M23C6 carbides, leading to increased hardness. The influence of solution annealing temperature on mechanical properties was studied by Öztürk et al. [10], who identified 1175 °C as the optimum solution treatment temperature. After solution annealing at 1175 °C for 3 h followed by aging at 850 °C for 4 h, the alloy exhibited a tensile yield strength (TYS) of 683 ± 23 MPa and an ultimate tensile strength (UTS) of 829 ± 58 MPa, representing the most favorable combination of mechanical properties among the investigated conditions.

Therefore, this study focuses on the thermal stability and heat-treatment response of cast Co–28Cr–6Mo alloy, including a detailed characterization

of the associated microstructural and phase transformations. The relationship between these changes and the resulting mechanical properties is evaluated with the objective of optimizing the alloy for biomedical applications.

2 Experimental Methods

In this work, a commercially manufactured knee implant produced by Prospon spol. s.r.o. using precision casting was investigated. Individual specimens were sectioned from the implant using an ATM Brillant 220 metallographic cutting machine (see Fig. 1) and subsequently subjected to various heat-treatment regimes. To evaluate the thermal stability of the alloy, annealing treatments were carried out at temperatures ranging from 200 to 1000 °C for 2 h. The resulting samples were designated as HT_*temperature*. An additional sample, designated HT_T6, was subjected to a T6 heat-treatment regime consisting of solution annealing at 1200 °C for 2 h followed by aging at 900 °C for 5 h. After heat treatment, all samples were water-quenched.

The Vickers hardness of all samples was measured using a load of 1 kg (HV 1) applied for 10 s. For each sample, 10 indentations were performed at evenly spaced positions across the sample cross-section. The results are reported as mean values with corresponding 95% confidence intervals.

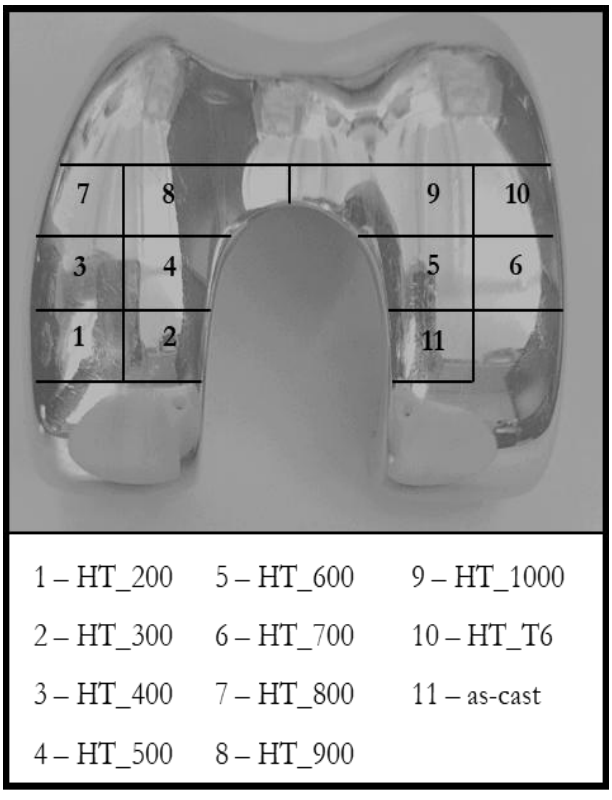


Fig. 1 *Schematic illustration of sample extraction from the knee implant*

For selected samples (as-cast, HT_800, and HT_T6), microstructural characterization was performed using a Nikon Eclipse MA200 optical microscope and a Tescan Mira 2 LMU scanning electron microscope equipped with a BSE detector. Prior to observation, the samples were prepared by sequential grinding using SiC abrasive papers with grit sizes ranging from P400 to P2500, followed by polishing with a 3 μm diamond suspension and final polishing using a 0.06 μm Al_2O_3 suspension. The polished surfaces were etched in concentrated aqua regia for 2 min to reveal the microstructure. Furthermore, phase composition analysis was subsequently carried out by X-ray diffraction (XRD) using a PANalytical X'Pert Pro diffractometer equipped with a Co anode. Finally, compression tests were performed in accordance with DIN 50106 on three specimens of each material, each with a height of 3 mm.

