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Influence of the Addition of Tellurium and Heat Treatment on the Microstructure of Hypoeutectic White Cast Iron

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Abstract

This study investigates how the addition of tellurium and heat treatment affects the microstructure of hypoeutectic white cast iron that has been modified with alloying elements such as titanium, chromium and vanadium. Samples with different chemical compositions were prepared and subjected to a two-step heat treatment process. Microstructural characterisation was performed using optical and scanning electron microscopy. The results show that introducing tellurium significantly affects the morphology of the cementite and carbide phases, causing them to fragment and become more evenly distributed. Furthermore, heat treatment enhanced matrix refinement and promoted phase stability. The combination of tellurium addition and heat treatment produced the most favourable microstructures, characterised by the high dispersion of hard phases within a fine-grained matrix.

Keywords:

microstructure, white cast iron, heat treatment, hypoeutectic white cast iron, tellurium

1. INTRODUCTION

White cast irons are widely valued for their excellent hardness and wear resistance, primarily due to the presence of hard carbide phases within their microstructure. To further enhance these properties for specific engineering applications, alloying elements and heat treatments are commonly employed. Among the various alloying elements, titanium (Ti), chromium (Cr), and vanadium (V) are known to refine the microstructure, promote carbide formation, and significantly improve overall hardness and abrasion resistance [1]. While less extensively studied in cast irons, tellurium (Te) has recently garnered interest due to its potential to modify solidification behavior and influence the morphology of eutectic carbides and graphite phases [2, 3]. Tellurium acts as a surface-active element that can affect nucleation and growth mechanisms during solidification, potentially leading to improved material performance [2, 3].

Concurrently, heat treatment remains a highly effective method for tailoring the microstructure of cast alloys. By precisely controlling heating rates, holding temperatures, and cooling conditions, significant changes can be achieved in the phase composition, matrix structure, and mechanical properties of cast irons. The synergistic combination of alloying and heat treatment offers a powerful approach to customize material behavior for diverse engineering applications.

The microstructure of classic hypoeutectic white cast irons is primarily governed by their chemical composition, cooling rate, and the presence of alloying additives or modifiers. In hypoeutectic structures, the main microstructural constituents are primary cementite (Fe_3C), ledeburitic eutectic, and a matrix that can be pearlitic, austenitic, or martensitic depending on the heat treatment conditions [4, 5]. Cementite typically forms needle-like or plate-like precipitates, often creating continuous networks along grain boundaries. In high-chromium cast irons, the presence of M_7C_3-type carbides is also observed, which contribute to greater hardness and abrasion resistance but can also increase material brittleness [4–6].

In alloyed cast irons with additions of Ti, Cr, or V, additional carbides such as TiC, VC, and Cr_7C_3 may precipitate, primarily in inter-dendritic zones, appearing as bright particles with varied morphologies [5, 7]. The specific phase system and size of these carbides depend on element concentration and solidification parameters. Directional cooling can lead to the orientation of precipitates in accordance with the temperature gradient, potentially resulting in anisotropic material properties [4]. Without modification, significant grain size and uneven distribution of hard phases are often observed in the microstructure [3, 8].

Previous research has highlighted tellurium as a promising modifier in aluminum and steel alloys, demonstrating its ability to alter eutectic morphologies, reduce dendrite arm spacing, and modify inclusion behavior [3, 9]. For instance, studies on Al-Si alloys have shown that Te can effectively transform sharp, plate-like intermetallics into more compact, rounded forms, thereby enhancing microstructural uniformity and stability during thermal cycles [10]. However, the specific role of tellurium in cast irons, especially when combined with complex alloying systems and subsequent heat treatment, remains largely underexplored.

This research aims to address this knowledge gap by systematically evaluating the influence of the addition of tellurium on the microstructure of hypoeutectic white cast iron, both with and without supplementary alloying elements (Ti, Cr, and V), and critically, both before and after a specific heat treatment process. The study focuses on key microstructural features such as carbide morphology, dendritic structure (quantified by Secondary Dendrite Arm Spacing – SDAS), inclusion formation, and matrix transformations. The overarching goal is to elucidate the mechanisms by which tellurium modifies solidification and phase evolution in these complex cast iron systems. Notably, SDAS is a critical parameter that reflects casting microstructure quality, as it correlates strongly with structural homogeneity, phase precipitate distribution, and segregation tendencies [11]. A reduction in SDAS, as observed with tellurium additions in other alloys [3], indicates a finer and more homogeneous microstructure due to increased nucleation frequency and intensified crystallization.

