UDK 620.186:669.245 ISSN 1580-2949
Original scientific article/Izvirni znanstveni članek MTAEC9, 57(6)655(2023)

EFFECT OF SOLUTION TREATMENT ON THE MICROSTRUCTURE AND MECHANICAL BEHAVIOR OF THE NICKEL-BASED ALLOY N06625

VPLIV RAZTOPNEGA ŽARJENJA NA MIKROSTRUKTURO IN MEHANSKE LASTNOSTI NIKLJEVE ZLITINE VRSTE N06625

Lu Yao[1], Yugui Li[1,2*], Yaohui Song[1], Haosong Sun[1], Yibo Lu[2], Jiayao Wang[2]

[1]School of Materials Science and Engineering, Taiyuan University of Science and Technology, Taiyuan, China
[2]School of Mechanical Engineering, Taiyuan University of Science and Technology, Taiyuan, China

Prejem rokopisa – received: 2023-07-18; sprejem za objavo – accepted for publication: 2023-10-22

doi:10.17222/mit.2023.942

We have studied the effects of different solution temperatures and holding times on the microstructure and room-temperature mechanical properties of the alloy using methods such as electron backscatter diffraction, hardness testing and tensile testing. The results showed that the average grain size increased significantly as the solution temperature increased, and many annealing twins appeared in the grains. The fraction of twin boundaries reached its maximum value at 1080 °C. The hardness, yield strength and tensile strength of the alloy decreased with an increase in the solution temperature, but abnormal yielding occurred at 1160 °C. The elongation after fracture and the area reduction increased with an increase in the solution temperature. The fracture morphology of the alloy was irregular, conical, accompanied by a large number of ductile dimples, and the material exhibited typical ductile fracture. At the same time, as the solution temperature increased, the number of dimples on the fracture surface continued to increase, the depth of the dimples gradually increased, and the distribution became more uniform.

Keywords: solution treatment, annealing twin, hardness, tensile behavior

Avtorji opisujejo študijo vpliva različnih temperatur in časov zadrževanja na temperaturi raztopnega žarjenja na mikrostrukturo in mehanske lastnosti pri sobni temperaturi Ni zlitine vrste N06625. Za karakterizacijo so uporabili vrstični elektronski mikroskop z metodo povratno sipanih elektronov, merilnik mikro trdote in natezni preizkuševalni stroj. Rezultati so pokazali, da povprečna velikost kristalnih zrn močno narašča z naraščajočo temperaturo raztopnega žarjenja in v mikrostrukturi se pojavi tudi mnogo dvojčičnih lamel. Delež dvojčičnih kristalnih mej doseže svoj maksimum pri 1080 °C. Trdota, meja plastičnosti in natezna trdnost izbrane zlitine se zmanjšujejo z naraščajočo temperaturo in časom raztopnega žarjenje. Pri temperaturi 1160 °C pa nastopi pojav nenormalnega plastičnega tečenja. Raztezek in kontrakcija po porušitvi preizkušancev naraščata z naraščajočo temperaturo raztopnega žarjenje. Prelom preizkušancev je nepravilne konične oblike in presek preizkušancev je tipično duktilen (žilav) z velikim številom duktilnih jamic. Istočasno z naraščajočo temperaturo raste tudi število in globina duktilnih jamic na površini preloma in njihova porazdelitev postaja enakomernejša.

Ključne besede: raztopno žarjenje, dvojčki nastali v mikrostrukturi zaradi žarjenja, trdota, natezni preizkus in obnašanje zlitine pod natezno obremenitvijo

1 INTRODUCTION

Nickel-based alloys are widely used in various industrial processes such as chemical and petrochemical processing, marine engineering, oil and gas production and transportation, and nuclear reactors.[1,2] Solution heat treatment is applied to heat-resistant alloys after hot working and before service. Its aim is to completely dissolve the precipitated phase into the matrix after appropriate hot working and a coarse grain size.[3,4] Coarse grains can reduce the grain boundaries, free energy and lattice mismatch ratio of the alloy. In most cases, coarse-grained alloys are more stable than fine-grained alloys.[5] Grain size plays a decisive role in the tensile properties of metals, and the obstacles to the dislocation movement caused by grain boundaries are very critical.[6] For example, Lan and Zhang[7] studied the effects of the annealing time and temperature on the mechanical properties of Fe-22Mn-0.5C TWIP steel. They showed that in order to obtain products with excellent strength and ductility, a specific range of grain sizes should be achieved during an annealing process. Zhang[8] studied the microstructure characteristics and tensile mechanical properties of gradient-grained nickel-based high-temperature alloys at different temperatures (room temperature, 650 °C, 750 °C) and found that microstructural characteristics such as precipitated phases and micro-twins affect the tensile deformation behavior of gradient-grained nickel-based high-temperature alloys.