3 Results and Discussion

3.1 Microstructure and Thermal Stability

The as-cast Co–28Cr–6Mo alloy exhibited the typical dendritic microstructure shown in Fig. 2. The dendritic regions consisted predominantly of the ε-phase with HCP structure, which accounted for approximately 33 wt.% according to XRD analysis. In contrast, the interdendritic regions were enriched in the γ-phase, FCC solid solution. In addition, approximately 2 wt.% of $M_{23}C_6$ carbides were detected. Based on previous studies of this material system, these carbides are primarily enriched in Cr and Mo [14]. The resulting microstructure is therefore relatively heterogeneous, reflecting the solidification behavior of the alloy. Nevertheless, no significant structural defects, such as porosity, inclusions, or shrinkage cavities, were observed that could adversely affect its suitability for biomedical applications. The observations obtained by optical and scanning electron microscopy are consistent with the expected microstructure and agree well with previous reports describing the as-cast Co–28Cr–6Mo alloy in detail [12, 15, 16]. The effect of cooling rate during casting on the resulting microstructure has been described extensively in the literature. Higher cooling rates generally lead to a finer microstructure and a lower fraction of carbide precipitates [17]. Considering the relatively fine dendritic structure and the limited amount of carbides observed in the present material, it is likely that comparatively rapid cooling conditions were employed during casting. The resulting structure was relatively homogeneous overall with only slight chemical segregation.