2. METHODOLOGY

This study investigated the influence of tellurium (Te) addition and heat treatment on the microstructure of hypoeutectic white cast iron, both in its base form and when alloyed with titanium (Ti), chromium (Cr), and vanadium (V). Thermal analysis cups, pre-dosed with tellurium paste at the base, were utilized as the tellurium source. These cups were first filled with the base cast iron melt and subsequently served as the mechanism for introducing the tellurium into the alloy during the experiment, a method intended to enhance tellurium recovery in the tested samples.

2.1. Sample preparation and chemical composition

A series of samples were prepared with different chemical compositions to systematically evaluate the effects of the alloying elements and tellurium. The designations for the samples are as follows:

- **W0:** Baseline white cast iron (no alloying additives).
- **W0T:** Baseline white cast iron with tellurium addition (One Tellurium Thermal Analysis Cup).
- **W1:** Baseline cast iron with titanium addition (3% Fe-Ti by weight of the charge).
- **W1T:** Baseline cast iron with titanium and tellurium addition (Alloy W1 plus one Tellurium Thermal Analysis Cup).
- **W2:** Baseline cast iron with titanium and chromium additions (3% Fe-Ti; 3.5% Fe-Cr by weight of the charge).
- **W2T:** Baseline cast iron with titanium, chromium, and tellurium additions (Alloy W2 plus one Tellurium Thermal Analysis Cup).
- **W3:** Baseline cast iron with titanium, chromium, and vanadium additions (3% Fe-Ti; 3.5% Fe-Cr; 0.2% Fe-V by weight of the charge).
- **W3T:** Baseline cast iron with titanium, chromium, vanadium, and tellurium additions (Alloy W3 plus one Tellurium Thermal Analysis Cup).

The chemical compositions of the W0, W1, W2, and W3 samples are detailed in Table 1, showing the weight percentages of carbon (C), silicon (Si), phosphorus (P), sulfur (S), chromium (Cr), titanium (Ti), and vanadium (V).

Table 1
Chemical composition of samples W0, W1, W2 and W3

Sample number	Chemical composition [wt. %]						
	C	Si	P	S	Cr	Ti	V
W0	3.050	0.078	0.040	0.014	0.038	0.003	<0.001
W1	2.860	0.085	0.043	0.015	0.035	1.560	0.048
W2	3.000	0.152	0.045	0.017	2.710	1.560	0.056
W3	3.020	0.177	0.047	0.017	2.950	1.010	0.220

2.2. Microstructural characterisation

Microstructural investigations were performed using two primary techniques:

- Optical Microscopy: A Leica MEF4M optical microscope, coupled with a computer and Leica Qwin software, was used for general microstructural observations and for measuring structural parameters. All optical micrographs were taken at a magnification of 500×.
- Scanning Electron Microscopy (SEM): A JEOL 5500VL scanning electron microscope was utilized for more detailed microstructural analysis and to identify crystallized phases. All SEM micrographs were taken at a magnification of 1500×.

A key quantitative parameter determined during the study was the Secondary Dendrite Arm Spacing (SDAS). SDAS was measured at a magnification of 200× to assess the homogeneity and fineness of the dendritic structure. Figure 1 presents the scheme for determining the SDAS parameter. Note that for samples W0 and W1 after heat treatment, dendrites were not observed, preventing SDAS determination for these specific cases.

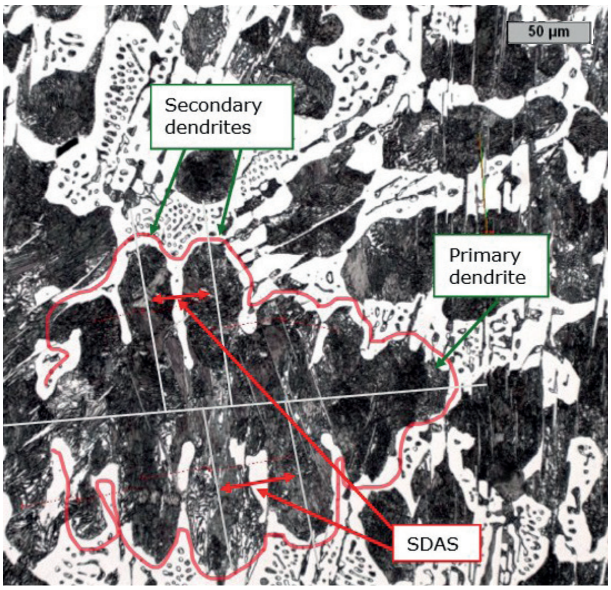

Fig. 1. Examples of determining the SDAS coefficient

2.3. Heat treatment process

Selected samples underwent a two-step heat treatment process to investigate its impact on microstructure. The scheme of the conducted heat treatment is presented in Figure 2.

