

GANG HO LEE^{1,2}, MINHA PARK¹, SANGHOON NOH², BYOUNGKOO KIM^{1*}, BYUNG JUN KIM^{1*}**MICROSTRUCTURE AND MECHANICAL PROPERTIES OF MODIFIED AISI 4140 STEEL
WITH ADDITION OF CR AND W ELEMENTS**

High-temperature environments require materials with exceptional properties, including strength, oxidation resistance, and wear resistance. Quenched and tempered (QT) AISI 4140 steel, a chromium-molybdenum low-alloy steel, is known for its superior strength and toughness, making it widely used in industries such as automotive, aerospace, and oil & gas. The outstanding characteristics of 4140 steel stem from its alloying elements: chromium (Cr), molybdenum (Mo), and manganese (Mn), along with the quenching and tempering treatment temperature. These alloying elements facilitate carbide formation with carbon (C), resulting in finer grains and improved mechanical properties. This study aimed to enhance high-temperature performance by adjusting the chromium content, a key element influencing high-temperature properties. Modified AISI 4140 steel was produced using various QT treatment conditions. Tensile tests conducted at room temperature and at 400°C, 500°C, and 600°C revealed that increasing the tempering temperature generally decreased tensile strength while increasing elongation. At 600°C, the tensile strength decreased for all specimens; however, higher chromium content and lower tempering temperatures improved the high-temperature strength of the modified 4140 steel.

Keywords: AISI 4140; micro-alloying; microstructure; mechanical property; heat-treatment

1. Introduction

AISI 4140, a chromium-molybdenum (Cr-Mo) alloy steel, is widely employed in critical components due to its exceptional mechanical properties, particularly its resistance to high temperatures exceeding 500°C. This thermal stability is crucial for industries such as automotive and aerospace, where components operate under severe conditions [1,2]. To optimize the performance of AISI 4140 in these demanding environments, a comprehensive understanding of microstructure-property relationships is essential. Heat treatment, specifically quenching and tempering, is a cornerstone in tailoring the microstructure of AISI 4140 [2,3]. Additionally, the precise balance of alloying elements, including chromium, niobium, tungsten, and carbon, significantly influences the formation and distribution of carbides, which in turn affect the material's strength, toughness, and creep resistance [4,5]. This study aims to enhance the high-temperature performance of AISI 4140 by systematically investigating the effects of tempering conditions and chromium and tungsten content on the microstructure and mechanical properties. The ultimate goal is to develop a superior AISI 4140

alloy that surpasses the capabilities of commercially available materials in high-temperature applications.

2. Experimental

In this study, the high-temperature strength of AISI 4140 steel (S0) was enhanced by modifying its alloying elements to produce two variants: S1 and S2 AISI 4140 mod. forged specimens. The chemical composition of these materials is detailed in TABLE 1. Key alloying elements, including Cr, Mo, V, and W, were added due to their ability to form stable carbides at high temperatures. Specifically, S1 was produced with 4 wt.% Cr, while S2 contained 3 wt.% Cr and 1 wt.% W, with all other elements remaining constant. The materials were heat-treated by austenitizing at 920°C for 1 hour, followed by water quenching. To compare the microstructure and mechanical properties at different tempering temperatures, three tempering conditions were applied: 590°C, 620°C, and 650°C, each for 1.5 hours, followed by water quenching. Microstructure analysis was performed using an optical microscope after the specimens were ground,

¹ ENERGY SYSTEM GROUP, KOREA INSTITUTE OF INDUSTRIAL TECHNOLOGY, BUSAN 46938, REPUBLIC OF KOREA

² PUKYONG NATIONAL UNIVERSITY, DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING, 48547, BUSAN, REPUBLIC OF KOREA

* Corresponding authors: jun7741@kitech.re.kr, bungkim@kitech.re.kr



Chemical compositions of AISI 4140 (S0) and AISI 4140 Mod. (S1, S2)

Element (wt.%)	C	Si	Mn	Cr	Ni	Mo	Cu	V	Al	W	Fe
S0 (AISI 4140)	0.41	0.26	0.81	1.04	0.077	0.14	0.17	0.005	0.012	—	Bal.
S1 (4% Cr add)	0.42	0.24	0.82	3.78	0.48	1.01	0.3	0.53	0.025	—	Bal.
S2 (3% Cr & 1% W add)	0.41	0.26	0.81	2.79	0.47	1.01	0.2	0.45	0.038	0.96	Bal.

polished, and etched for 1 minute with a 2% nital solution. To observe precipitates, Field Emission Transmission Electron Microscopy (FE-TEM) was conducted using a JEOL/JEM-F200 microscope operating at 200 kV. TEM samples, approximately 3 mm in diameter, were prepared using a solution of 10% perchloric acid and 90% ethanol at -20°C with Struers Tenupol-5 equipment. Tensile tests were performed at room temperature on ASTM E8 subsize specimens using a 100 kN MTS E45 tensile tester at a strain rate of $10^{-3}/\text{sec}$. High-temperature tensile tests were carried out at 400°C , 500°C , and 600°C according to ASTM E21 standards. Charpy impact tests were conducted at room temperature using ASTM E23 CVN specimens and an automatic mechanical impact pendulum apparatus (Zwick/Roell PSW750).