In addition, nickel-based alloys, as typical polycrystalline materials, have extremely important grain boundary characteristics that have a significant impact on physical and mechanical properties.[9] For example, Yuan et al.[10] studied the effect of annealing on Fe-25Mn-3Cr-3Al-0.3C-0.01 N TWIP steel. They found that an increased annealing temperature led to higher densities of Σ3 grain boundaries and mechanical twins. Studies have shown that an introduction of high-density

*Corresponding author's e-mail:
liyugui@tyust.edu.cn (Yugui Li)

twin boundaries (TBs) in materials such as Cu,[11] Ti,[12] stainless steel[13] and high-entropy alloys has proved to simultaneously improve strength and ductility. Although ductility can reach a high level, the yield strength of solution-strengthened nickel-based alloys is moderate due to the limited solution strengthening effect of solute atoms. It was reported that in polycrystalline nickel-based high-temperature alloys, coherent TBs are the most vulnerable part for strain localization and subsequent crack initiation under mechanical loads in different environments.[14] Due to a low stacking-fault energy, polycrystalline nickel-based high-temperature alloys are prone to produce a high proportion of annealing twins after thermomechanical processing, and more than 50 % of high-angle grain boundaries (HAGBs) in many high-temperature alloys are twins.[15]

Therefore, in this research we study the microstructure characteristics, microhardness and room temperature tensile properties of nickel-based alloys at different solution temperatures, discussing the effects of microstructure on the mechanical properties of an alloy, and providing a theoretical basis for practical production.

2 EXPERIMENTAL PART

The material used in this experiment was forged N06625 alloy, whose main chemical composition (*w*/%) is shown in **Table 1**. Specimens were placed in a box-type resistance furnace where solution treatment at (1050, 1080, 1130, 1160 and 1190) °C for 50 min, and at 1130 °C for (10, 30, 50, and 70) min was carried out to study the effect of holding time on the mechanical properties, and then water-quenched to room temperature. The grain size was calculated using the linear intercept method, and the changes between different grain boundaries were analyzed using electron backscatter diffraction (EBSD). The microhardness of the alloy after solution treatment was tested with a microhardness tester. The test area had to avoid the scratch area. Each sample was tested eight times, and the maximum and minimum values were removed. The average of the remaining six values was taken as the actual microhardness of the sample. Quasi-static tensile tests were carried out on a universal testing machine. Detailed dimensions of the tensile specimens are shown in **Figure 1**. The tensile rate was 1 mm/min. An online computer recorded the load-displacement data. After the test, the tensile properties of the specimens such as yield strength, ultimate tensile strength, elongation of specimens and reduction of area were measured. In addition, scanning electron microscopy (SEM) was used to observe the fracture surfaces of the alloy tensile specimens.

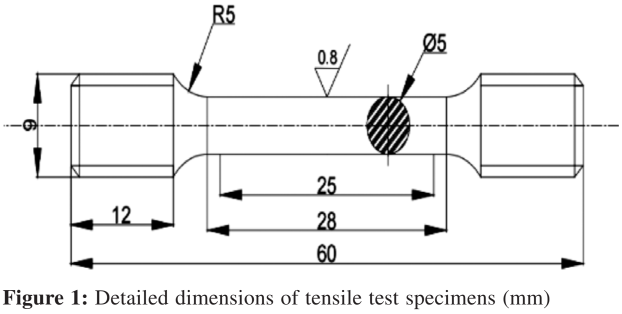

Figure 1: Detailed dimensions of tensile test specimens (mm)

Table 1: Chemical composition of the N06625 nickel-based alloy (wt.%)

Ni	Cr	Mo	Cu	C	Nb
Bal.	20.4	8.2	6.1	0.06	3.1

3 RESULTS AND DISCUSSION

3.1 Effect of solution treatment on the microstructure

The microstructures of the alloy after solution treatment at different temperatures for 50 min are shown in **Figure 2**. It can be seen that the grain size increases with the increase of solution treatment temperature. In addition, a large number of annealing twins are found in the alloy, which is because for nickel-based alloys with face-centered cubic structure, due to their particular structural composition, the stacking-fault energy of the alloy is relatively low,[16] and a large number of annealing twins are formed during the heat-treatment process. From the microstructure diagram, it can be seen that the twins show different morphologies. Some twins appear at the grain-boundary junctions, some penetrate through the whole grain, and some terminate at the grain interior. The average grain size and twin-boundaries fraction after solution treatment are shown in **Table 2**.

Table 2: Average grain size and twin-boundary fractions of alloy N06625

solution treatment	average grain size (mm)	twin boundary fractions (Σ3, Σ9, Σ27, %)
1050 °C-50 min	18.49	47.59
1080 °C-50 min	27.98	75.76
1130 °C-50 min	48.19	50.28
1160 °C-50 min	108.79	40.74
1190 °C-50 min	198.63	39.53

The data in **Table 2** shows that at the same holding time, as the solution temperature increases, the average grain size increases continuously. When the solution temperature increases from 1080 °C to 1130 °C, the average grain size increases by about two times, indicating that when the solution temperature is higher than 1080 °C, the driving force for grain growth is greater than the resistance. It is well known that grain growth is characterized by grain-boundary migration. From a thermodynamic point of view, a higher solution temperature increases the grain-boundary migration rate and the driving force for grain growth, causing some grains to push their boundaries towards other surrounding grains and then achieve mutual engulfment between the grains to form