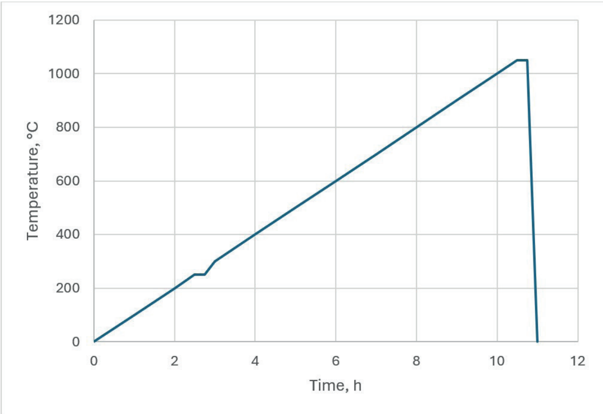

Fig. 2. Heat treatment scheme

The heat treatment procedure was carried out using a Czylok FCF 22H chamber furnace.

The samples were placed inside the furnace at room temperature (RT). The heating cycle involved the following stages:

- Stage 1 (Initial Heating): The samples were heated together with the furnace at a rate of 100°C/h up to a temperature of 250°C.
- Stage 2 (First Hold): The samples were held at 250°C for 15 minutes.
- Stage 3 (Main Heating): The temperature was again increased at a rate of 100°C/h until the final annealing temperature of 1050°C was reached.
- Stage 4 (Second Hold/Annealing): The samples were held at 1050°C for 15 minutes.
- Stage 5 (Cooling): Following the annealing stage, the samples were subjected to water quenching.

Samples subjected to heat treatment were designated with the suffix "_OC" (e.g., W0_OC, W0T_OC, W1_OC, W1T_OC, etc.).

The combined approach of different chemical compositions, applying a controlled heat treatment, and employing advanced microscopic techniques allowed for a comprehensive analysis of the influence of tellurium addition and heat treatment on the microstructure of hypoeutectic white cast iron.

3. RESULTS

The microstructures obtained during melting and after subsequent heat treatments are presented in Figures 3–6. During microscopic observations, given the appearance of various carbides in the structure, the primary focus was on analyzing their potential influence on the abrasion resistance of the obtained alloys.

Figure 3 displays the microstructures of the baseline samples (W0, W0T, W0_OC, W0T_OC). The reference sample (W0) exhibited secondary ledeburite with visible plates of ferrite cementite embedded within an austenitic matrix. The cementite formed a continuous, web-like structure. The addition of tellurium (W0T) to the reference sample resulted in a distinct fragmentation and rounding of these cementite plates. Conversely, the application of heat treatment (W0_OC) led to further fragmentation of the cementite and a transformation of the austenitic matrix into a martensitic phase. The combination of tellurium addition and heat treatment (W0T_OC) yielded the most favorable microstructure among all baseline variants, characterized by the highest level of homogeneity and stability. This was achieved by inhibiting the transformation of austenite into martensite and preventing the dissolution of carbides.

Figure 4 illustrates the microstructures of the samples containing titanium (W1, W1T, W1_OC, W1T_OC). In sample W1 (with Ti addition), bright TiC carbide inclusions were visible, primarily located at the grain boundaries. Their presence caused fragmentation of the structure and partial modification of the cementite shape. With the presence of tellurium (W1T), the distribution of TiC phases became more uniform, and the morphology of cementite was further altered. Sample W1_OC (Ti with heat treatment) exhibited a finer matrix structure and less continuous secondary cementite. The sample designated W1T_OC (Ti, Te with heat treatment) was characterized by a homogeneous phase distribution and highly fragmented cementite.

Figure 5 shows the microstructures of samples containing titanium and chromium (W2, W2T, W2_OC, W2T_OC). The addition of chromium to sample W2 resulted in the formation of additional elongated Cr_7C_3-type carbides, visible as bright, sharp-edged needles in the microstructure, which is typical for high-chromium cast irons [12]. In the sample identified as W2T (Ti + Cr + Te), the presence of tellurium led to shortened, rounded Cr_7C_3 carbides and fragmented cementite. Sample W2_OC (Ti + Cr with heat treatment) exhibited carbide phases with a more regular morphology, accompanied by fragmented secondary cementite. W2T_OC (Ti + Cr + Te with heat treatment) displayed a structure characterized by fine and uniformly distributed Cr_7C_3 and TiC carbides. It was observed that tellurium effectively reduced the length of needle-like Cr_7C_3 carbides, improving their morphology, while heat treatment fragmented the matrix and increased martensite content.

