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Effect of Titanium on the Microstructure and Mechanical Properties of High-Carbon Martensitic Stainless Steel 8Cr13MoV

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Academic Editor: Soran Biroscu

Received: 20 May 2016; Accepted: 17 August 2016; Published: 22 August 2016

Abstract: The effect of titanium on the carbides and mechanical properties of martensitic stainless steel 8Cr13MoV was studied. The results showed that TiCs not only acted as nucleation sites for δ -Fe and eutectic carbides, leading to the refinement of the microstructure, but also inhibited the formation of eutectic carbides M_7C_3 . The addition of titanium in steel also promoted the transformation of M_7C_3 -type to $M_{23}C_6$ -type carbides, and consequently more carbides could be dissolved into the matrix during hot processing as demonstrated by the determination of extracted carbides from the steel matrix. Meanwhile, titanium suppressed the precipitation of secondary carbides during annealing. The appropriate amount of titanium addition decreased the size and fraction of primary carbides in the as-cast ingot, and improved the mechanical properties of the annealed steel.

Keywords: carbide; mechanical property; high-carbon martensitic stainless steel; titanium

1. Introduction

High-carbon martensitic stainless steels have high hardness, high strength, and good corrosion and wear resistance. They have been widely used to produce knives and scissors, valves, structural components [1–4]. The high-carbon martensitic stainless steel 8Cr13MoV is currently used to produce high-grade knives and scissors [4].

Carbon atoms can combine with alloying elements to form carbides, which can improve the strength and wear resistance of the steel. For martensitic stainless steel, carbides precipitate in the matrix through heat treatment in the final process, which can achieve secondary hardening [4–6]. However, high carbon content can also result in some undesired problems, especially for the HMSS. Because of the segregation of the alloying elements, many large eutectic carbides precipitate in the cooling process [7]. These carbides can hardly be removed in the following hot working and heat treatment [8,9]. In the working process of steel, large carbides can induce a stress concentration [8], causing the generation of cracks in steel [10,11]. Edges crazing is one of the most common failure modes during the cold rolling of high-carbon martensitic stainless steels used for high-grade knives and scissors. Eutectic carbides should be responsible for the edges crazing, which also occurs in tool steel and die steel production [12–14]. Therefore, before cold rolling, high ductility and low hardness of steel are desired. These mechanical properties of steel could be improved by optimizing the microstructure and carbides in the steel. In the practical production process, the segregation is inevitable so measures are taken such as decreasing or refining the eutectic carbides, increasing nucleation or inhibiting the growth of eutectic carbides. However, methods such as accelerating the cooling rate [15,16], adopting low superheat [17], adding an alloy element [18–21] or rare earth for modification treatment [22–25] bring a very limited improvement to the mechanical properties of

steel. The addition of alloying elements in high-carbon tool steels is one of the countermeasures in controlling carbides in these steels. However, the effect of alloying elements on carbides in high-carbon martensitic stainless steels has not been studied yet.

Titanium is a strong carbide-forming element, and its ability to combine with carbon is higher than that of chromium [26]. Formation of TiC could partially substitute M_7C_3 in high-carbon high-Cr tool steel, consequently improving the crack resistance of the steel [14]. In this study, the effect of titanium on the carbides and mechanical properties of martensitic stainless steel 8Cr13MoV was studied. The transformation of microstructure and carbides in the steel after electroslag remelting (ESR), forging and spheroidizing annealing were analyzed. The effect of titanium on the microstructure and mechanical properties of high-carbon martensitic steel 8Cr13MoV was revealed.

2. Experimental

2.1. Experimental Materials and Experimental Process

The 8Cr13MoV steel was melted in a vacuum induction furnace. Different amounts of ferro-titanium were added into liquid steel to adjust composition. The liquid steel was cast in a mold, and then forged into electrode with a diameter of 100 mm. The electrode was electroslag remelted to produce as-cast ingot of 160 mm in diameter. The electric current was 2400 A and the voltage was 40 V in the ESR process. The remelting process was conducted in the argon atmosphere. The chemical composition of samples after ESR was confirmed by inductively coupled plasma optical emission spectrometer, which is shown in Table 1. The experiment process also included forging and spheroidizing annealing. The as-cast ESR ingots were forged after held at 1200 °C for 120 min. The forging finish temperature was no less than 800 °C. For spheroidizing annealing, the specimens that were taken from the forged steel were heat treated in an electric resistance furnace, consisting of two holding process and a cooling process. The thermal history in heat treatment is shown in Figure 1.

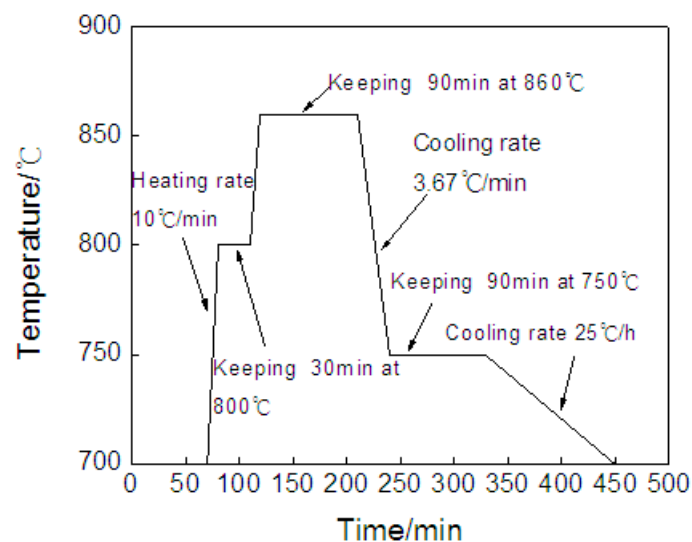


Figure 1. The flow chart of spheroidizing annealing.

Table 1. Chemical composition of 8Cr13MoV steel (mass %).

Sample No.	C	Cr	Mo	Mn	Si	V	Ni	P	S	Ti	Fe
No.1	0.72	13.6	0.43	0.5	0.32	0.14	0.16	0.03	0.004	0.043	Bal.
No.2	0.71	13.44	0.41	0.44	0.33	0.16	0.16	0.031	0.004	0.771	Bal.
No.3	0.73	14.05	0.42	0.42	0.35	0.16	0.16	0.029	0.003	1.22	Bal.

