

Effect of Annealing Parameters on Recrystallization and Grain Growth in AISI 347H Stainless Steel Containing 0.55 wt.% Nb

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تأثير مؤشرات التلدين على نمو الحبيبات وإعادة التبلور في سبيكة الصلب 347 مع 0.55% نيوبيوم

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Abstract:

The effects of annealing temperature and holding time on recrystallization and grain growth in Nb-stabilized AISI 347H austenitic stainless steel containing 0.55 wt.% Nb were investigated under isothermal conditions. Specimens were annealed at 1000°C and 1200°C for 5, 10, and 30 min. Recrystallization at 1000°C was characterized by scanning electron microscopy–electron backscatter diffraction (SEM–EBSD), while grain size was quantified by optical metallography using ImageJ software. At 1000°C, the material was approximately 65% recrystallized after 5 min and approximately 95% recrystallized after 10 min; after 30 min, the microstructure was fully recrystallized and exhibited substantial grain growth. At 1200°C, rapid transition from precipitate-controlled boundary pinning to rapid grain growth where fully recrystallized structure was obtained within the first 5 min, followed by pronounced grain coarsening with increasing holding time. The measured mean grain sizes at 1200°C were 57, 85, and 235 μm after 5, 10, and 30 min, respectively. The accelerated grain growth at 1200°C is consistent with increased grain-boundary mobility and reduced effectiveness of Nb-containing precipitates as boundary-pinning agents. A power-law grain-growth model was applied to the 1200°C data, giving a growth exponent of 1.597 and predicting a grain size of approximately 162 μm after 20 min. The results demonstrate the strong influence of annealing temperature and time on recrystallization and subsequent grain-boundary migration in AISI 347H.

Keywords: AISI 347H, annealing, EBSD, grain growth, recrystallization.

الملخص

تمت دراسة تأثيرات درجة حرارة التخمير وزمن التسخين على إعادة التبلور والنمو الحبيبي في الفولاذ المقاوم للصدأ الأوستنيتي المصنف AISI 347H والمثبت بالنيوبيوم بنسبة وزنية تبلغ 0.55%، وذلك تحت ظروف حرارية متساوية (درجة حرارة ثابتة). خُمِرت العينات عند درجتَي حرارة 1000 درجة مئوية و1200 درجة مئوية لأزمنة بلغت 5 و10 و30 دقيقة. جرى توصيف إعادة التبلور عند 1000 درجة مئوية بواسطة المجهر الإلكتروني الماسح وحيود ارتداد الإلكترونات (SEM-EBSD)، بينما حُدد الحجم الحبيبي كمياً بواسطة الفحص الميتالورجي الضوئي باستخدام برنامج

ImageJ.

عند درجة حرارة 1000 درجة مئوية، كانت المادة معاد تبلورها بنسبة 65% تقريباً بعد مرور 5 دقائق، وبنسبة 95% تقريباً بعد 10 دقائق؛ وبعد 30 دقيقة، تمت إعادة تبلور البنية المجهرية بالكامل وظهر نمو حبيبي ملحوظ. وعند درجة حرارة 1200 درجة مئوية، حدث انتقال سريع من مرحلة تثبيت الحدود البلورية المحكوم بالرواسب إلى مرحلة النمو الحبيبي السريع، حيث تم الحصول على بنية معاد تبلورها بالكامل خلال الدقائق الخمس الأولى، تبع ذلك تضخم واضح في الحبيبات مع زيادة زمن الاستبقاء. بلغت أبعاد متوسط الحجم الحبيبي المقاس عند 1200 درجة مئوية 57 و85 و235 ميكرومتر بعد 5 و10 و30 دقيقة على التوالي. ويتوافق هذا النمو الحبيبي المتسارع عند 1200 درجة مئوية مع زيادة حركة الحدود الحبيبية وانخفاض فاعلية الرواسب المحتوية على النيوبيوم كعوامل لتثبيت الحدود البلورية.