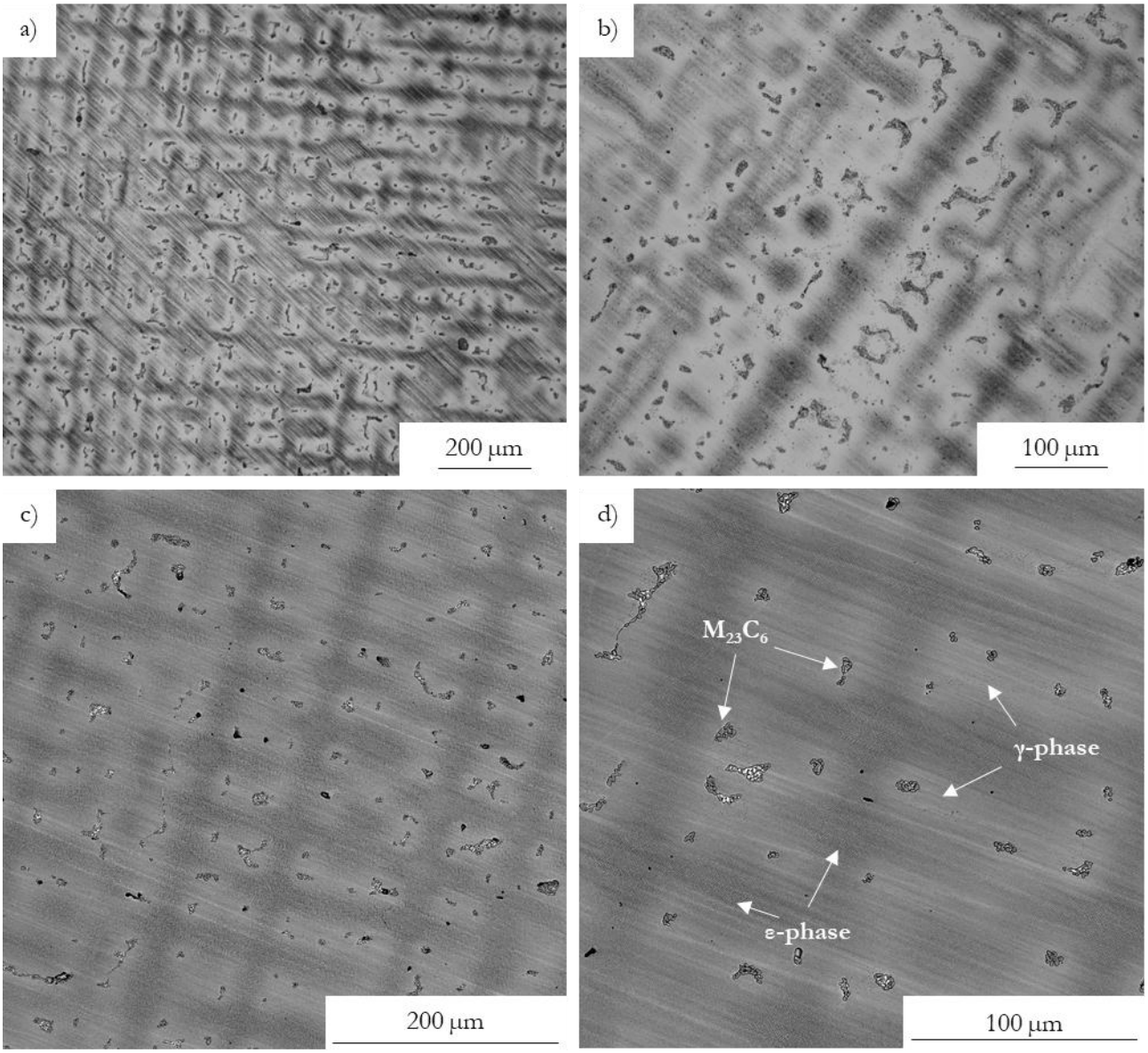


Fig. 2 *Microstructure of the as-cast Co-28Cr-6Mo alloy: a, b) OM; c, d) SEM-BSE images*

Heat treatment induces microstructural changes in Co–28Cr–6Mo alloys, which are reflected in their mechanical properties. To evaluate the thermal stability of the investigated material, the dependence of HV1 hardness on annealing temperature was determined. For all samples, the annealing time was fixed at 2 h. This duration was selected based on previous studies [12, 18], which demonstrated that it is sufficient to promote precipitation hardening while minimizing excessive grain coarsening that could adversely affect the mechanical properties. The results of the hardness measurements (see Fig. 3) show that the highest HV1 values were achieved after annealing at 800 and 900 °C. This behavior is consistent with the findings reported by Roudnická et al. [12] for Co–28Cr–6Mo alloys, where the highest hardness values were likewise observed in a similar temperature range. The authors attributed this increase in hardness to a combination of σ-phase precipitation and an isothermal martensitic transformation, resulting in an increased fraction of lamellar ε-phase in the microstructure [12].

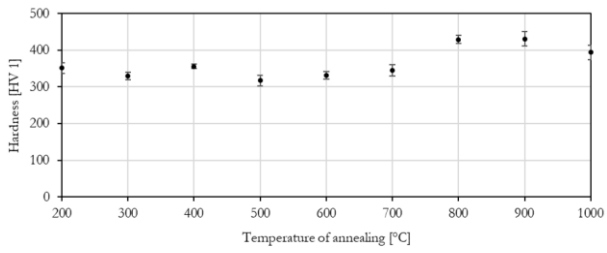


Fig. 3 *Dependence of hardness on annealing temperature*

3.2 Heat Treatment

Based on the thermal stability results, the HT_800 sample, corresponding to direct aging at 800 °C for 2 h, was selected for detailed characterization because it exhibited the highest hardness. According to

the XRD analysis (see Fig. 4), changes in phase composition occurred during this treatment, and the resulting microstructure consisted of approximately 65 wt.% ε-phase and 35 wt.% γ-phase. In contrast, the HT_T6 condition, which involved solution annealing at 1200 °C for 2 h followed by aging at 900 °C for 5 h, exhibited a significantly lower ε-phase fraction of only 9 wt.%. This reduction is attributed to the stabilization of the γ-phase during solution treatment and its retention after quenching. In addition, the expected presence of M23C6 carbide precipitates was detected [10, 11, 18].