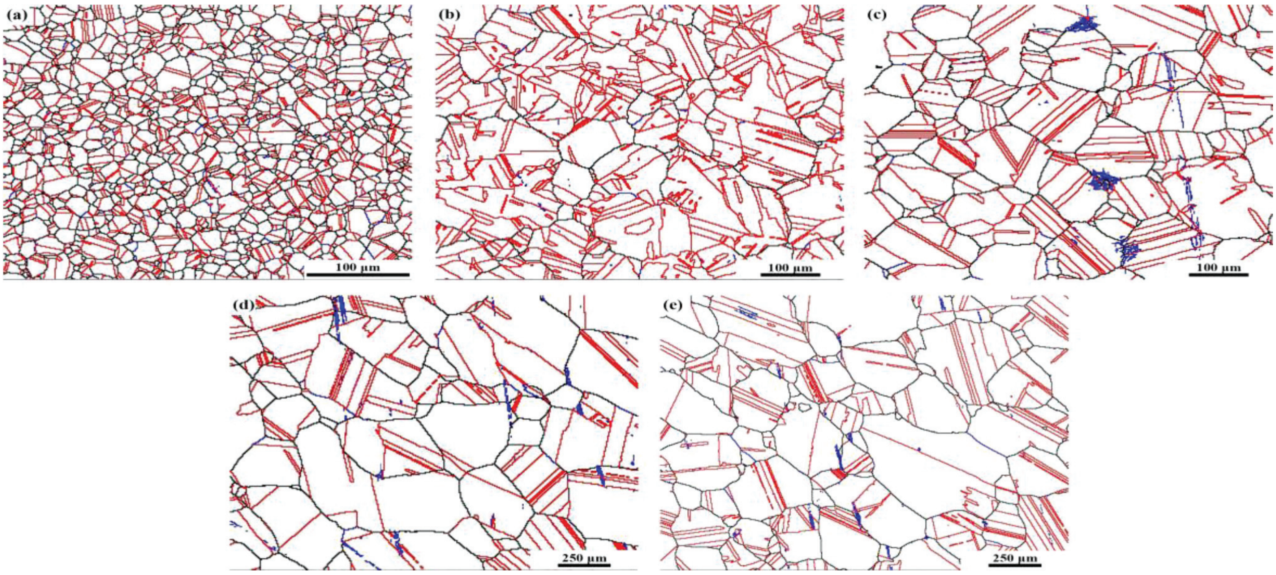

Figure 2: Microstructures of alloy specimens after solution treatment: (a) 1050 °C, (b) 1080 °C, (c) 1130 °C, (d) 1160 °C, (e) 1190 °C, black line: HAGBs, blue line: LAGBs, red line: TBs

large grains. At the same holding time, grains annealed at higher temperatures will grow to larger sizes due to the higher grain-boundary migration rate. For low-angle grain boundaries (LAGBs), grain-boundary migration is mainly induced by dislocation slip and climb. However, as the dislocation spacing decreases for HAGBs, HAGBs cannot migrate like LAGBs. Usually, atomic jumps between adjacent boundaries are the primary migration mechanism of HAGBs.[9]

The annealing twins in the grains should be formed during the grain growth process. When the grains grow through grain-boundary migration, the stacking order of atomic layers at the grain-boundary corners encounters unexpected obstacles. Annealed twins moving towards HAGBs. As the HAGBs grow during movement, if an incorrect layering occurs and a misaligned layer is formed, a complete through-grain annealing twin is formed. At the same time, through analysis, it can be found that the fraction of TBs is controlled at around 40 % as the solution temperature increases, and the maximum proportion of TBs is at 1080 °C. This is because at this temperature, the grain size is small and the grain-boundary area is large, and the obstacles to dislocation movement also increase accordingly. Many dislocation accumulations lead to stress concentration and provide the necessary driving force for twins[17]. As the solution temperature increases, the fraction of annealing twins decreases. This is because growing grains collide with each other as annealing progresses, causing the grain-boundary migration rate to decrease. Therefore, the further development of annealing twins is complex.[9] **Figure 2** shows that at 1130 °C, LAGBs are more clustered, with a small amount distributed within the grains. This is because there is an orientation difference between two adjacent grains. The larger the orientation difference, the higher the interface energy and the higher the grain-boundary energy. The higher the grain-boundary energy, the more unstable the grain boundary and the greater its migration rate, resulting in a significant increase in the average grain size at this temperature.

3.2 Microhardness

Figure 3 shows the average hardness values of the alloy after holding for 50 min at different solution temperatures. The results show that as the solution temperature increases, the hardness of the alloy shows a gradual downward trend. The hardness of the alloy specimens is affected by factors such as the microstructure, cooling rate, and alloy composition. It has been reported that hardness and grain size have a Hall-Petch relationship, so the hardness of the material decreases as the grain size increases. After solution treatment, the grain size of the alloy specimens gradually increases with the increase in temperature, and even coarsening occurs, so the hardness will gradually decrease. At the same time, under high-temperature conditions, the deformation mechanisms of the material increase, and plastic deformation is likely to occur, which manifests as a decrease in strength and a weakening of deformation strengthening, resulting in a hardness lower than that of a low-temperature solution. When the solution temperature is 1050 °C, its hardness value is 221.65 Hv. When the temperature is further increased to 1190 °C, the hardness value is the lowest, which is 183.72 Hv. At the same solution-treatment temperature, the hardness of the alloy changes little with the extension of time. This phenomenon may be because when holding at this solution temperature, the second phase particles in the alloy continue to dissolve. The holding time is short, and the dissolution rate is not much different, so the hardness change of the alloy tends to be stable.