2.2. Microstructure and Carbides

Firstly, ESR ingot was forged into 100 mm × 100 mm × 30 mm steel plate. Secondly, the steel plate was spheroidizing annealed. A steel sample of 12 mm × 12 mm × 5 mm was taken from the edge of ESR ingot, forged steel plate and the spheroidizing annealed steel plate. Finally, the metallographic samples were analyzed by SEM (FEI MLA250, FEI, Hillsboro, OR, USA) after grinding, polishing and etching with FeCl₃ hydrochloric acid alcohol (FeCl₃ 5 g, 38% HCl 25 mL, C₂H₅OH 25 mL). Meanwhile, the samples of the ESR ingot were corroded by the potassium permanganate solution (KMnO₄ 20 g, 0.5 mol/L NaOH 300 mL, H₂O 200 mL), this corrodent can only corrode carbides and it was of no effect on the matrix. The carbides were observed using OM (Leica DM4M Leica, Wetzlar, Germany) and the number and size of carbides were analyzed by Image Analysis Software-Image Pro Plus (IPP).

2.3. Carbides Collection Using Electrolytic Extraction Technique

The samples taken from ESR ingot and annealed steel plate were machined to Ø15 mm × 80 mm round bar. The carbides were extracted from steel matrix in organic solution (methanol, tetramethylammonium chloride, glycerin, diethanol amine) by electrolysis. Part of the carbides were analyzed by XRD (Rigaku D_{max}-RB, Rigaku, Tokyo, Japan) to confirm the type, part of carbides were observed by SEM for the morphology.

2.4. Mechanical Properties

The ESR ingot and spheroidizing annealed steel plates were sampled and machined to Ø8 mm × 80 mm tensile samples based on the Chinese national standard GBT228-2002. The mechanical properties were tested by universal material testing machine (Tinius Olsen H50K, Tinius Olsen, Shanghai, China).

3. Results

3.1. Influence of Titanium on Microstructure

3.1.1. Influence of Titanium on Microstructure of As-Cast ESR Ingot

The SEM images of the ESR ingot microstructure are shown in Figure 2a–c. The grain sizes of samples No. 1 and No. 2 were similar, while the grain size of No. 3 was smaller. Five SEM-BES images were selected from each sample, and the grain size and volume of martensite were calculated using the Count/Size module of IPP. The grain size of sample No. 1 and No. 2 was similar, and the average grain diameter of sample No. 1 is $369.11 \pm 46.33 \mu\text{m}$, while the grain size of sample No. 3 was much smaller with the average diameter of $233.05 \pm 25.74 \mu\text{m}$. The amount of martensite was larger and the acicular structure of martensite was much finer. Results showed that the volume fraction of martensite in sample No. 1 is $32.61\% \pm 3.22\%$, while that in samples No. 2 and No. 3 was doubled. Carbides in sample No. 1 were distributed on the grain boundaries, which were typical eutectic carbides with a large size.

These carbides presented two kinds of morphology in sample No. 2, granular carbides with small size and some irregular carbides, as shown in Figure 2e. According to EDS analysis, the complex carbides were confirmed to be primary carbides of TiC as a nucleus of eutectic carbides M₇C₃. The EDS results for Figure 2d–g are shown in Table 2. Carbides in sample No. 3 have three kinds of morphologies, which included single granular and irregular flake as shown in Figure 2f, and rod-like with an interior tiny laminar structure as shown in Figure 2g. The eutectic carbides were separated.

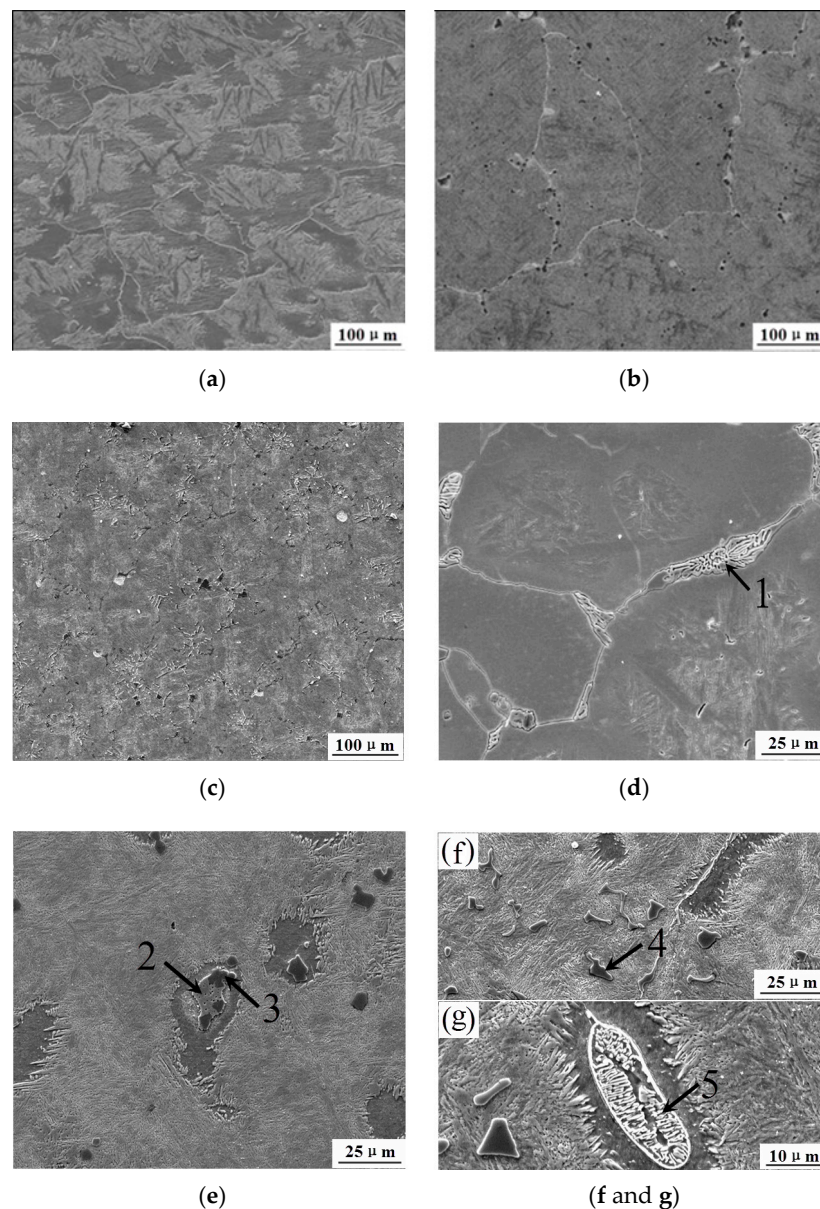


Figure 2. SEM images of as-cast ESR ingot microstructure: (a) and (d) sample No. 1; (b) and (e) sample No. 2; (c) and (f) and (g) sample No. 3.