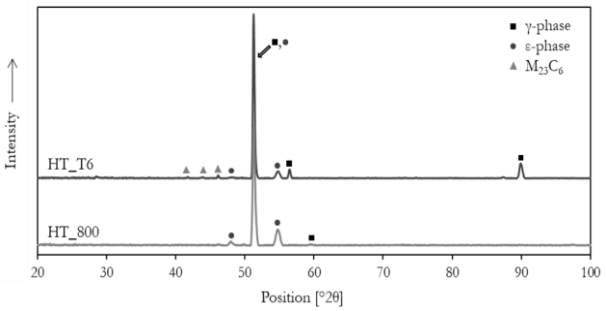


Fig. 4 *X-ray diffraction patterns of Co-28Cr-6Mo alloy after annealing at 800 °C and after T6 heat treatment*

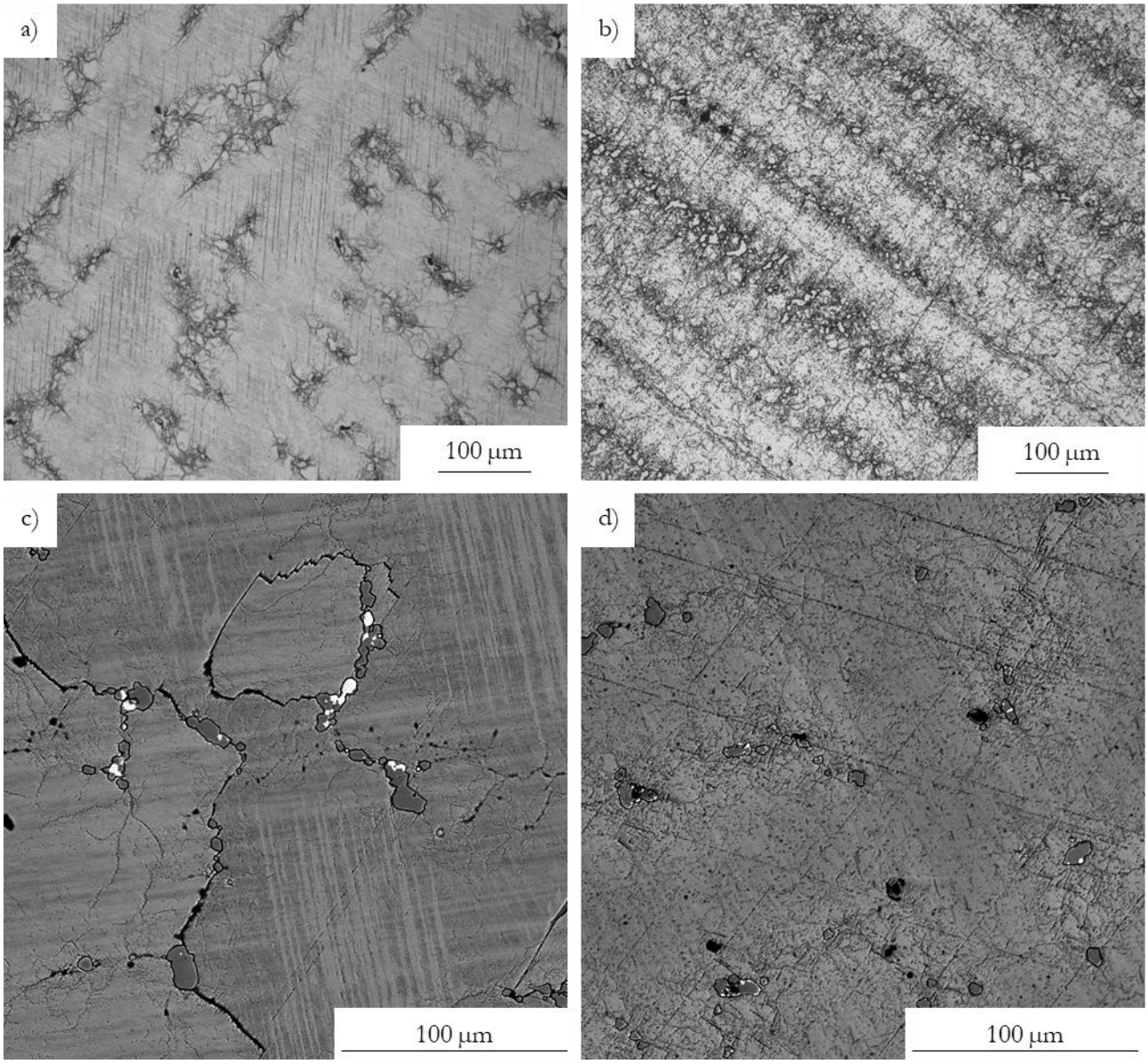


Fig. 5 *Microstructure of Co-28Cr-6Mo alloy after annealing at 800 °C (a,c) and after T6 heat treatment (b,d): a, b) OM; c, d) SEM-BSE*

In addition to changes in phase composition, heat treatment also led to noticeable microstructural evolution, as revealed by optical and scanning electron microscopy (see Fig. 5). In the HT_800 sample, the characteristic dendritic microstructure was largely preserved, with the ε-phase remaining predominant in the dendritic regions and the γ-phase located primarily in the interdendritic areas. Carbide precipitates enriched in Cr and Mo were also observed, preferentially located along grain and dendrite

boundaries [12]. Although the size and concentration of these particles were comparable to those observed in the as-cast condition, imaging with the BSE detector revealed a more pronounced chemical segregation within the microstructure. In contrast to the as-cast condition, the HT_T6 sample exhibited a markedly different microstructure as a result of recrystallization during solution annealing at 1200 °C [10, 18]. The grain size of the recrystallized structure is known to depend strongly on both the annealing temperature and holding time. As reported by Mori et al. [13], grain growth becomes more pronounced with increasing annealing temperature and duration. In Co–28Cr–6Mo alloys, recrystallization is also accompanied by the formation of annealing twins, which can contribute to the mechanical performance of the material [13, 15]. During the subsequent aging treatment, carbide precipitates formed preferentially along grain boundaries. However, their morphology differed from that observed in the as-cast condition. Consistent with the observations of Kaiser et al. [16], the HT_T6 sample contained finer carbides with a more spherical morphology, indicating that the precipitation behavior was significantly influenced by the preceding solution treatment and recrystallization process. Differences in carbide size and morphology were also observed. In the HT_800 condition, the carbide size was comparable to that in the as-cast state, with an average size of