تم تطبيق نموذج قانون القوة للنمو الحبيبي على البيانات المستخرجة عند 1200 درجة مئوية، مما أعطى أساً للنمو يبلغ 1.597 وتوقع حسابه حجماً حبيبياً يقارب 162 ميكرومتر بعد مرور 20 دقيقة. وتظهر هذه النتائج التأثير القوي لدرجة حرارة وزمن التخمير على إعادة التبلور وهجرة الحدود الحبيبية اللاحقة في فولاذ **AISI 347H**.

الكلمات المفتاحية: إعادة تبلور، تخمير، حركة حدود الحبيبات، كربونيتريد النيوبيوم، نمو الحبيبات.

Introduction

Austenitic stainless steel because of its corrosion resistance to water environments and high temperatures is one of the most common types of steel used in industries, especially in oil and gas industry, refinery and electric power stations [1]. AISI 347H is a niobium-stabilized austenitic stainless steel widely used in high-temperature environments. Its microstructural evolution during heat treatment is governed by the competition between thermally activated grain-boundary migration and the pinning effect of fine Nb-containing precipitates [2],[3]. The present study examines the influence of annealing temperature and holding time on recrystallization and grain growth in AISI 347H containing approximately 0.55 wt.% Nb, with particular emphasis on the transition from precipitate-controlled grain-boundary stabilization to rapid grain coarsening at elevated temperature.

Grain size is an important microstructural parameter governing the mechanical and service properties of austenitic stainless steels [3]. During annealing, stored deformation energy provides the driving force for recrystallization, after which grain boundaries migrate to reduce the total grain-boundary energy [4]. Accordingly, increasing the annealing temperature is generally expected to increase grain-boundary mobility and accelerate grain coarsening.

In Nb-stabilized AISI 347H, grain-boundary motion is also strongly influenced by Nb(C,N) precipitates. Fine precipitates distributed within the austenitic matrix interact with migrating boundaries and exert a retarding force commonly described by Zener pinning [7]. The effectiveness of this mechanism depends on particle size, morphology, distribution, and volume fraction. A high population of fine precipitates can therefore reduce effective grain-boundary mobility and suppress or delay grain growth, even at elevated annealing temperatures [8]. The final grain structure is therefore determined by the competition between the thermodynamic driving force for grain-boundary migration and the retarding force associated with Nb(C,N) precipitates [9]. At lower annealing temperatures, relatively stable fine precipitates can restrict boundary motion and limit grain growth. With increasing temperature, precipitate coarsening and/or dissolution can reduce their pinning effectiveness, allowing grain boundaries to become progressively more mobile [10]. This transition is particularly important when heat treating hot-rolled material, where significant stored deformation energy is available to drive recrystallization.

Despite the technological importance of AISI 347H, the interaction among grain-boundary mobility, Nb(C,N) precipitation, and high-temperature grain growth remains important for optimizing heat-treatment conditions. Identifying the transition from precipitate-controlled boundary pinning to rapid grain growth is essential for controlling the final microstructure and, consequently, the properties of the alloy. The transition from precipitate-controlled boundary pinning (Zener pinning) to rapid or abnormal grain growth in hot-rolled steels occurs when the thermal-driving force for grain boundary migration exceeds the retarding pinning pressure exerted by microalloy precipitates [11]. Accordingly, this work investigates the effects of annealing temperature and holding time on recrystallization and grain-growth behavior in Nb-stabilized AISI 347H containing approximately 0.55 wt.% Nb. Particular attention is given to the evolution of the recrystallized fraction at 1000°C, the subsequent development of grain size, and the pronounced grain growth observed at 1200°C. The experimental grain-size data at 1200°C are further analyzed using a classical power-law grain-growth model to quantify the kinetics of microstructural evolution.