Table 2. The EDS results for carbides (mass %).

Point	Element				
	C	Cr	Fe	Ti	Mo
1	13.22	51.89	31.25	—	1.45
2	13.81	53.38	26.94	1.05	2.48
3	23.86	4.43	8.89	51.76	7.79
4	20.28	2.91	12.2	61.47	3.14
5	8.68	42.53	47.90	—	1.40

3.1.2. Influence of Titanium on Forged Microstructure and Annealed Organization

The SEM images of the forged ESR ingot microstructure were shown in Figure 3a–c. The eutectic carbides in sample No. 1 were broken. Meanwhile, the small secondary carbides in sample No. 1

precipitated around the eutectic carbides. No small secondary carbides precipitated around the broken eutectic carbides as shown in sample No. 2 and No. 3. It was found that secondary carbides precipitated along the grain boundaries in these three samples. These secondary carbides were much less after titanium was added to the steel. The precipitated carbides in sample No. 3 along the grain boundaries were granule-shaped. The martensite structure of sample No. 2 was the finest, followed by that in sample No. 3.

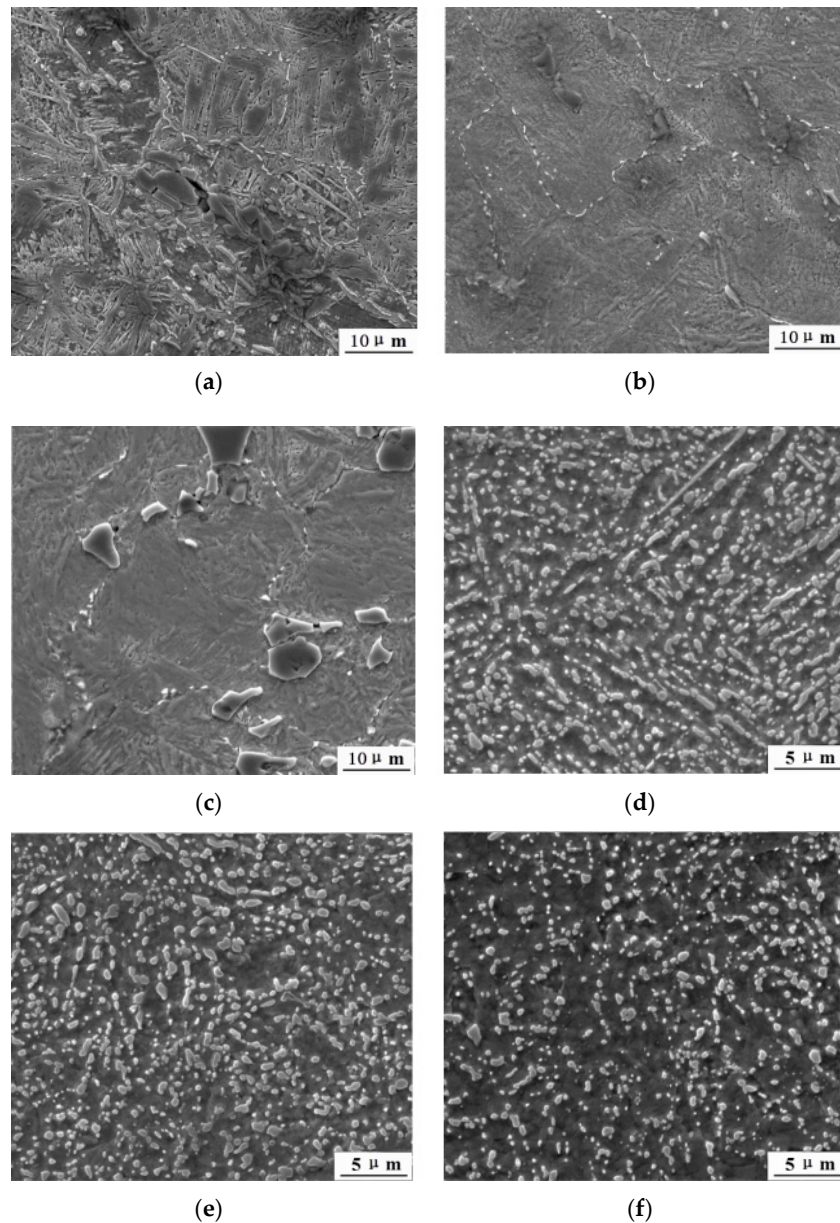


Figure 3. SEM images of specimens before and after spheroidizing annealing: (a–c) samples No. 1, No. 2, No. 3 before spheroidizing annealing; (d–f) samples No. 1, No. 2, No. 3 after spheroidizing annealing.

The SEM images of the spheroidizing annealed microstructure were shown in Figure 3d–f. The amount of carbides decreased from sample No. 1 to No. 3, which was 1.27 ± 0.02 particles per μm^2 , 1.06 ± 0.05 particles per μm^2 and 0.93 ± 0.04 particles per μm^2 , respectively. The average diameter of carbides in samples No. 1, No. 2 and No. 3 is $0.62 \pm 0.03 \mu\text{m}$, $0.52 \pm 0.05 \mu\text{m}$ and $0.44 \pm 0.03 \mu\text{m}$, in turn. The martensite structure was different before annealing so that the most carbides of sample No. 1 were chains and had certain directivity. During annealing, the carbides

would precipitate along the acicular martensite and become a long strip shape [27]. The precipitated carbides have certain directivity after being annealed if separated incompletely during annealing. In summary, the addition of titanium could inhibit the precipitation of the secondary carbides during heat treatment, and this effect increases with the increasing titanium content.

3.2. Influence of Titanium on Carbides

3.2.1. Carbides Amount

The number of carbides was analyzed by the Count/Size module in IPP. Six images for each sample were analyzed, and the results are shown in Figures 4 and 5. According to the statistical results, the volume fraction of carbides decreased first and then increased with the increasing titanium content. The number of carbides in sample No. 1 is the smallest among these three samples. The volume fraction of carbides in sample No. 2 was the smallest among the three samples while the total amount of carbides was 1.7 times larger than that in sample No. 1. Obviously, the volume fraction of carbides in sample No. 2 was the smallest and the carbides distributed diffusely, which is favorable for improving the mechanical properties of steel.