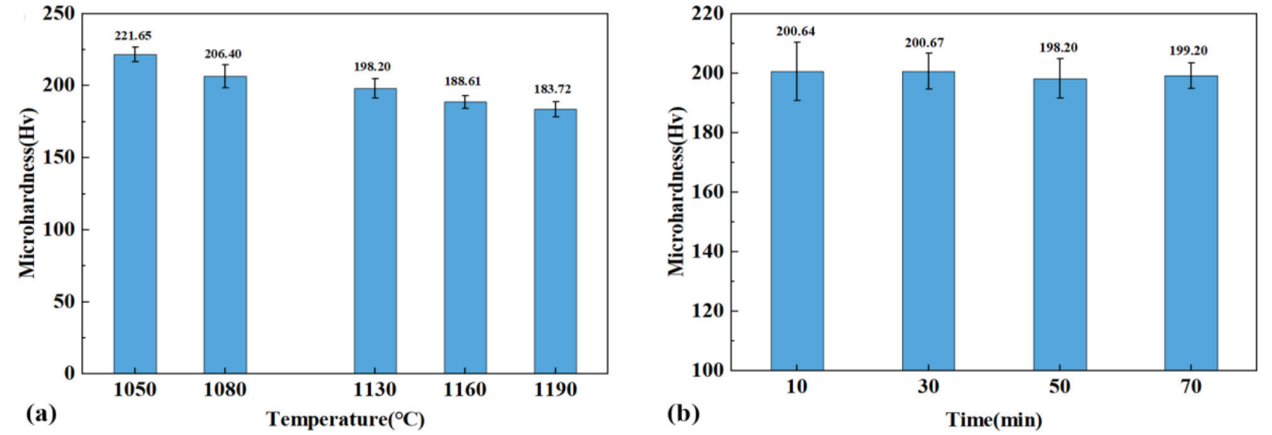

Figure 3: Hardness profile under different solution temperatures and holding times: a) different solution temperatures holding for 50 min, b) different holding time at 1130 °C

3.3 Room-temperature tensile properties

The engineering-stress vs. engineering-strain curves of the specimens are shown in **Figure 4**. It can be seen from **Figure 4** that the tensile curve of the alloy is smooth, and it shows different tensile behaviors in different tensile-test temperature ranges.

When the alloy is tensile tested at different solution temperatures, the tensile strength decreases with an increase of the solution temperature, and the engineering stress/strain curve has no obvious yield point. During the whole tensile-test process, the flow stress increases first and then decreases. When the solution temperature increases from 1050 °C to 1190 °C, both the tensile strength and ductility of the alloy show changes, indicating that compared with the holding time, the mechanical properties of the alloy are more sensitive to the change of grain size with solution temperature. It is primarily found that when the solution temperature is 1080 °C and 1130 °C for 50 min, the tensile curve changes similarly. This is because the fraction of twins is high at this solution temperature, and due to the twin boundary hindering dislocation movement, there will be a large stress concentration at the interface.[18] When the twin-growth mechanism dominates in plastic deformation, twins will continue to expand. The propagation of twins will be hindered by grain boundaries, leading to severe stress concentration at the grain boundaries and reducing the plastic deformation coordination ability of high-temperature alloys.[19]

Under the solution-treatment conditions studied in this paper, the tensile strength ranges from 733 MPa to 833 MPa, and the total elongation ranges from 63.2 % to 80.08 %. When holding at 1130 °C for 10 min to 70 min, the engineering stress-strain curve changes little. Except for holding at 1130 °C for 50 min, with the extension of holding time, the yield strength and tensile strength of the alloy change little.

Figure 5 shows the curves of room-temperature tensile strength and tensile ductility of the alloy specimens as a function of solution temperature. Tensile strength is a typical indicator of resistance to deformation, indicating the metal's strength. It can be seen from **Figure 5a** that when the solution temperature is below 1130 °C, the room-temperature tensile strength and room-temperature