Experimental part

The investigated material was Nb-stabilized AISI 347H stainless steel with a nominal chemical composition of 0.06%C–0.4%Si–1.2%Mn–18.2%Cr–11%Ni–0.55%Nb–0.015%N (wt.%).

Specimens were sectioned from hot-rolled plate material into dimensions of 20 × 15 × 2.6 mm. The specimens were annealed in a fluidized-bed furnace (FH24H) and subsequently air cooled.

To evaluate the effects of annealing temperature and holding time on the hot-rolled austenitic microstructure, specimens were annealed at 1000°C and 1200°C for 5, 10, and 30 min. A thermocouple was attached to selected specimens to verify that the target temperature was maintained. All specimens were air cooled after annealing.

For optical metallography, the longitudinal surfaces were cleaned, ground, and polished using conventional metallographic procedures. Microstructural observations and micrographs were obtained using an OLYMPUS BX51M optical microscope. Grain size was measured using ImageJ software, with annealing twin boundaries excluded from the grain-size measurement. The austenite grain size was determined using the linear-intercept method, with approximately 300–400 intercepts counted for each image.

Recrystallization was characterized using a Leo 1530 scanning electron microscope equipped with a Gemini column and a Nordlys II EBSD detector. EBSD analysis was used to estimate the recrystallized fraction and characterize grain structure. A magnification of 500 $\times$ and a step size of 0.67 μm were used to obtain sufficient spatial resolution while capturing a representative number of grains.

Results and Discussion

Annealing at 1000°C

Annealing at 1000°C produced a progressive transition from a heterogeneous, partially recrystallized structure to a fully recrystallized and coarsened microstructure. After 5 min, relatively large elongated grains remained near the sheet mid-plane, while finer equiaxed grains were observed away from the mid-plane, indicating a heterogeneous recrystallization response.

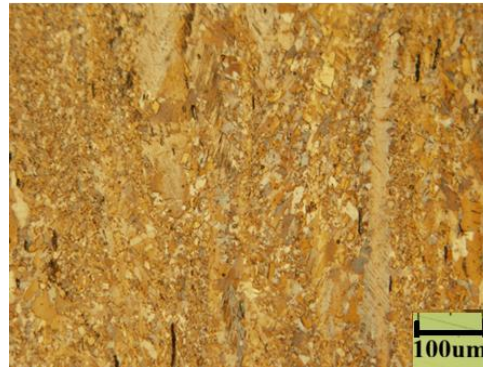


Figure 1: Partially recrystallized microstructure (approximately 65%) of AISI 347H - 0.55 wt.% Nb after annealing at 1000°C for 5 min.

The EBSD inverse pole figure (IPF) map for the specimen annealed at 1000°C for 5 min confirms the heterogeneous, partially recrystallized microstructure (Figure 2).

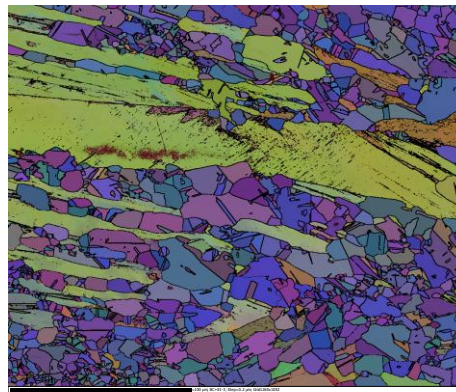


Figure 2: EBSD IPF map of AISI 347H - 0.55 wt.% Nb after annealing at 1000°C for 5 min, showing an estimated recrystallized fraction of approximately 65%.