3. Results and discussion

Fig. 1 shows the microstructure observation results of the AISI 4140 (S0-As) material and the S1 and S2 materials containing Cr and W. In Fig. 1a, it can be seen that the S0 material exhibits a mixed microstructure of acicular ferrite and bainite. In the case of S1 and S2, which contain Cr and W, ferrite and pearlite were observed before heat treatment. After QT (quenching and tempering) treatment, the microstructure of S1 and S2 changed according to the tempering temperature. At 590°C , very fine tempered martensite was observed due to tempering. At 620°C and 650°C , a sorbite structure was observed in both cases, along with partially observed lath martensite. When the tempering tem-

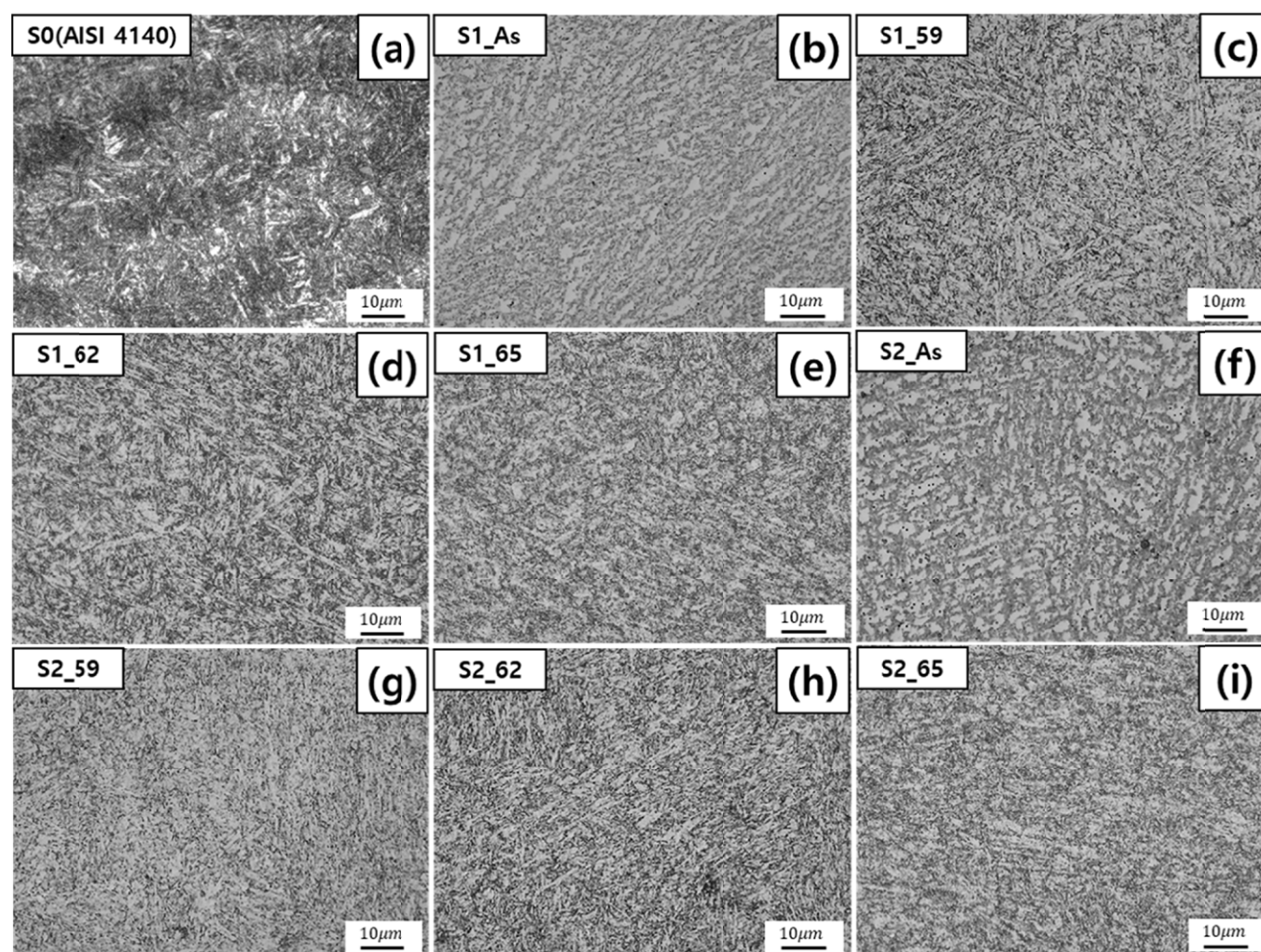


Fig. 1. Optical micrograph of AISI 4140 (S0) and modified (S1 and S2)