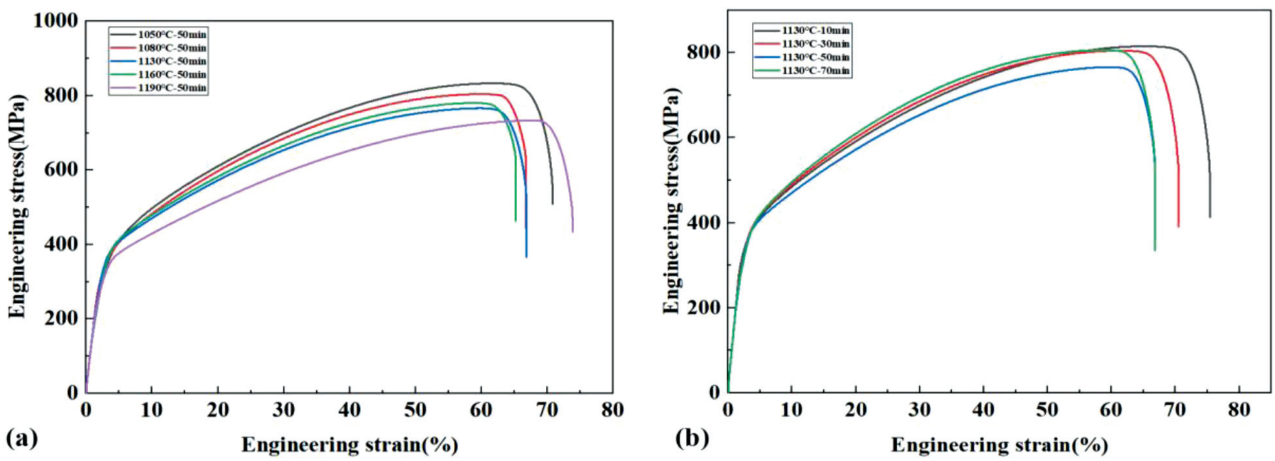

Figure 4: Comparison between engineering stress-strain curves: a) different solution temperatures holding for 50 min, b) different holding time at 1130 °C

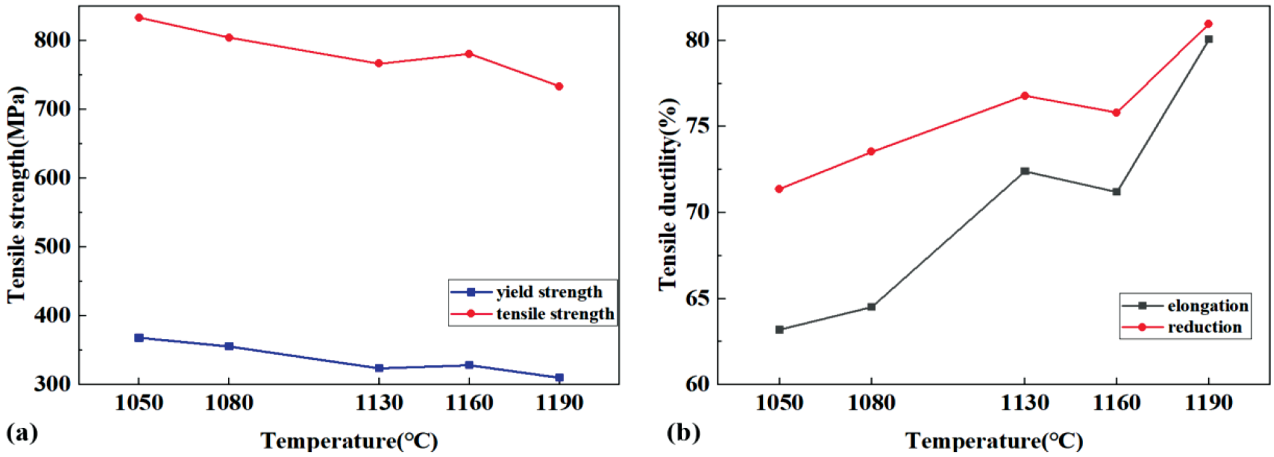

Figure 5: Comparison of mechanical properties at different solution temperatures: (a) yield strength and tensile strength, (b) elongation after fracture and reduction of area

yield strength gradually decrease with increasing temperature. When the solution temperature increases from 1130 °C to 1160 °C, the alloy's yield strength and tensile strength show a significant upward trend and abnormal yielding occurs. The yield strength reaches 328.48 MPa at 1160 °C, which is the abnormal yield strength. When the solution temperature increases from 1160 °C to 1190 °C, under the action of thermal activation, the yield strength and tensile strength of the alloy show a significant downward trend. Elongation after fracture is an important parameter reflecting the plasticity of metals. **Figure 5b** shows the elongation and reduction of the area of the alloy at different solution temperatures. For the ductility of the alloy, when the solution temperature increases to 1130 ° C, the elongation increases to 72.4 %. However, when the temperature continues to increase to 1160 °C, the change of reduction of area is consistent with that of elongation, both showing a significant downward trend.

3.4 Fracture morphology observation

Figure 6 shows the nickel-based alloy specimens obtained after tensile testing at different solution temperatures. The tensile fracture color is dark and dull, the obtained specimen diameter is smaller than the original diameter, the fracture surface is rough, mainly composed of dimples and tearing edges, and some sharp spikes appear locally. The fracture edge is irregular, cone-shaped, and the fracture shape and morphology of these specimens are shown in **Figure 6**. By observing the fracture microstructure, it can be found that there are many dimples on the fracture surface, and there are pits of different depths inside the structure. The pits are caused by local micropore aggregation caused by grain-boundary sliding or dislocation movement[20], which is the main micro characteristic of metal plastic fracture.