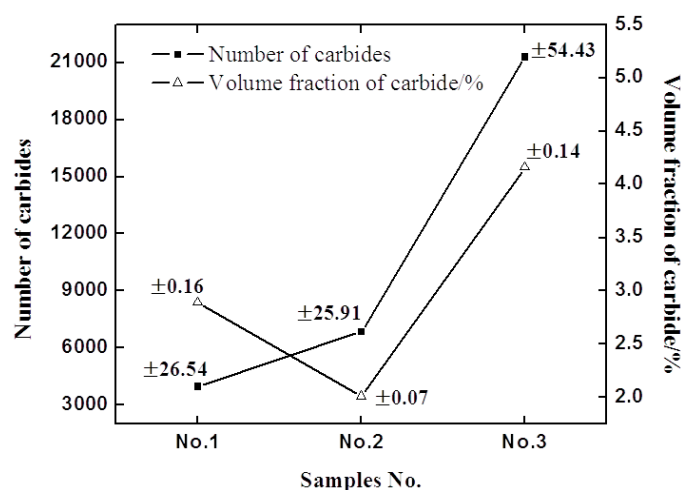


Figure 4. Statistical result of carbides in three samples with different titanium content: values above each point were the standard deviation for each statistic.

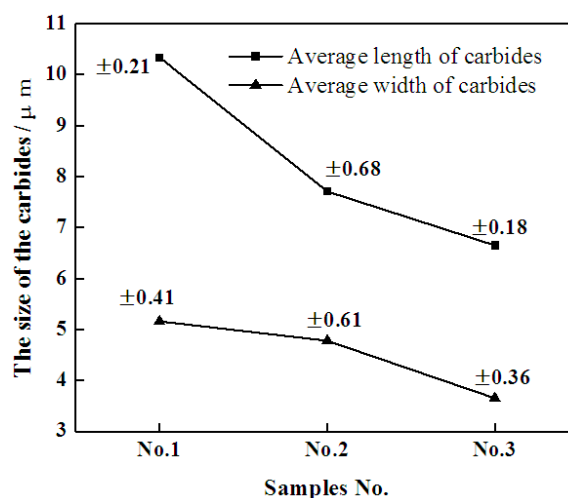


Figure 5. The size of carbides in cast-ingot: values above each point were the standard deviation for each statistic.

3.2.2. The Type of Carbides

Carbides extracted from the steel matrix were analyzed by XRD and the results are shown in Figure 6. Carbides in sample No. 1 were confirmed to be M_7C_3 . The type of carbides changed after the addition of titanium because titanium combined carbon and nitrogen to form TiC and Ti(C, N). Meanwhile, M_7C_3 changed to $M_{23}C_6$ after the addition of titanium. This result indicated that titanium could enhance the complete transition from M_7C_3 to $M_{23}C_6$.

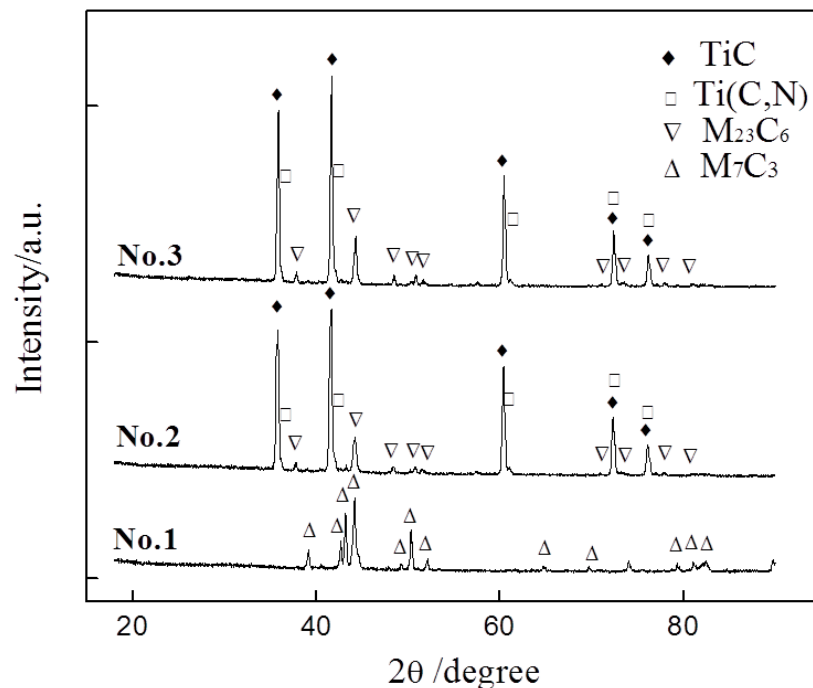


Figure 6. XRD results for three samples with different titanium content: (a) sample No. 3; (b) sample No. 2; (c) sample No. 1.

3.2.3. The Morphology of Carbides

The SEM images of carbides extracted from steel are shown in Figure 7. In sample No. 1, the size of the carbides was large, and the maximum size was over 50 μm . The carbides were typical eutectic carbides and their morphology was a skeleton shape made of a cluster of long-strip carbide, as shown in Figure 7a,d.

In sample No. 2, the size of the carbides was relatively small. Most of the carbides were the complex structure of TiC combined with $M_{23}C_6$. Others were pure TiC, as shown in Figure 7b. The size of the complex carbides was large, and their morphology was similar with that of eutectic carbides, but different from that in sample No. 1, as shown in Figure 7e. It was deduced from the morphology that the large carbides $M_{23}C_6$ were transformed from eutectic carbides M_7C_3 rather than precipitated directly from austenite.

In sample No. 3, the morphology of most carbides was small, irregular flake TiC and Ti(C, N), as shown in Figure 7c. Only a small amount of carbides $M_{23}C_6$ were regular shapes as shown in Figure 7e, which corresponded to the rod-like carbides shown in Figure 2g. The small carbides $M_{23}C_6$ in sample No. 3 were different from those in sample No. 2. These carbides were transformed from M_7C_3 precipitated from austenite. There were no eutectic carbides among the extracted carbides, which indicated that the addition of titanium inhibited the formation of eutectic carbides.