perature exceeds 600°C, aggregated cementite particles form a sorbite structure together with partially observed lath martensite [2]. The difference in microstructure between S0 and S1, S2 is attributed to the addition of Cr and W, which stabilizes the phase and inhibits grain growth. Specifically, Cr has been reported to influence the initial growth and formation of cementite during tempering. On the other hand, W, due to its large atomic weight, has a smaller effect on the material per unit weight, resulting in no significant microstructural differences between S1 and S2 [4].

Fig. 2 presents the mechanical properties of each material at various tempering temperatures. Fig. 2a demonstrates the tensile and yield strength of S0, S1, and S2. Compared to the base material S0, both S1 and S2 exhibit significantly increased tensile and yield strengths. Additionally, S2, with added W, showed a slight increase in strength compared to S1. While the strength of S1 and S2 increased significantly compared to S0, their elongation remained nearly identical to S0 at a tempering temperature of 650°C (Fig. 2b). As the tempering temperature increases, strength decreases, and elongation increases. This trend is attributed to the microstructural differences shown in Fig. 1. The addition of elements like Cr and W leads to the spheroidization and coarsening of cementite, resulting in a softer matrix [6]. The hardness measurements in Fig. 2c confirm that S1 and S2 have higher hardness values than S0, consistent with their increased strength. However, like strength, hardness also decreases with increasing tempering temperature due to matrix softening. The impact test results in Fig. 2d show that as temper-

ing temperature decreases, the increased strength of the material leads to lower impact absorption energy. However, depending on the conditions, the impact absorption energy did not decrease significantly compared to S0, indicating that S1 and S2 improved both strength and toughness. The tempered martensite formed during the tempering process with the addition of Cr and W induces hardening of the material, but this effect is partially offset by the softening of the matrix, preventing a significant reduction in toughness.

Fig. 3 presents the tensile properties, including tensile and yield strength, of S0(ref), S1, and S2 at high temperatures. The high-temperature tensile data for the commercial alloy S0(ref) were taken from the study by D.T. Pierce (2022) [7], and it exhibited the lowest strength across all test temperatures, whereas S2, containing both Cr and W, showed the highest strength. In particular, S2 with added W showed superior high-temperature strength compared to S1 due to the formation of WC precipitates and improved phase stability at high temperatures. When comparing the materials at each tempering temperature, S2 consistently maintained higher strength than S1, attributable to the additional strengthening effect of W in high-temperature environments. However, an exception to this overall softening trend was observed in the S2-62 alloy, where yield strength slightly increased at 500°C. This deviation may be attributed to dynamic strain aging (DSA), a mechanism in which diffusing solute atoms such as carbon or nitrogen temporarily pin dislocations, thereby increasing flow stress in the intermediate temperature