Figures 7a and **7b** show the fracture morphology and the corresponding pit morphology of the specimen at 1050 °C. The cross-sectional diameter of the fracture decreases to 2.584 mm. Compared with the original specimen, the number of dimples on the fracture increases, but the depth of the pits is still shallow. This is because adjacent cracks are difficult to aggregate at relatively low temperatures.[21]

Figures 7c and **7d** show the fracture morphology at 1080 °C. At this solution temperature, many deeper pits begin to appear, the dimple size becomes more significant, the fracture surface fluctuates wildly, and there are

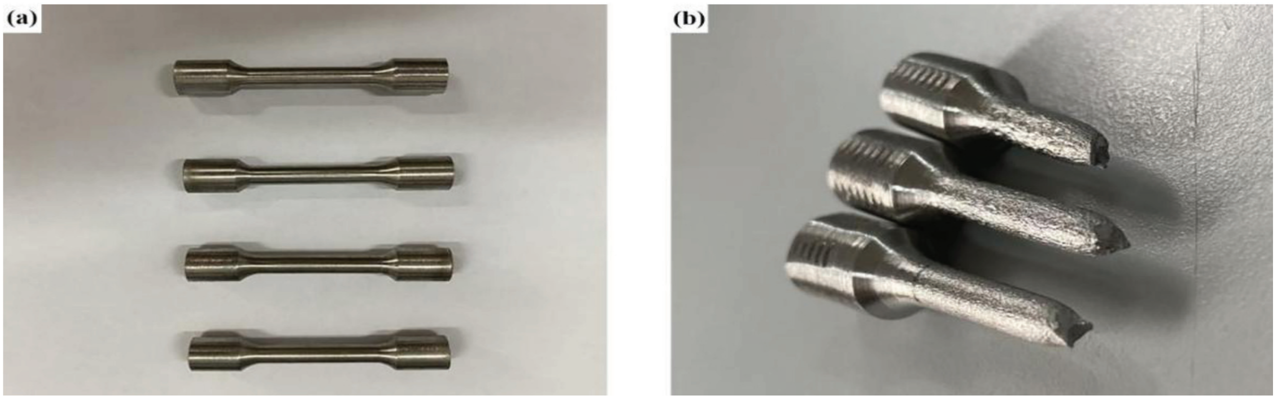

Figure 6: Tensile specimens of alloy N06625

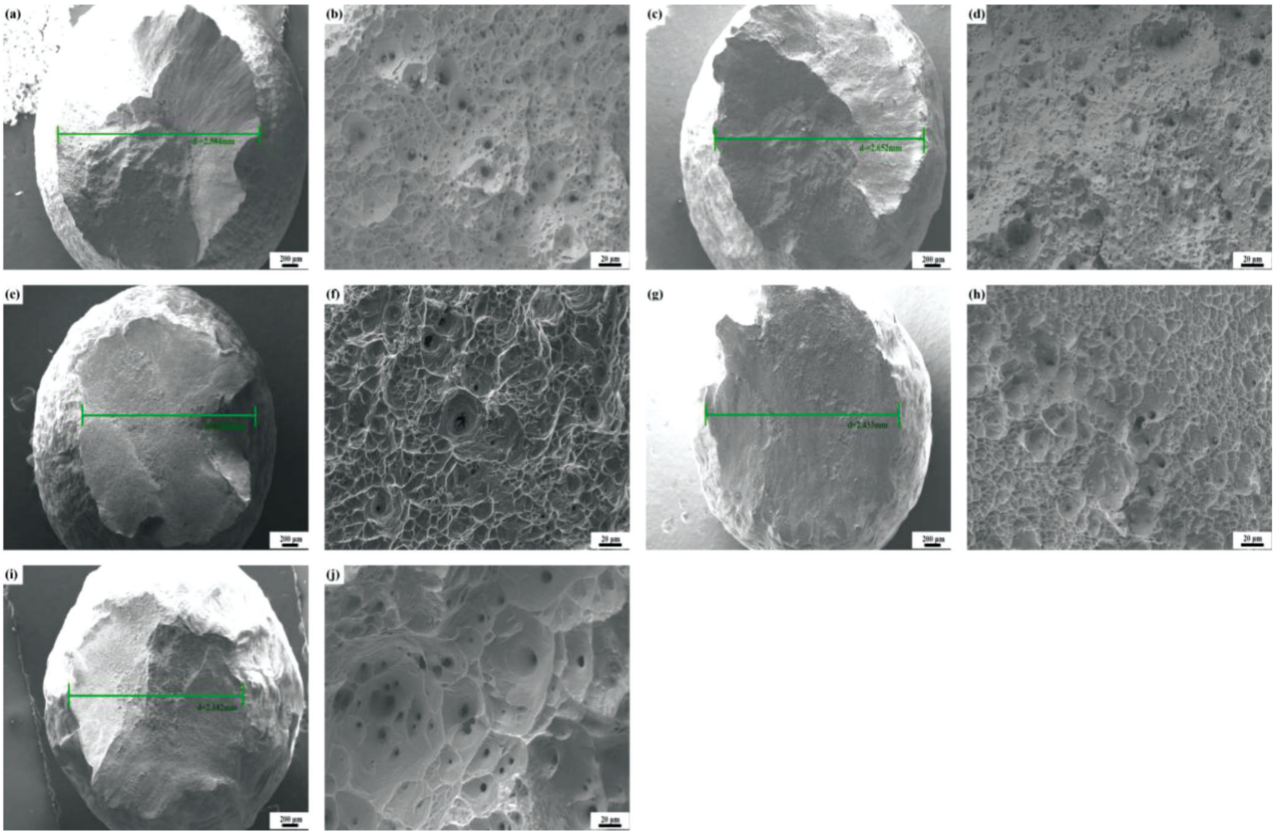

Figure 7: Fracture morphology of the alloy under room-temperature tensile: a), b) 1050 °C, c), d) 1080 °C, e), f) 1130 °C, g), h) 1160 °C, i), j) 1190 °C

still small dimples with smaller sizes on the fracture edge. At solution temperatures of 1130 °C and 1160 °C, the dimple structure morphology is shown in **Figures 7f** and **7h**. It is worth mentioning that as the degree of deformation increases, the dimples form undulating and bending stripe morphology, and the stripe pattern is smoothed by deformation, which is generally called the serpentine sliding characteristic.[22] The reason for its formation is that after large plastic deformation, shear separation along the slip plane, mutual restraint, and traction between grains with different orientations, it is impossible to slip only along a particular slip plane but along many intersecting slip planes. Then, the intersection of multiple sliding systems leads to the appearance of this characteristic.[23,24]

As the solution temperature increases, at 1190 °C, from the pit morphology shown in **Figure 7j**, it can be seen that at this time, the number of dimples increases significantly, and there are many large and deep dimples. The dimple size increases significantly, and the fluctuation of the fracture surface becomes more evident. The number of tiny dimples on the edge decreases. The results show that as the solution temperature increases, the degree of cross-sectional shrinkage becomes larger and larger. That is the necking degree and the pit size becomes larger. The more and larger the dimples, the stronger the resistance to local instability, so the plasticity is better.[25]

4 CONCLUSIONS

A series of N06625 alloy samples with different microstructures were prepared by controlling different solid-solution temperatures. The effect of solid-solution treatment on the microstructure evolution and mechanical properties of nickel-based N06625 alloy was studied through tissue observation, hardness measurement, and room-temperature tensile mechanical tests. Based on the above results and discussion, the following conclusions can be drawn:

(1) As the solution temperature increases, the average grain size increases. There are a large number of annealing twins inside the grains, and the fraction of twin boundaries reaches its maximum at 1080 °C, because the driving force for twin nucleation is optimal at this temperature.

(2) As the solid-solution temperature increases, the microhardness and tensile strength show a decreasing trend, and the tensile ductility decreases at 1160 °C. This may be due to a further decrease in the twin-boundary fraction.

(3) The fracture morphology of the alloy is irregular conical shape with a large number of dimples, which is a typical ductile fracture. As the solution temperature increases, the number of pits on the fracture surface increases, the depth of pits gradually increases, and the distribution becomes more uniform.

Acknowledgment

This project was supported by the Key Core Technology and Common Technology Research and Development Project of the Shanxi Province (20201102017).

5 REFERENCES

[1] L. Tan, X. Ren, K. Sridharan, Corrosion behavior of Ni-base alloys for advanced high temperature water-cooled nuclear plants, Corrosion Science, 50 (**2008**) 11, 3056–3062, doi:10.1016/j.corsci.2008.08.024

[2] L. Wang, H. Li, Q. Liu, Effect of sodium chloride on the electrochemical corrosion of Inconel 625 at high temperature and pressure, Journal of Alloys and Compounds, 703 (**2017**), 523–529, doi:10.1016/j.jallcom.2017.01.320

[3] H. Monajati, M. Jahazi, R. Bahrami, The influence of heat treatment conditions on γ' characteristics in Udimet® 720, Materials Science and Engineering: A, 373 (**2004**) 1–2, 286–293, doi:10.1016/j.msea.2004.01.027

[4] Q. Liu, Z. Liu, G. Gan, Effect of solid solution treatment on microstructure and hardness of Haynes282 heat resistant alloy, Heat Treatment of Metals, 41 (2016) 1, 52–57, doi: 10.13251/j.issn.0254-6051.2016.01.011

[5] Z. L. Tian, S. B. Jiang, Z. Z. Chen, Microstructural evolution and mechanical properties of a new Ni-based heat-resistant alloy during aging at 750°C, Journal of Iron and Steel Research, International, 024 (2017) 005, 513–519, doi:10.1016/S1006-706X(17)30078-X

[6] H. Suo, L. Wang, X. Wu, Feasible evolution process of tensile property dominant effect factor in annealed high purity nickel by a combination of in situ tensile technique and EBSD, Materials Today Communications, 35 (**2023**), doi:10.1016/j.mtcomm.2023.105718

[7] P. Lan, J. Zhang, Tensile property and microstructure of Fe-22Mn-0.5C TWIP steel, Materials Science and Engineering: A, 707 (**2017**), 373–382, doi:10.1016/j.msea.2017.09.061