approximately 17.5 μm (see Table 1). In contrast, the HT_T6 condition exhibited smaller carbides, with an average size of 11.3 μm. Furthermore, the carbides in the HT_T6 sample showed a finer distribution and a lower tendency to form agglomerates. The image analysis also revealed differences in the area fraction of carbides in the material, with the highest value observed in the HT_T6 sample. This finding is consistent with an increased carbide content resulting from precipitation hardening.

Tab. 1 *Carbide size and area fraction determined by image analysis in ImageJ software*

Sample	Size [μm]	Area fraction [%]
as-cast	17.3 ± 3.0	5.0 ± 0.3
HT_800	17.7 ± 4.9	4.3 ± 0.8
HT_T6	11.3 ± 4.0	11.8 ± 0.9

HV1 hardness measurements revealed a significant effect of heat treatment, with both investigated conditions exhibiting an increase in hardness of approximately 30 % compared to the as-cast state (see Fig. 6). However, the underlying strengthening mechanisms differed between the two heat-treatment regimes. In the HT_800 sample, the increase in hardness can be attributed primarily to the higher fraction of the ε-phase, in agreement with the findings of Roudnická et al. [12]. In their study, a 20 % increase in hardness was associated with an increase in the ε-phase content from approximately 30 to 50 %. In contrast, the HT_T6 sample exhibited a reduced ε-phase fraction. Therefore, the hardness increase in this condition is more likely related to the precipitation of fine $M_{23}C_6$ carbides during aging [10, 12]. Considering the predominance of the γ-phase together with the presence of finely dispersed carbides, the HT_T6 condition can also be expected to exhibit favorable mechanical properties, particularly in terms of strength and ductility. This assumption is supported by the work of Hassani et al. [19], who investigated the effect of solution annealing at 1230 °C for 3 h followed by different cooling regimes on cast Co–28Cr–6Mo alloy. Their results demonstrated that rapid water quenching retained the high-temperature γ-phase, thereby promoting good ductility, while the concurrent precipitation of carbides contributed to strengthening. Compared with the as-cast condition, the authors reported an increase in strength of approximately 40 % and an improvement in ductility of nearly 60 % [19].