The EBSD map indicates an estimated recrystallized fraction of approximately 65%, consistent with a short 5 min anneal at 1000°C following hot rolling. Large, elongated, pancake-shaped deformed grains remain in the central and right-hand regions and retain features associated with the prior rolling deformation. In contrast, fine equiaxed recrystallized grains are concentrated around the deformed regions, particularly near the upper and lower margins. Their distribution is consistent with nucleation at high-energy regions such as prior grain boundaries and deformation bands. The fine recrystallized grains observed after the 1000°C/5 min treatment are consistent with the expected influence of the 0.55 wt.% Nb addition and Nb-containing precipitates. These precipitates can exert a Zener pinning force on migrating grain boundaries, limiting boundary motion and thereby restricting rapid grain growth during the short annealing period. Increasing the holding time at 1000°C to 10 min produced a more equiaxed austenitic microstructure, as shown in Figure 3.

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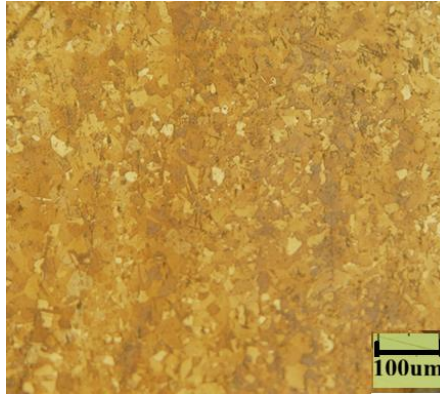


Figure 3: Optical microstructure of AISI 347H - 0.55 wt.% Nb after annealing at 1000°C for 10 min.

The optical micrograph shows growth of the equiaxed grains despite the continued influence of Nb-containing precipitates. The additional 5 min of annealing allowed the recrystallized grains to broaden and develop more regular polyhedral morphologies, with measured grain dimensions of approximately 28–32 μm. The same specimen was examined by SEM–EBSD, revealing a predominantly recrystallized austenitic structure, as shown in Figure 4.

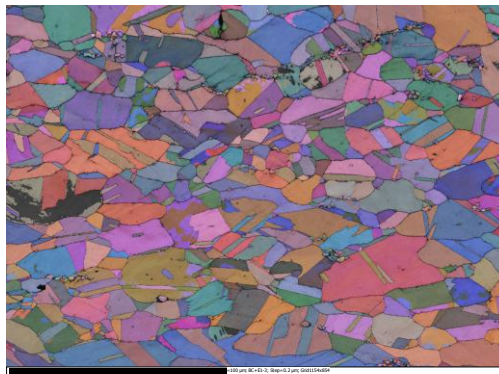


Figure 4: EBSD IPF map of AISI 347H - 0.55 wt.% Nb after annealing at 1000°C for 10 min.

The EBSD map in Figure 4 shows that the deformed regions have been largely consumed. The thick, elongated unrecrystallized structures observed after 5 min are reduced to small, isolated regions, indicating substantial progress of static recrystallization. The recrystallized fraction is estimated at approximately 95%. The indexed grains also show an increased occurrence of straight, parallel boundaries, consistent with the development of annealing twins in the austenitic structure. After 30 min at 1000°C, further grain growth occurred and annealing twins became clearly visible, as shown in Figure 5.



Figure 5: Optical microstructure of AISI 347H - 0.55 wt.% Nb after annealing at 1000°C for 30 min.

The 1000°C/30 min condition produced polygonal, equiaxed austenitic grains with relatively straight and well-defined boundaries. The average grain size was approximately 80–95 μm . The morphology and recrystallization state of the microstructure are further illustrated by the EBSD analysis in Figure 6.



Figure 6: EBSD IPF map of AISI 347H containing 0.55 wt.% Nb after annealing at 1000°C for 30 min.

The EBSD map confirms that the grains are substantially larger than those observed after 5 and 10 min at 1000°C, demonstrating that grain growth has progressed. The grains are equiaxed and polygonal with well-defined boundaries, while numerous annealing twin boundaries are visible. The relatively uniform orientation within the grains indicates that most of the residual deformation has been removed.