Figure 6 presents the microstructures of samples containing titanium, chromium, and vanadium (W3, W3T, W3_OC, W3T_OC). W3 showed a fine-grained structure with VC phases, consistent with existing literature on the influence of V on cast irons. Subsequent optimization of the microstructure and increased homogeneity of phase distribution were observed. In the case of sample W3T (Ti + Cr + V + Te), the presence of tellurium was found to impede the agglomeration of VC carbides, thereby facilitating their more even distribution. The phase composition of W3_OC (Ti + Cr + V with heat treatment) was characterized by the presence of fragmented cementite along with an ordered matrix structure. The W3T_OC sample (Ti + Cr + V + Te with heat treatment) demonstrated a structure with a high degree of fragmentation of carbide phases (TiC, Cr_7C_3, VC) and their uniform distribution.

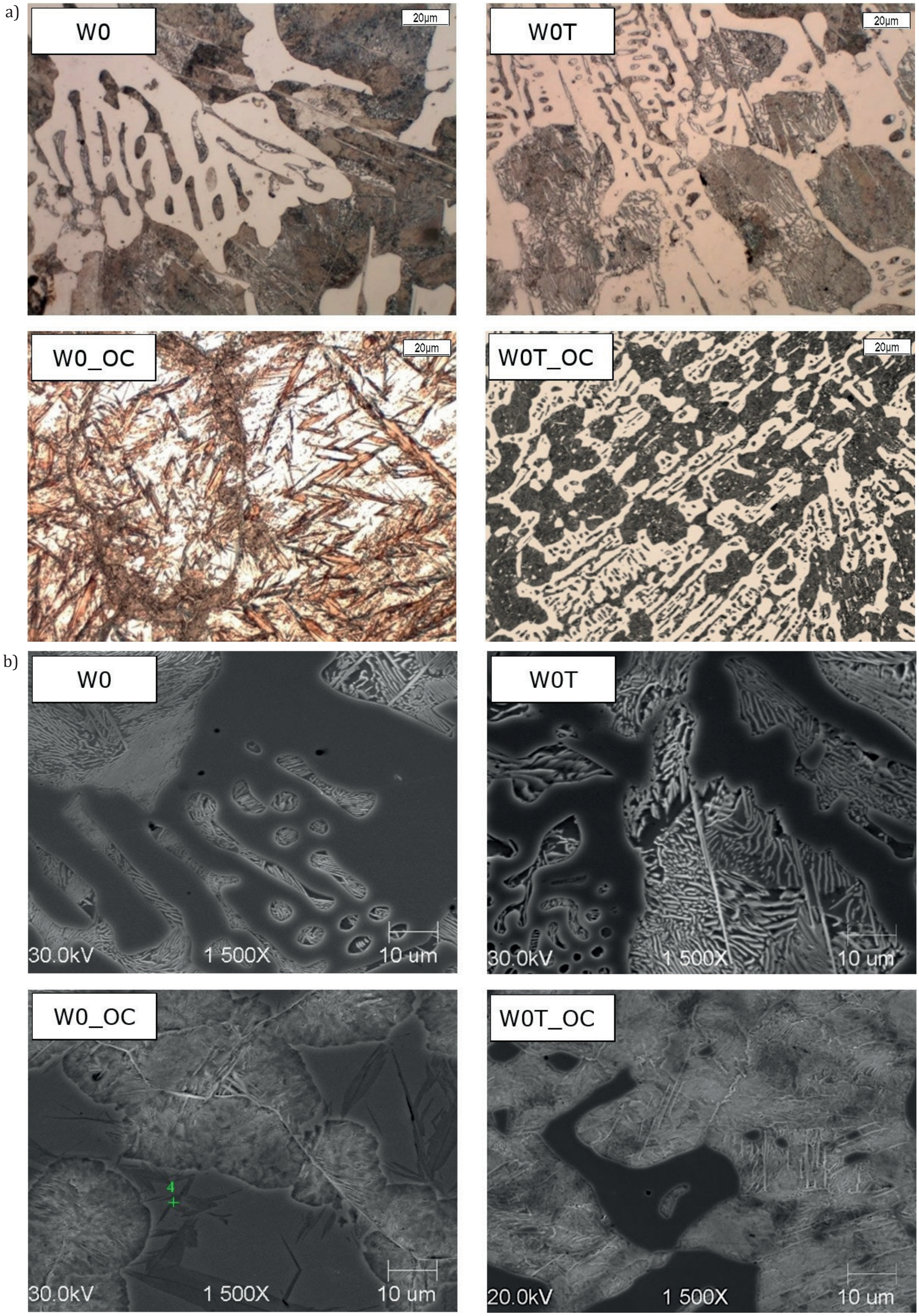

Fig. 3. Microstructures of samples W0, W0T, W0_OC and W0T_OC: a) optical micrographs (Nital etched, 500× magnification); b) scanning electron micrographs (SEM, 1500× magnification)