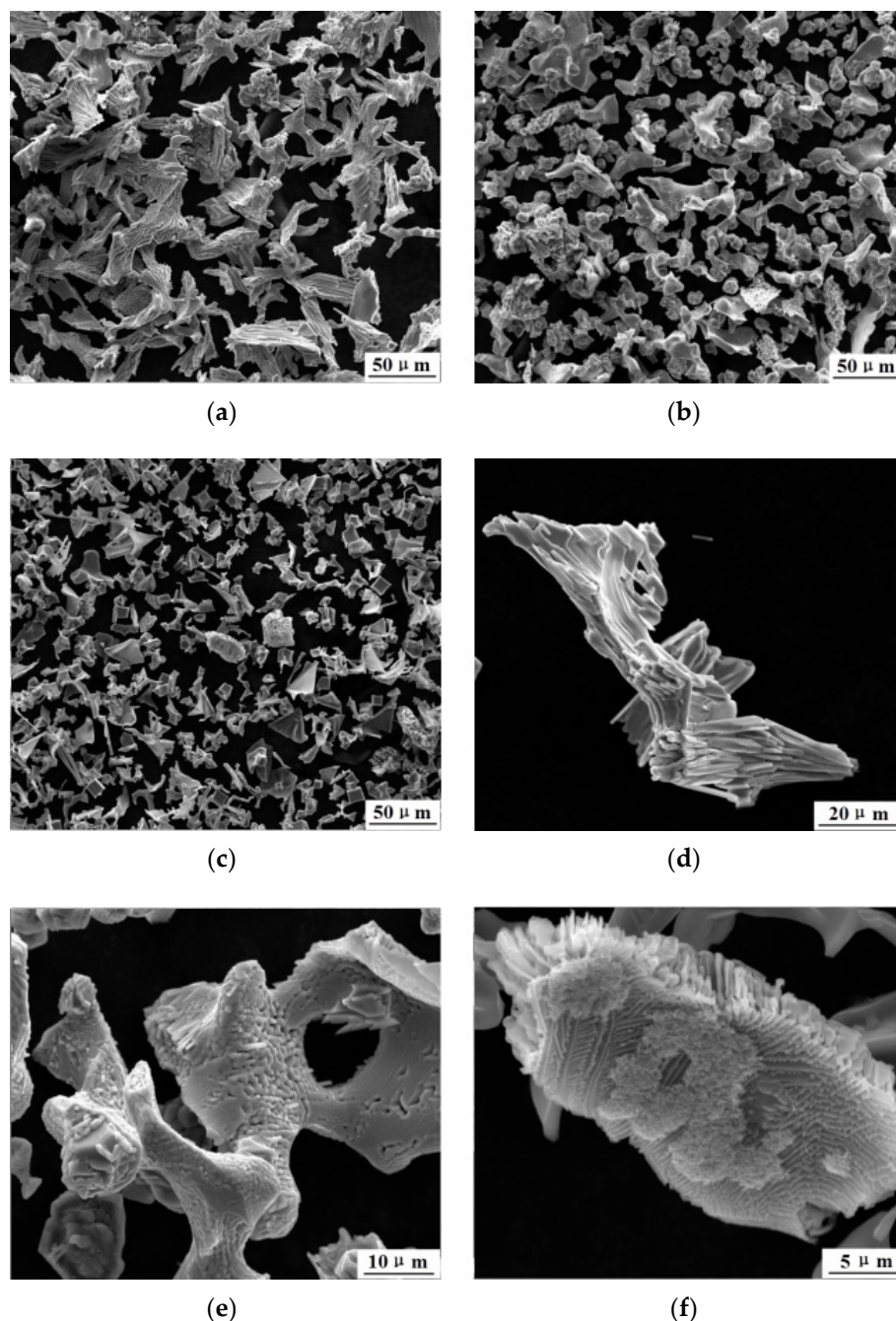


Figure 7. SEM images of carbides power: (a) and (d) sample No. 1; (b) and (e) sample No. 2; (c) and (f) sample No. 3.

3.2.4. The Composition of Carbides

In sample No. 1, there existed a little titanium. It was found by EDS, as shown in Figure 8a, that there was an enrichment of titanium, vanadium and nitrogen in the area where (Ti, V)N precipitated. Thus, (Ti, V)N has a high melting point and acts as the core of the eutectic carbides after precipitating from liquid steel. It was proved that titanium was prior to combine with nitrogen when the content of titanium was low. The chromium content of carbides $M_{23}C_6$ in samples No. 2 and No. 3 was less than that of sample No. 1 as shown in Table 3. In sample No. 2, it was clear that nitrogen, vanadium, molybdenum and titanium are enriched in the same area, confirming that molybdenum had the

tendency to dissolve into TiC. The EDS result for the compound containing titanium in Figure 8 is shown in Table 4.

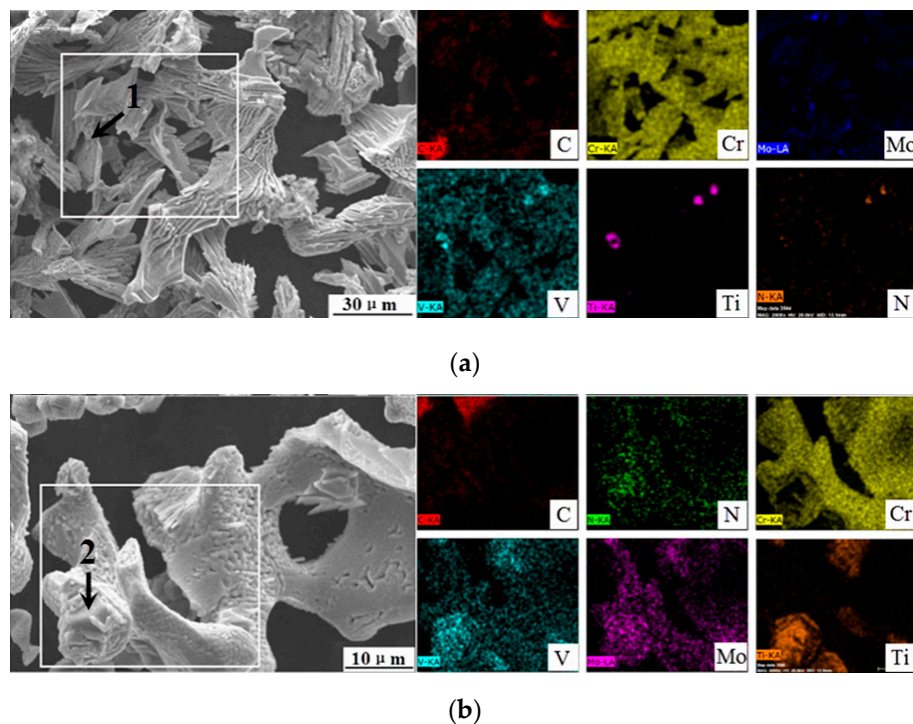


Figure 8. EDS element mappings of carbides: (a) sample No. 1; (b) sample No. 2.

Table 3. EDS-analyzed results of carbides containing chromium (mass %).

Sample No.	Element					
	C	Cr	Fe	Mo	V	Ti
No. 1	14.59	53.90	26.25	2.33	2.93	0.0
No. 2	13.10	37.53	40.19	2.79	1.69	2.6
No. 3	11.08	43.98	28.07	2.67	1.41	2.8

Table 4. EDS-analyzed results of compound containing titanium (mass %).