[8] X. Zhang, Y. Chen, L. Cao, Microstructures and tensile properties of a grain-size gradient nickel-based superalloy, Journal of Alloys and Compounds, 960 (**2023**), doi:10.1016/j.jallcom.2023.170344

[9] X.-M. Chen, Y. C. Lin, F. Wu, EBSD study of grain growth behavior and annealing twin evolution after full recrystallization in a nickel-based superalloy, Journal of Alloys and Compounds, 724 (**2017**), 198–207, doi:10.1016/j.jallcom.2017.07.027

[10] X. Yuan, L. Chen, Y. Zhao, Influence of annealing temperature on mechanical properties and microstructures of a high manganese austenitic steel, Journal of Materials Processing Technology, 217 (**2015**), 278–285, doi:10.1016/j.jmatprotec.2014.11.027

[11] Y. Zhang, Y. S. Li, N. R. Tao, High strength and high electrical conductivity in bulk nanograined Cu embedded with nanoscale twins, Applied Physics Letters, 91 (**2007**) 21, 282–285, doi:10.1063/1.2816126

[12] C. Dai, P. Saidi, Z. Yao, Deformation-free nanotwin formation in zirconium and titanium, Materials Letters, 247 (**2019**), 111–114, doi:10.1016/j.matlet.2019.03.029

[13] F. K. Yan, G. Z. Liu, N. R. Tao, Strength and ductility of 316L austenitic stainless steel strengthened by nano-scale twin bundles, Acta Materialia, 60 (**2012**) 3, 1059–1071, doi:10.1016/j.actamat.2011.11.009

[14] C. A. Stein, A. Cerrone, T. Ozturk, Fatigue crack initiation, slip localization and twin boundaries in a nickel-based superalloy, Current Opinion in Solid State and Materials Science, 18 (**2014**) 4, 244–252, doi:10.1016/j.cossms.2014.06.001

[15] N. Bozzolo, N. Souaï, R. E. Logé, Evolution of microstructure and twin density during thermomechanical processing in a γ-γ' nickel-based superalloy, Acta Materialia, 60 (**2012**) 13–14, 5056–5066, doi:10.1016/j.actamat.2012.06.028

[16] E. G. Astafurova, K. A. Reunova, M. Y. Panchenko, Temperature dependence of tensile behavior, deformation mechanisms and fracture in nitrogen-alloyed FeMnCrNiCo(N) Cantor alloys, Journal of Alloys and Compounds, 925 (**2022**), doi:10.1016/j.jallcom.2022.166616

[17] Y. Li, H. Fang, X. Zhang, Forming mechanism of growth twins and microstructure evolution on improvement of strength and toughness properties by β-eutectoid element in Ti-7Mo-4Al-4Zr-3Nb-2Cr-xFe alloys, Journal of Alloys and Compounds, 947 (**2023**), doi:10.1016/j.jallcom.2023.169507

[18] Q. U. Pengfei, Y. Wenchao, Y. Quanzhao, The Research and Development of Micro-Twinning Formation Mechanism in Nickel-based Superalloys, Materials Reports, 33 (**2019**) 23, 3971–3978, doi:10.11896/cldb.18120160

[19] I. S. Kim, B. G. Choi, H. U. Hong, Anomalous deformation behavior and twin formation of Ni-base superalloys at the intermediate temperatures, Materials Science and Engineering: A, 528 (**2011**) 24, 7149–7155, doi:10.1016/j.msea.2011.05.083

[20] X. Z. Zhang, T. J. Chen, Y. S. Chen, Effects of solution treatment on microstructure and mechanical properties of powder thixoforming 6061 aluminum alloy, Materials Science and Engineering: A, 662 (**2016**), 214–226, doi:10.1016/j.msea.2016.03.060

[21] Y. Huang, C. Liu, Z. Xiao, Hot tensile deformation and fracture behaviours of Hastelloy C-276 alloy, Materials Science and Technology, 34 (**2017**) 5, 620–627, doi:10.1080/02670836.2017.1407566

[22] G. Bai, J. Li, R. Hu, Effect of temperature on tensile behavior of Ni–Cr–W based superalloy, Materials Science and Engineering: A, 528 (**2011**) 4–5, 1974–1978, doi:10.1016/j.msea.2010.11.053

[23] Z. Xiao, Y. Huang, L. Hui, Hot Tensile and Fracture Behavior of 35CrMo Steel at Elevated Temperature and Strain Rate, Metals, 6 (**2016**) 9, 210, doi:10.3390/met6090210 6(9)

[24] Y. C. Lin, J. Deng, Y. Q. Jiang, Hot tensile deformation behaviors and fracture characteristics of a typical Ni-based superalloy, Materials & Design, 55 (**2014**), 949–957, doi:10.1016/j.matdes.2013.10.071

[25] E. Pu, W. Zheng, Z. Song, Evolution of microstructure and tensile properties during solution treatment of nickel-based UNS N10276 alloy, Materials Science and Engineering: A, 705 (**2017**), 335–347, doi:10.1016/j.msea.2017.08.101