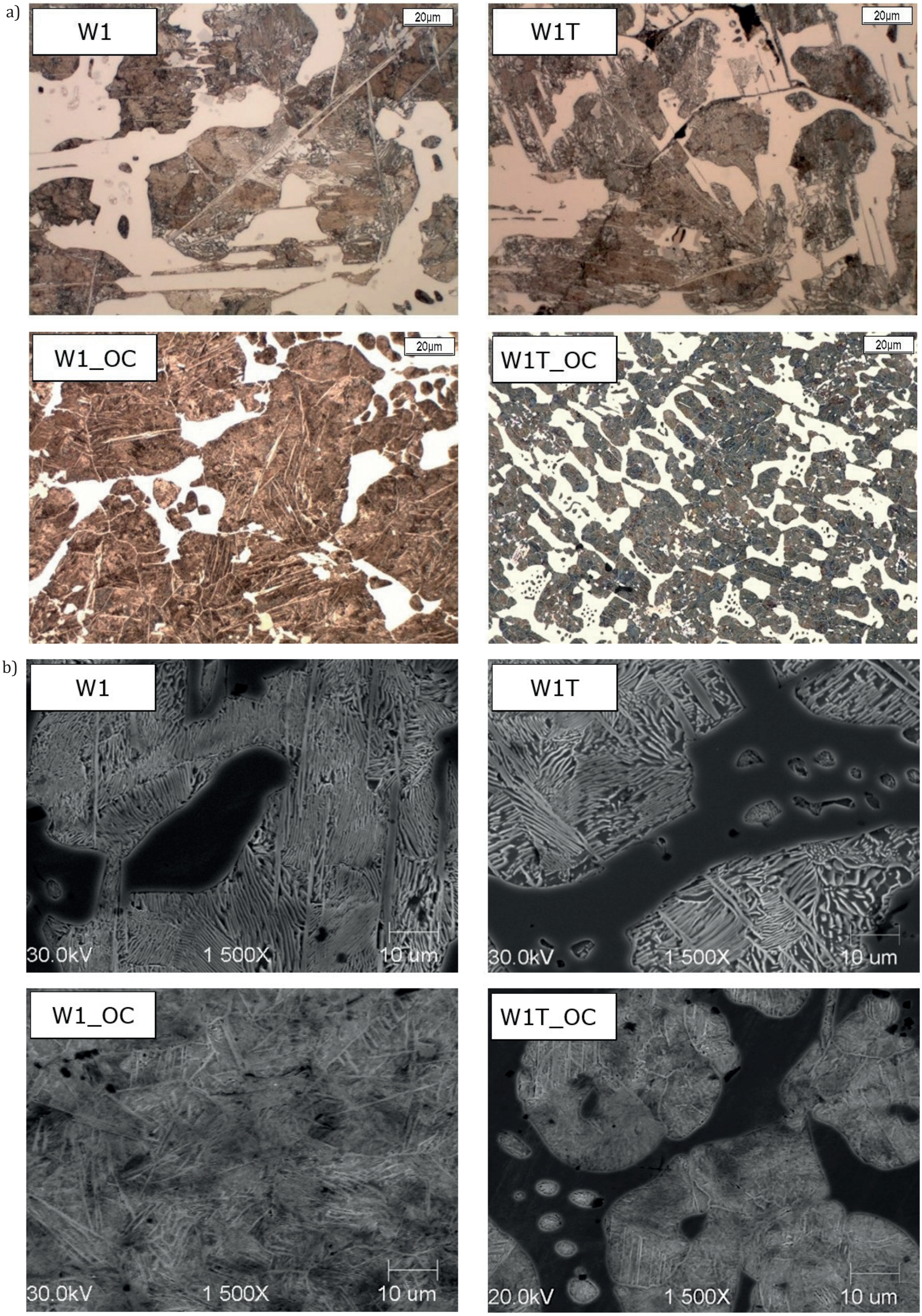

Fig. 4. Microstructures of W1, W1T, W1_OC and W1T_OC samples: a) optical micrographs (Nital etched, 500× magnification); b) scanning electron micrographs (SEM, 1500× magnification)

a)

b)