Point	Element						
	C	N	Cr	Fe	Ti	Mo	V
1	15.20	15.57	1.32	1.28	64.44	0.98	1.21
2	26.66	—	2.76	1.21	62.76	5.46	1.15

3.2.5. Morphology of Carbides after Forging and Heat Treatment

The electrolysis method was employed to extract the carbides in samples after spheroidizing annealing, and the result of the SEM analysis is shown in Figure 9. A large amount of fine carbides precipitated after being spheroidized. As shown in Figure 9b, there are no large complex carbides in sample No. 2. This indicated that most of carbides $M_{23}C_6$ surrounding TiC dissolved, and a small number of carbides $M_{23}C_6$ were spheroidized as shown in Figure 9e. The eutectic carbides in sample No. 1 were spheroidized to some degree, but the size was still large, as shown in Figure 9d. The size of carbides in sample No. 2 was similar to that in sample No. 3.

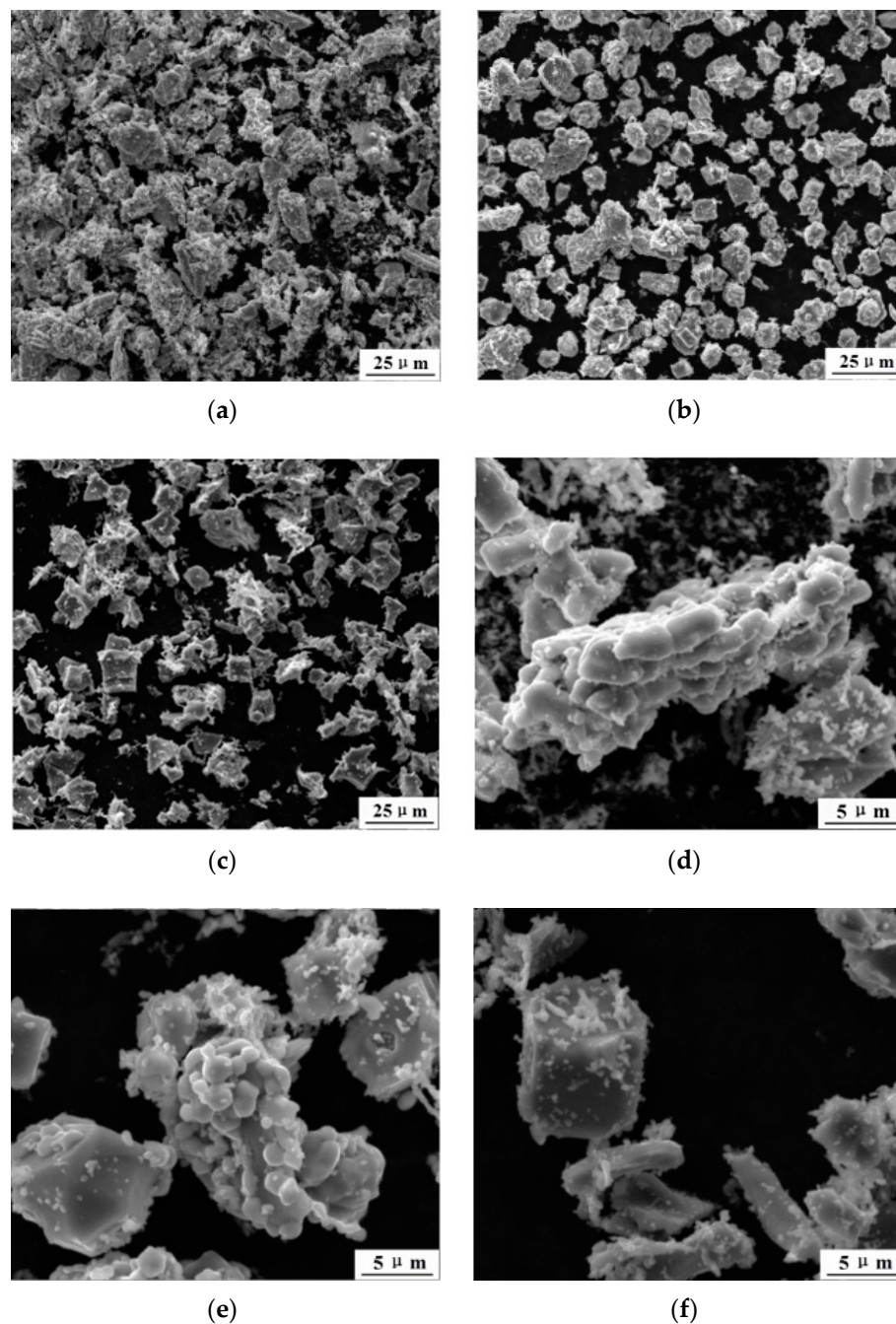


Figure 9. SEM images of carbides power after spheroidizing annealing: (a) and (d) No. 1; (b) and (e) No. 2; (c) and (f) No. 3.

3.3. Influence of Titanium on Mechanical Property of Steel before and after Heat Treatment

The hardness and tensile strength of the ESR ingot were measured, and the results are shown in Table 5. The hardness and tensile strength of cast alloy increased greatly when titanium was added in steel. The tensile strength of sample No. 3 was 1315.66 MPa. Titanium could refine the grain, increase the hardness and tensile strength, and combine with carbon to form TiC to inhibit the formation of carbides containing chromium, resulting in the dissolution of chromium in the matrix and increasing the hardenability and the quantity of martensite.

Table 5. Mechanical properties of steel samples before and after heat treatment

Sample No.	Hardness		Tensile Strength/MPa		Elongation after Fracture/%	
	Before/HRC	After /HRB	Before	After	Before	After
No. 1	52.9 ± 0.21	95.2 ± 0.14	635.95	739.53	1	17.85
No. 2	56.7 ± 0.15	93.6 ± 0.29	974.49	714.01	1	20.95
No. 3	57.6 ± 0.31	94.1 ± 0.52	1315.66	694.39	1	20.41

The morphology of carbides in samples No. 2 and No. 3 was apparently different. In sample No. 2, complex carbides formed by TiC and $M_{23}C_6$ were large in size, and most single TiCs were granular. In sample No. 3, most TiCs had a laminated structure with a multi-direction which was beneficial to matrix strengthening in comparison with the granular structure.

The tensile fracture after spheroidizing annealing is shown in Figure 10. There were large carbides at the fracture surface of sample No. 1, which are labeled in Figure 10a. There are no large carbides in the fracture of sample No. 2. TiC particles distributed on the fracture surface of samples No. 2 and No. 3 uniformly. The number of TiC in sample No. 3 was larger than that in sample No. 2. Due to the existence of a large amount of TiC, the tensile strength and elongation after fracture decreased. It suggested that a moderate addition of titanium was in favor of improving the property of steel, while the excessive addition of titanium would increase the volume fraction of TiC and deteriorate the mechanical property of steel.