3.2 Annealing at 1200°C

The hot-rolled condition contains substantial stored deformation energy, which provides a strong driving force for static recrystallization. At the higher annealing temperature, increased thermal activation promotes rapid recrystallization and subsequent grain-boundary migration. The microstructural response at 1200°C differs markedly from that at 1000°C because atomic diffusion and grain-boundary mobility are substantially higher. These conditions promote rapid formation and growth of strain-free grains. At the same time, the effectiveness of Nb-containing precipitates as grain-boundary pinning agents may decrease through coarsening and/or dissolution, allowing boundaries to migrate more readily and promoting rapid grain growth. The microstructure after annealing at 1200°C for 5 min is fully recrystallized and consists predominantly of equiaxed austenitic grains with a limited number of annealing twins as shown in Figure 7.



Figure 7: Optical microstructure of AISI 347H - 0.55 wt.% Nb after annealing at 1200°C for 5 min.

In Figure 7, a fully recrystallized equiaxed austenitic structure containing a limited number of annealing twins can be observed with an average grain size of approximately 57 μm . Increasing the holding time at 1200°C to 10 min resulted in rapid grain coarsening, as illustrated in Figure 8. The reduced effectiveness of Nb-containing precipitates as boundary-pinning agents is consistent with the increased grain-boundary mobility observed at this temperature.

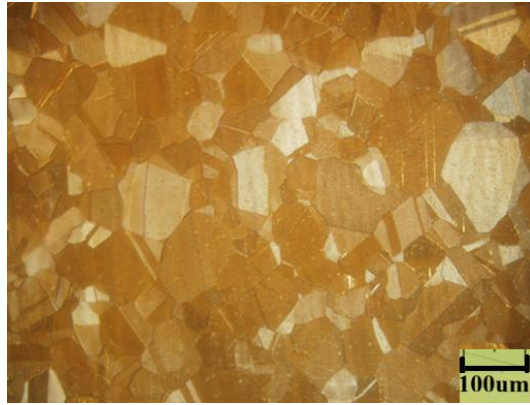


Figure 8: Optical microstructure of AISI 347H - 0.55 wt.% Nb after annealing at 1200°C for 10 min.

The microstructure exhibits pronounced grain growth with increasing holding time, and annealing twins become more apparent. The average grain size after 10 min was approximately 85 μm. After 30 min at 1200°C, extensive grain coarsening produced very large equiaxed austenitic grains with an average grain size of 235 μm and numerous annealing twins as seen in Figure 9.

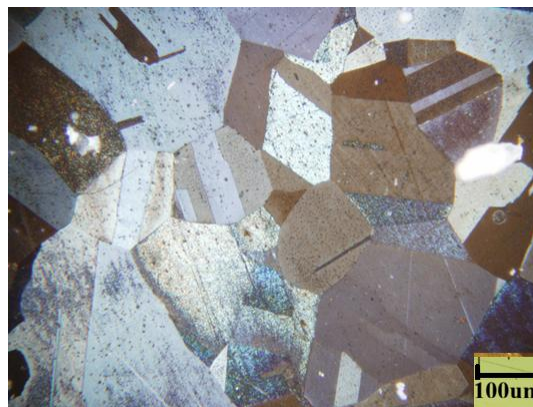


Figure 9: Optical microstructure of AISI 347H - 0.55 wt.% Nb after annealing at 1200°C for 30 min.

The 1200°C/30 min condition contains no obvious distorted, elongated grains characteristic of the hot-rolled state; instead, the microstructure consists of large, strain-free equiaxed grains. Many individual grains approach or exceed 200 μm in diameter. The pronounced coarsening is consistent with a substantial reduction in the effectiveness of precipitate pinning and the resulting increase in grain-boundary mobility. The grains exhibit relatively smooth boundaries and stable triple junctions, indicating a reduction in total grain-boundary energy. A high density of annealing twins is also visible, consistent with the characteristic twinning behavior of FCC austenitic stainless steels. The measured grain sizes for the specimens annealed at 1200°C are summarized in Table 1.

Table (1). Grain size of AISI 347H after annealing at 1200°C.