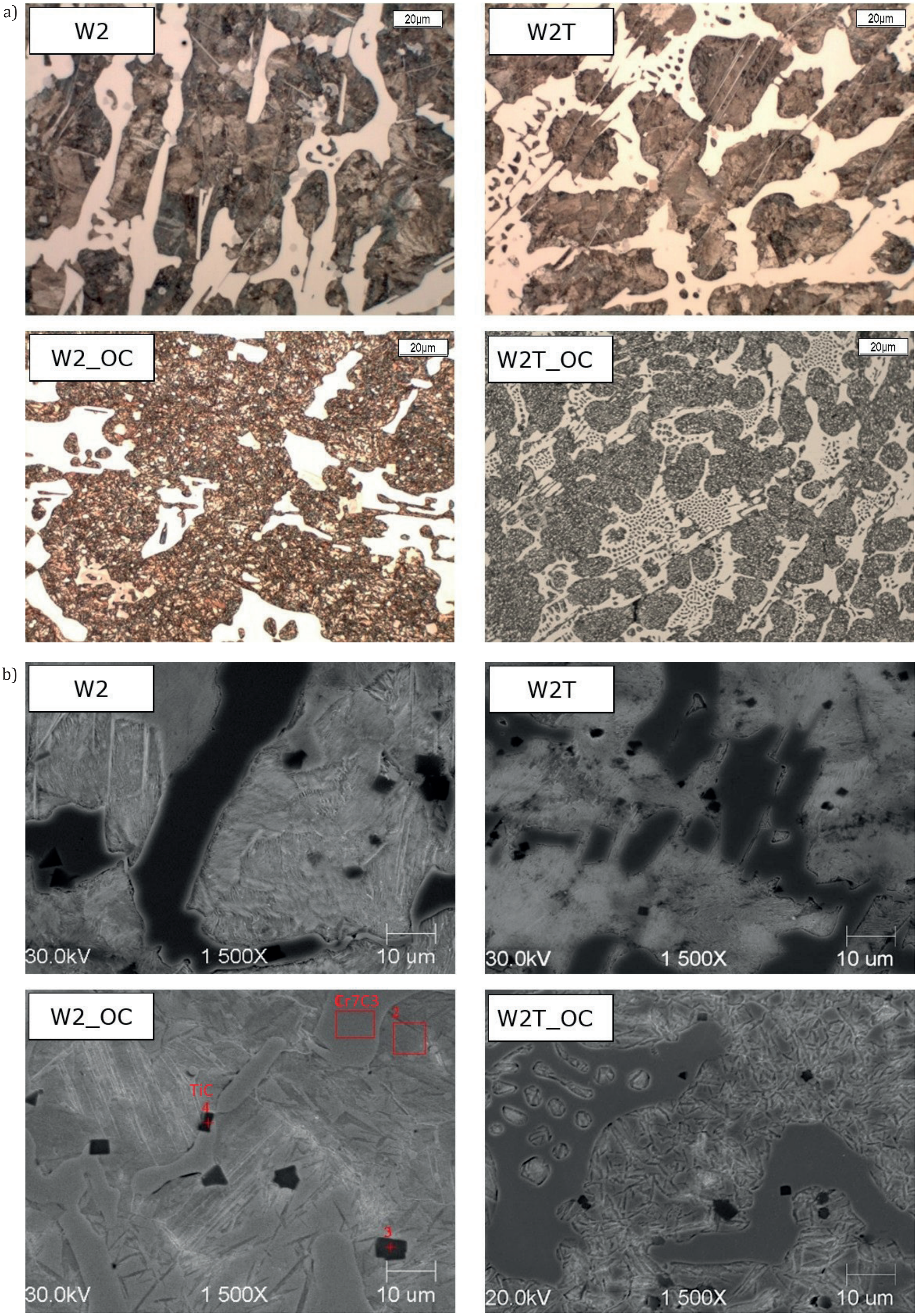

Fig. 5. Microstructures of W2, W2T, W2_OC and W2T_OC samples: a) optical micrographs (Nital etched, 500× magnification); b) scanning electron micrographs (SEM, 1500× magnification)