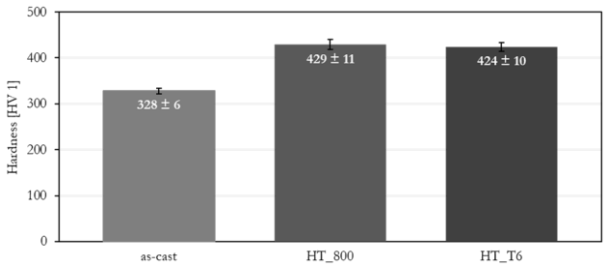


Fig. 6 *Comparison of the HV 1 hardness of the Co–28Cr–6Mo alloy before and after heat treatment*

The assumption of improved plasticity was supported by the compression test results (Fig. 7). The HT_T6 sample exhibited a relative deformation of 27%, indicating good resistance to brittle fracture. Regarding the compressive yield strength, an increase was observed compared with the as-cast condition (426 ± 45 MPa). For the HT_800 condition, the yield strength increased by approximately 70%, reaching 734 ± 54 MPa. The HT_T6 sample exhibited a yield strength of 541 ± 59 MPa, representing a considerable improvement over the as-cast condition while retaining very good plasticity. However, unlike the as-cast condition, fracture damage was observed in both heat-treated conditions.

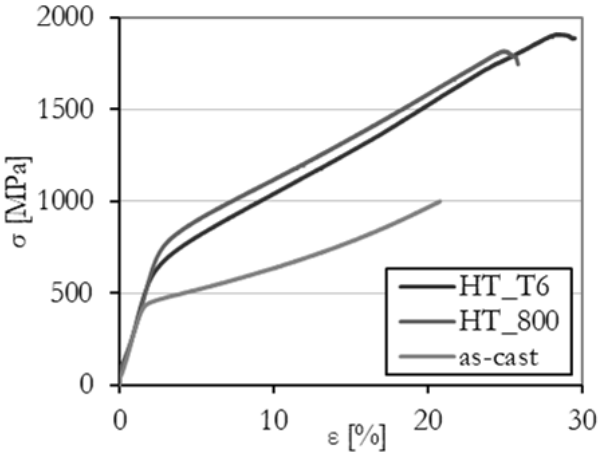


Fig. 7 *Compressive stress-strain curves of the Co–28Cr–6Mo alloy before and after heat treatment*

4 Conclusion

The present study evaluated different heat-treatment strategies for cast Co–28Cr–6Mo alloy and assessed their influence on the resulting microstructure, phase composition, and mechanical properties relevant to biomedical applications. The main conclusions can be summarized as follows:

- The as-cast Co–28Cr–6Mo alloy exhibited a dendritic microstructure composed of ε-phase and γ-phase with a minor fraction of $M_{23}C_6$ carbides and no significant casting defects.
- The highest hardness was achieved after direct aging at 800 °C, which increased the ε-phase fraction and promoted phase-transformation strengthening.
- Solution annealing followed by aging produced a recrystallized microstructure dominated by the γ-phase and strengthened by fine $M_{23}C_6$ carbide precipitates.
- Both heat-treatment routes increased hardness by approximately 30 % compared to the as-cast condition, demonstrating the strong influence of heat treatment on the microstructure and mechanical properties of the alloy.
- The compression tests showed an increase in yield strength following both heat treatment regimes. However, the combination of solution annealing and aging resulted in higher ductility.

For biomedical applications, high material ductility is highly desirable, as it reduces the risk of brittle fracture. Therefore, the combination of solution annealing and aging appears to be a promising heat treatment strategy, providing a favourable balance between strength and ductility.

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Data Availability

The data mentioned in the present manuscript are accessible via the Zenodo repository: https://doi.org/10.5281/zenodo.21840555.

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