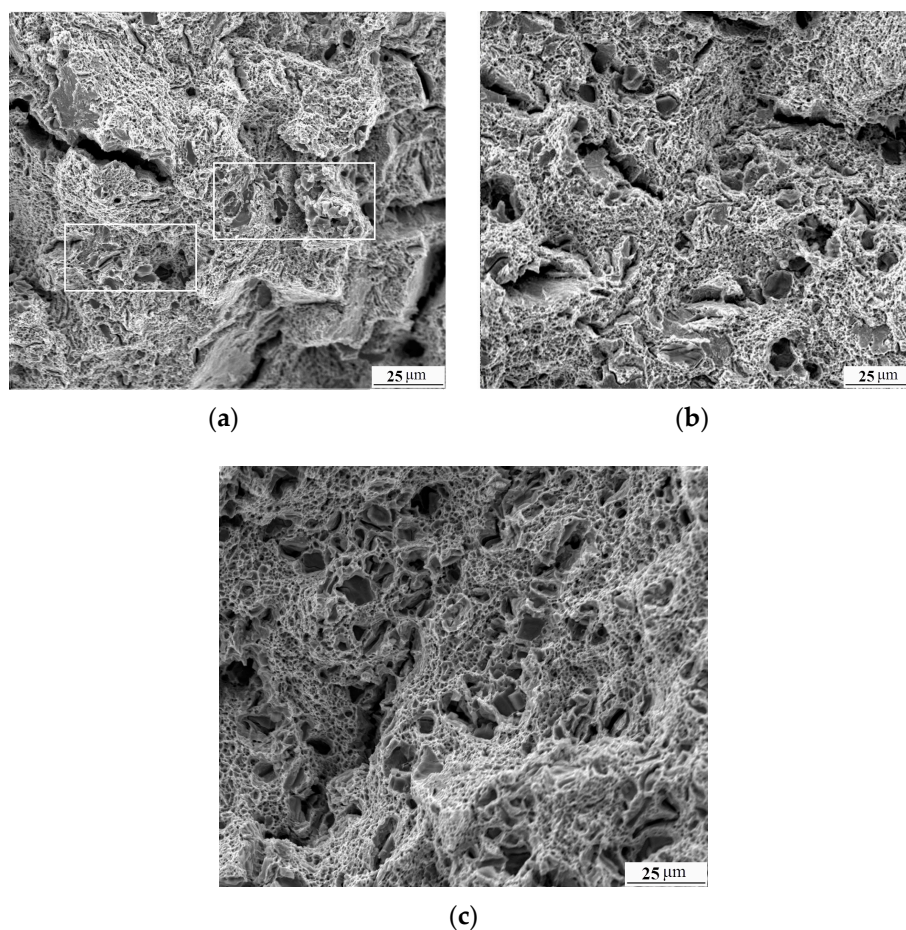


Figure 10. SEM images of tensile fracture after spheroidizing annealing: (a) sample No. 1; (b) sample No. 2; (c) sample No. 3.

4. Discussions

4.1. Effect of Ti on the Solidification Microstructure

The effect of titanium on the equilibrium phase during the cooling process of 8Cr13MoV was calculated by Thermo-Calc. The calculated results are shown in Figure 11. The precipitation temperature of TiC increased with increasing the titanium content. When the titanium content reached up to 0.5%, TiC precipitated at 1600 °C from liquid steel. It is the precipitation of TiC from liquid steel that provides an essential condition for the heterogeneous nucleation of other precipitates and the grain refinement of steel.

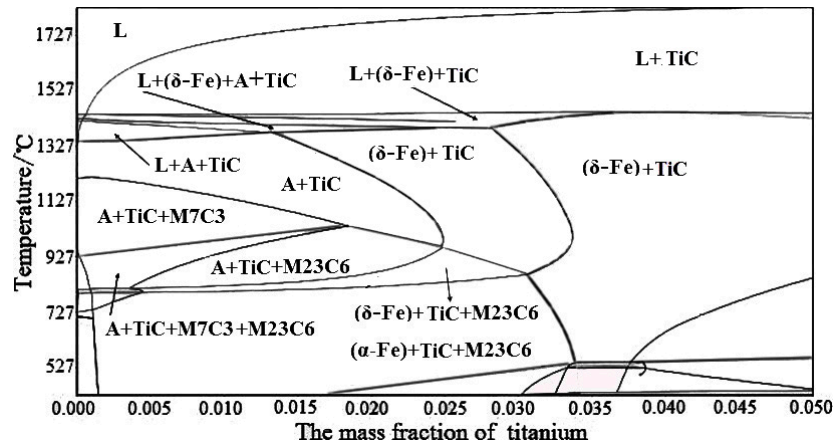


Figure 11. Equilibrium phase formation of 8Cr13MoV steel calculated using Thermo-Calc: L-Liquid, (δ-Fe)-(δ-Ferrite), A-Austenite, (α-Fe)-(α-Ferrite).

According to the Bramfitt theory [28], when the disregistry between the lattice parameters of the substrate and the nucleating phase is less than 6%, the nucleating agent is very effective for heterogeneous nucleation. If the disregistry equals to 6%–12%, the nucleating agent is moderately effective. If the disregistry is greater than 12%, the potency is poor. According to the calculation by Bramfitt [28], the disregistry between TiC and δ-Fe is 5.9%, and the promoting effect of TiC for the nucleation sites of liquid iron was proved by his experiment.

As shown in Figure 11, the microstructure of 8Cr13MoV steel was refined with the addition of titanium in the steel. This is attributed to the precipitation of TiCs, which served as heterogeneous nucleation sites for liquid steel. The present result is consistent with the findings that the addition of titanium in high-carbon high-chromium steel or cast iron could refine the eutectic carbides M_7C_3 and the grain size of the steel as reported by other researchers [26,27,29].

In the 8Cr13MoV steel with the Ti addition, eutectic carbides M_7C_3 were found to nucleate on TiC as shown in Figures 7e and 8b. The disregistry concept proposed by Bramfitt [28] was employed to predict the nucleation between TiC and M_7C_3 , as expressed in the following equation:

$$\delta_n^s = \sum_{i=1}^3 \frac{\left| \frac{d_{[uvw]_s^i} \cos \theta - d_{[uvw]_n^i}}{d_{[uvw]_n^i}} \right|}{3} \times 100 \quad (1)$$

(hkl)_s = a low-index plane of the substrate;

[uvw]_s = a low-index direction in (hkl)_s;

(hkl)_n = a low-index plane in the nucleated solid;

[uvw]_n = a low-index direction in (hkl)_n;

d[uvw]_n = the interatomic spacing along [uvw]_n;

$d[uvw]_s$ = the interatomic spacing along $[uvw]_s$;
 θ = the angle between the $[uvw]_s$ and $[uvw]_n$.