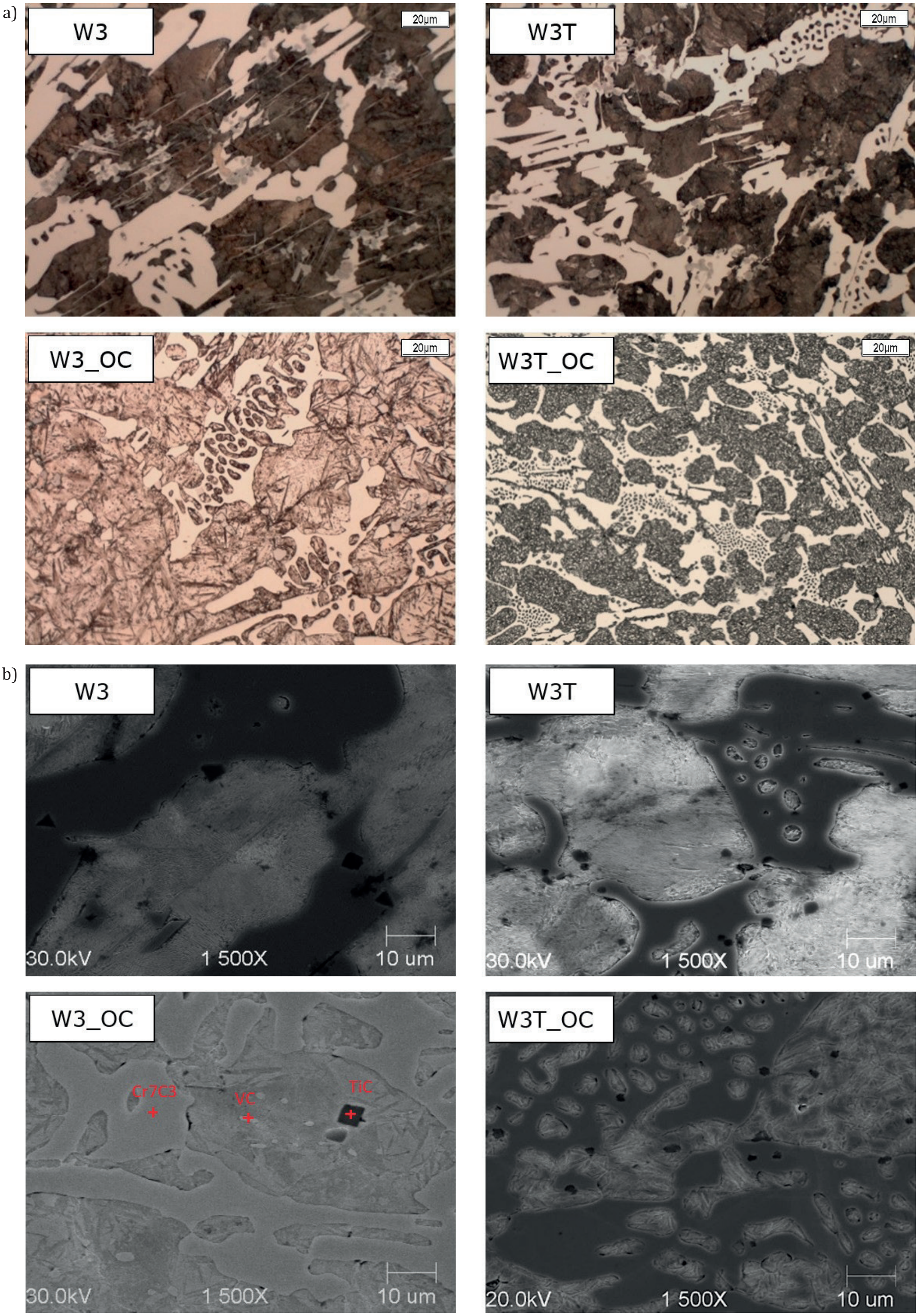

Fig. 6. Microstructures of W3, W3T, W3_OC and W3T_OC samples: a) optical micrographs (Nital etched, 500× magnification); b) scanning electron micrographs (SEM, 1500× magnification)

The application of heat treatment to all samples (W0_OC, W1_OC, W2_OC, W3_OC, W0T_OC, W1T_OC, W2T_OC, W3T_OC) consistently resulted in the refinement of cementite and improved regularity. In the combined samples (W0T_OC, W1T_OC, W2T_OC, W3T_OC), the synergy of tellurium and heat treatment produced the most favorable microstructures: highly fragmented cementite, a homogeneous matrix, and regular, fine inclusions of hard phases. Specifically, the W3T_OC sample, containing Ti, Cr, V, and Te after heat treatment, exhibited an optimal microstructural arrangement – very homogeneous, with a high content of dispersed hard phases within a fine-grained matrix.

In each analyzed sample, observations indicated that tellurium affected the morphology of cementite and carbides. Furthermore, it was evident that heat treatment led to their fragmentation and changes in the matrix structure. The combination of both methods resulted in the greatest fragmentation and ordering of the microstructure. In summary, the addition of tellurium acts as an effective modifier of the cementite and carbide microstructure, while heat treatment enables the further refinement and stabilization of the structure. The combination of both methods, particularly in the WxT_OC variants, significantly improved the microstructure of white cast iron, especially in alloys containing alloying additives (Ti, Cr, V).