Grain size (μm)	Annealing time (minutes)
57	5
85	10
235	30

3.3 Grain-growth modelling at 1200°C

The grain-growth kinetics at 1200°C were analysed using a classical power-law relationship as equation 1, with the first experimental point selected as the reference condition.

$$D^2 - D_r^2 = k (t - t_r)^m \quad (1)$$

where D is the average grain size at time t (μm), D_r is the reference grain size, t_r is the reference annealing time, k is the growth-rate coefficient, and m is the time-dependent growth exponent.

Using the first experimental point as the reference gives $t_r = 5$ min and $D_r = 57$ μm. The model can therefore be written in terms of the measured reference condition as in equation 2:

$$D^2 - 57^2 = k (t - 5)^m$$

(2)

Using the 10 min experimental value gives:

$$85^2 - 57^2 = k (10 - 5)^m \text{ or } 3976 = k 5^m$$

Using the 30 min experimental value of 235 μm and combining the two time points gives the growth exponent:

The calculated value of the growth exponent is $m = 1.597$, and the corresponding growth coefficient is:

$$k = 304.15$$

The resulting grain-growth model is therefore:

$$D^2 = 57^2 + 304.15(t - 5)^{1.597} \text{ or}$$

$$D(t) = \sqrt{3249 + 304.15 (t - 5)^{1.597}}$$

where D is expressed in μm and $t \geq 5$ min.

The experimental and model grain sizes are compared in Table 2 and Figure 10. The model provides an interpolation of grain size between the measured conditions and predicts a grain size of approximately 162 μm after 20 min at 1200°C.

Table (2). Experimental and modeled grain sizes at 1200°C.

Time (min)	Exp.	Model
5	57	57
10	85	85
15		123.6
20		162
25		199.1
30	235	235

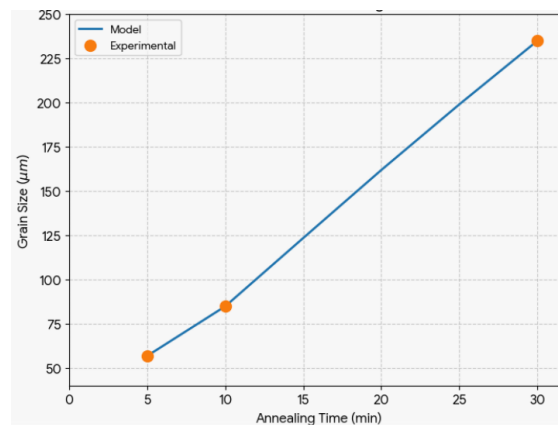


Figure 10: Experimental and modelled grain-growth behaviour at 1200°C.

Figure 10 shows that grain size increases consistently as the annealing time gets longer and reached to approximately **235 μm** . The continuous blue theoretical model passes directly through all three experimental markers, indicating an exceptionally high accuracy and validation of the predictive model. From Figure 10, the grain growth rate between 5 to 10 minutes annealing is:

$$\frac{85 - 57}{10 - 5} = 5.6 \mu\text{m}/\text{min}$$

and also the grain growth rate as time increased to 30 minutes is:

$$\frac{235 - 85}{30 - 10} = 7.5 \mu\text{m}/\text{min}$$

Therefore, the grain growth rate also increased by time increasing at high annealing temperature.

To find out pre-existing grain size (at time zero-Theoretically): back to y-intercept ($t=0$) where theoretical grain size is 20.8 μm , empirical model can be derived directly from three experimental coordinates as:

$d = 7.5t + 20.8$. when annealing time theoretically set to $t=0$, it is:

$$d_0 = 7.5 (0) + 20.8 = 20.8 \mu\text{m}/\text{m}$$

This means that before any isothermal grain growth occurred, the base matrix materials had a pre-existing average grain size approximately 20.8 μm . However, the transition from precipitate-controlled boundary pinning occurred at 1000°C to rapid grain growth observed at 1200°C can easily be identified at short time annealing at higher temperature.