The crystal structure of TiC and M_7C_3 was face-centered cubic and hexagonal, respectively. The lattice plane (0001) of M_7C_3 is superimposed on the lattice plane (001) of TiC. The lattice parameters for the corresponding crystal faces are 4.31 Å and 4.45 Å. The corresponding angles of crystal orientation are 15° and 30°, respectively. According to above equation, the discrepancy between TiC and M_7C_3 was calculated to be 4.7%, which proved that TiC could act as nucleation site for M_7C_3 . Therefore, it was concluded that TiC played an important role in the refinement of M_7C_3 .

4.2. Eutectic Carbides M_7C_3 and Secondary Carbides $M_{23}C_6$

All carbides in as-cast 8Cr13MoV steel containing 0.043% titanium are M_7C_3 -type. The chromium-containing carbides in samples No. 2 and No. 3 are $M_{23}C_6$ -type, instead of M_7C_3 -type. As shown in Figures 2e and 8b, a large amount of carbides in sample No. 2 are complex carbides consisting of TiC and $M_{23}C_6$. Carbides $M_{23}C_6$ formed around TiC. It can be seen, from the morphology and size, that carbides $M_{23}C_6$ exhibit the characteristics of eutectic carbides.

The Scheil module in Thermo-Calc software was employed to calculate the non-equilibrium solidification of liquid steel, as shown in Figure 12. As shown in Figure 12, M_7C_3 started precipitating from liquid steel when the mole fraction of the solid phase reached 90%. Prior to the precipitation of M_7C_3 , the solid phase consists of austenite and TiC. This indicated that carbides $M_{23}C_6$ arose from the transformation of eutectic carbides M_7C_3 .

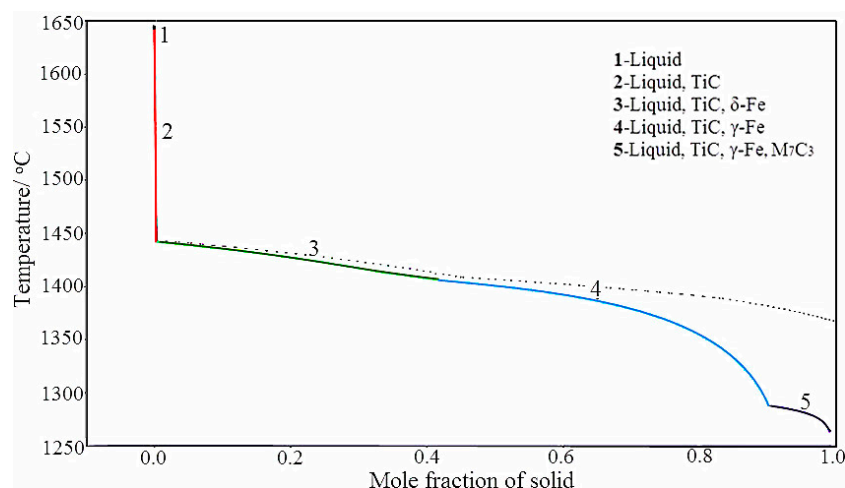


Figure 12. Mole fraction of solid phase as a function of temperature during non-equilibrium solidification.

During solidification under the equilibrium condition, carbides M_7C_3 precipitated from austenite, and then transformed to $M_{23}C_6$. As shown in Figure 11, the precipitation temperature range of M_7C_3 shrinks with the increasing titanium content, which indicated that titanium suppressed the precipitation of M_7C_3 . Meanwhile, the transformation temperature of M_7C_3 to $M_{23}C_6$ increased with the increase of the titanium content, which indicated that titanium can promote the transformation process of M_7C_3 to $M_{23}C_6$. Although M_7C_3 still precipitated from liquid steel containing 0.71% Ti (see Figure 8), they would transform to $M_{23}C_6$ eventually because of the effect of titanium during solidification and the cooling process of ESR casting.

Compared with carbides M_7C_3 , carbides $M_{23}C_6$ are easier to dissolve in the steel matrix during hot working and the heat treatment process. Hence, the transformation of M_7C_3 to $M_{23}C_6$ was expected. The results shown in Figures 9 and 10 indicated that large carbides $M_{23}C_6$ in sample No. 2 did dissolve in the steel matrix. The volume fraction of carbides in the as-cast No. 2 sample was the lowest. After hot processing, a large amount of large $M_{23}C_6$ dissolved, which is favorable for the subsequent

process and can improve the mechanical property of steel. This has been confirmed by the mechanical property measurements, which show the highest elongation after fracture and the lowest hardness of sample No. 2 after forging and spheroidizing annealing.

5. Conclusions

1. TiCs as the first phase formed from liquid steel could act as nucleation sites to refine the grain and the eutectic carbides M_7C_3 . The amount and size of eutectic carbides M_7C_3 decreased gradually with the increasing titanium content in 8Cr13MoV steel. The fraction of carbides in the as-cast ESR ingot decreased first and then increased with the increase of the titanium addition.

2. Titanium could promote the transformation from carbides M_7C_3 to carbides $M_{23}C_6$ during solidification and the cooling process. This is favorable for the dissolution of large carbides during hot processing, as demonstrated by the determination of extracted carbides from the steel matrix.

3. The 0.771% titanium addition decreased the fraction and the size of the primary carbides, and improved the distribution of these carbides in 8Cr13MoV steel, contributing to the increase of the mechanical properties of annealed steel in terms of hardness and elongation after fracture. However, excessive titanium addition led to the significant increase in the volume fraction of TiC. In addition, the titanium addition could inhibit the precipitation of the secondary carbides in the spheroidizing annealing process, and this effect increases with the increasing titanium content. These two factors above are adverse for the mechanical properties of annealed steel.

Acknowledgments: This work was financially supported by the National Natural Science Foundation of China (Grant No. 51574025).

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “W.-T.Y. and J.L. conceived and designed the experiments; W.-T.Y. and Q.-T.Z. performed the experiments; W.-T.Y. and C.-B.S. analyzed the data; J.L. contributed reagents/materials/analysis tools; W.-T.Y. wrote the paper.” Authorship must be limited to those who have contributed substantially to the work reported.

Conflicts of Interest: The authors declare no conflict of interest.

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