The SDAS (Secondary Dendrite Arm Spacing) coefficient was determined at a magnification of 200×. As shown in Figure 7, the SDAS value consistently decreases with each new element introduced to the alloy when tellurium is also present. Without tellurium, the coefficient value does not show any easily identifiable trend. For samples W0 and W1 after heat treatment, no dendrites were observed, hence the SDAS coefficient could not be determined.

4. CONCLUSION

This study thoroughly investigated the influence of tellurium (Te) addition and heat treatment on the microstructure of hypoeutectic white cast iron, both in its as-cast state and with different alloying elements (titanium, chromium, and vanadium). The key findings are summarized below:

- The addition of tellurium significantly impacts the morphology of cementite and carbide phases across all analyzed samples. It consistently promotes their fragmentation and leads to a more uniform distribution throughout the microstructure.
- Heat treatment independently contributes to further fragmentation of these hard phases and induces beneficial changes in the matrix structure.
- The combination of tellurium addition and heat treatment proved to be the most effective strategy, resulting in the highest degree of microstructural homogeneity and fragmentation. This synergy led to highly refined microstructures with finely dispersed hard phases within a uniform matrix.
- For the baseline sample (W0), the combined effect of tellurium addition and heat treatment (W0T_OC) yielded the greatest microstructural homogeneity and stability. This was attributed to the inhibition of austenite-to-martensite transformation and enhanced carbide stabilization.
- A crucial observation was that tellurium stabilizes the formed carbides. In samples without tellurium, carbides showed signs of degradation during heat treatment, whereas in tellurium-containing samples, their structure remained intact, highlighting tellurium's protective role.

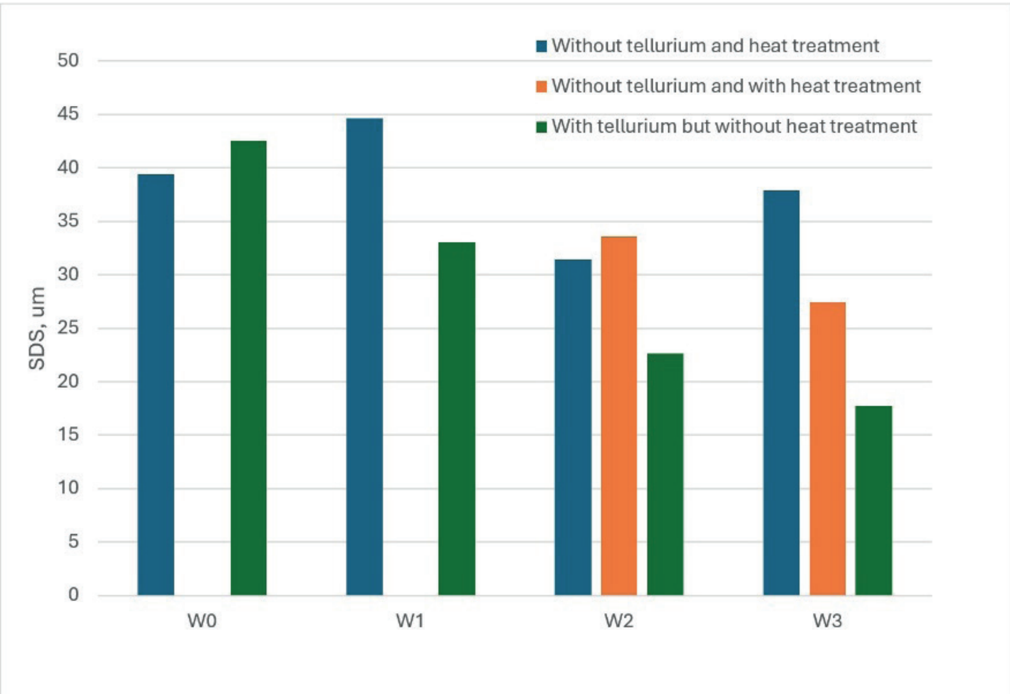

Fig. 7. Graph showing the results of determining the SDAS parameter for samples W0, W1, W2, W3, W0T, W1T, W2T, W3T, W0_OC, W1_OC, W2_OC, W3_OC

- Analysis of the Secondary Dendrite Arm Spacing (SDAS) parameter revealed that the presence of tellurium, particularly in combination with other alloying elements, leads to a significant reduction in the distance between dendrite arms. This suggests that tellurium intensifies the crystallization process, promoting a finer and more homogeneous casting structure.

In conclusion, tellurium acts as an effective modifier for the microstructure of cementite and carbides in hypoeutectic white cast iron. When combined with heat treatment, this approach offers a powerful method to achieve highly refined and stable microstructures, particularly beneficial in alloys containing titanium, chromium, and vanadium. These findings underscore the potential of tellurium as a critical alloying element for tailoring the properties of white cast iron for demanding applications.

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