Conclusion:

This work examines how **ANNEALING TEMPERATURE** and **HOLDING TIME** influence the austenitic structure of **0.55 WT.% NB-BEARING AISI 347H**. Both parameters heavily dictate experimental and theoretical **GRAIN GROWTH**, alongside **RECRYSTALLIZATION** mechanisms analysed through **EBSD**, as detailed below:

1. At 1000°C, the microstructure was approximately 65% recrystallized after 5 min and approximately 95% recrystallized after 10 min. After 30 min, the structure was fully recrystallized and exhibited substantial grain growth.
2. At 1200°C, a fully recrystallized structure was obtained within the first 5 min. Subsequent holding produced pronounced grain coarsening, with the measured mean grain size increasing from 57 µm at 5 min to 85 µm at 10 min and 235 µm at 30 min. This behaviour is consistent with increased grain-boundary mobility at the higher temperature and reduced effectiveness of Nb-containing precipitates as boundary-pinning agents.
3. Application of the grain-growth model to the 1200°C data gave a time exponent of $m = 1.597$ and a growth coefficient of $k = 304.15$. The model predicts an average grain size of approximately 162 µm after 20 min at 1200°C.
4. Overall, the results demonstrate that annealing temperature and holding time must be carefully controlled to obtain the desired recrystallized microstructure while limiting excessive grain coarsening. Due to rapid transition from precipitate-controlled boundary pinning to rapid grain growth.

5. Acknowledgment:

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Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

References

- N. Arivazhagan, Su. Singh, S. Prakash, (2011). Investigation on AISI 304 austenitic stainless steel to AISI 4140 low alloy steel dissimilar joints by gas tungsten arc, electron beam and friction welding. *Materials & Design*, 32 (5), 3036–3050.
- M. Opiela et al.(2022). Effect of Grain Size on the Microstructure and Strain Hardening Behavior of Solution Heat-Treated Low-C High-Mn Steel. *MDPI Materials*, 7(13)
- H. W. Luo, H. Dong, L. F. Chen, (2013). Grain growth in Nb-alloyed stainless steel of AISI 347 during heating, *Materials Science Forum*, (753), 345–348.
- Y. Ogino, H. Tanida, M. Kitaura, A. Adachi, (1971). Effect of Niobium Addition on Austenite Grain Size in Steels,” *Tetsu-to-Hagane*, 57(3), 533–546.
- W. Huibin et al., (2015). Effect of Nb addition on the microstructure and mechanical properties of an 1800 MPa ultrahigh strength steel, *Materials Science and Engineering A*, 622 (12), 61–66.
- W. Luo, H. Dong, L. Chen, (2013). Grain growth in Nb-alloyed stainless steel of AISI 347 during heating, *Materials Science Forum*, (753), 345–348.
- K. Ahomkah, C. Witness and W. Edmund, (2017). Austenite Grain Growth Kinetics after Isothermal Deformation in Microalloyed Steels with Varying Nb Concentrations, *ISIJ International*, 58(2), 333–339.
- T. Shaui et al., (2022). Effect of niobium alloying on the austenite grain growth and mechanical properties of ultrahigh-strength stainless steel, *Materials Research Express*, 9(2), Article 02651
- B. Bark and S. DaeKim, (2024). Effect of Nb on Austenite Grain Growth in 10Cr-3Co-2W Martensitic Heat-Resistant Steel,” *Metals and Materials International*, (12), 3311–3319
- A. Chamanfar et al., (2022). Austenite grain growth and hot deformation behaviour in medium carbon steels,” *Journal of Materials Research and Technology*, Vol. 9 (6), 12102–12114.
- D. Wue et al., (2018). Effect of Nb and V on Austenite Grain Growth Behaviour of the Cr-Mo-V Steel for Brake Discs,” *De Gruyter Brill*, 2018

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