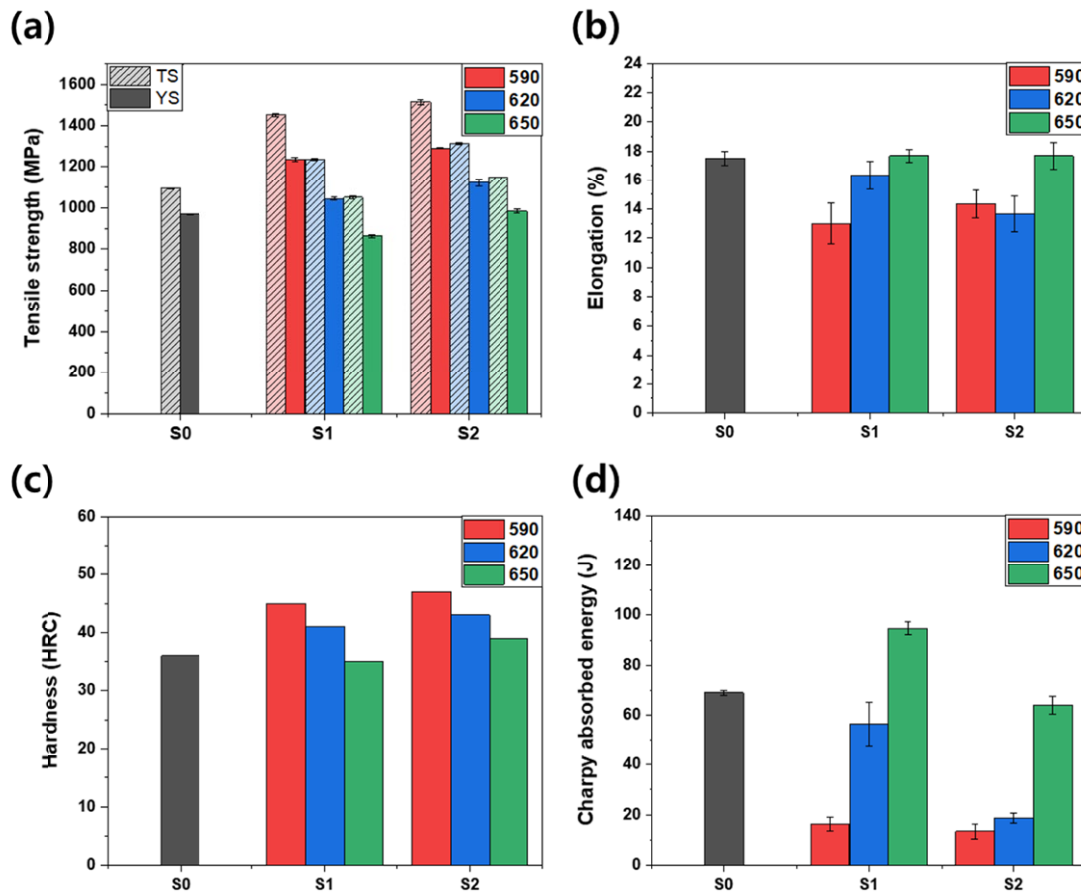


Fig. 2. Mechanical properties analysis of S0, S1, and S2; (a) tensile and yield strength, (b) elongation, (c) hardness, and (d) Charpy absorbed energy

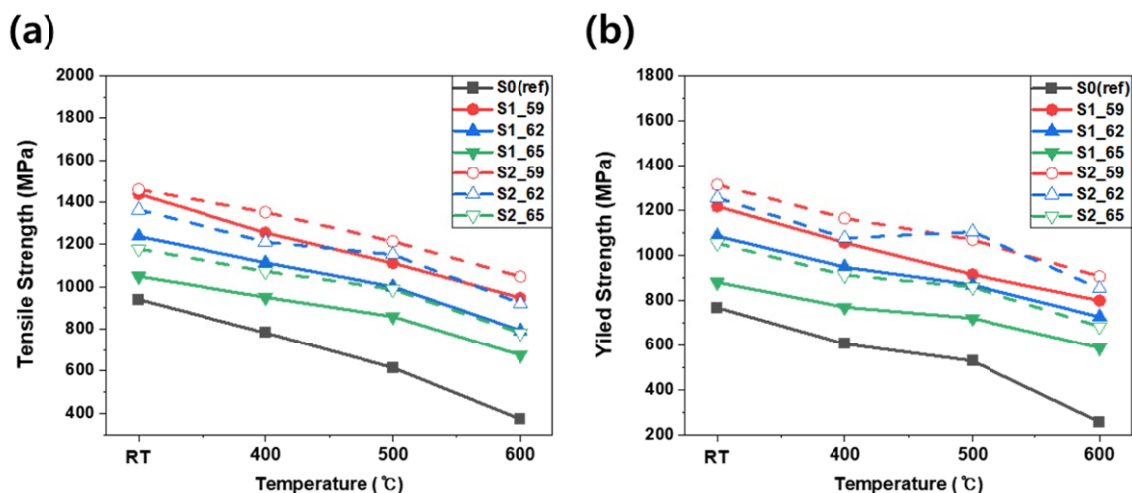


Fig. 3. Tensile properties of S0(ref), S1, and S2 at high temperatures; (a) tensile strength and (b) yield strength

range (typically 300-500°C) [8-10]. At 500°C, enhanced solute mobility may have activated DSA more effectively, resulting in the observed strength increase. The general decrease in tensile and yield strength with increasing tempering temperature, as shown in Fig. 2a, can be attributed to the influence of Cr and W. These elements form very hard and stable carbides at elevated temperatures, directly contributing to high-temperature strength [5,11-13]. Particularly, W promotes the formation of thermally stable WC-type precipitates that pin austenite grain boundaries during austenitizing heat treatment, suppressing grain growth

and facilitating grain refinement. This, in turn, helps maintain phase stability at high temperatures, contributing to the superior high-temperature strength observed in S2 [14-17].

Fig. 4 shows the microstructure of the precipitates observed using TEM-EDS. No precipitates were observed within the matrix of S0. In contrast, S1 contains Cr carbides and V precipitates (Fig. 4b). Similarly, S2 is characterized by the presence of W carbides distributed within the matrix, in addition to those observed in S1 (Fig. 4c). Cr carbides increase strength by hindering dislocation movement, while V precipitates improve mechanical

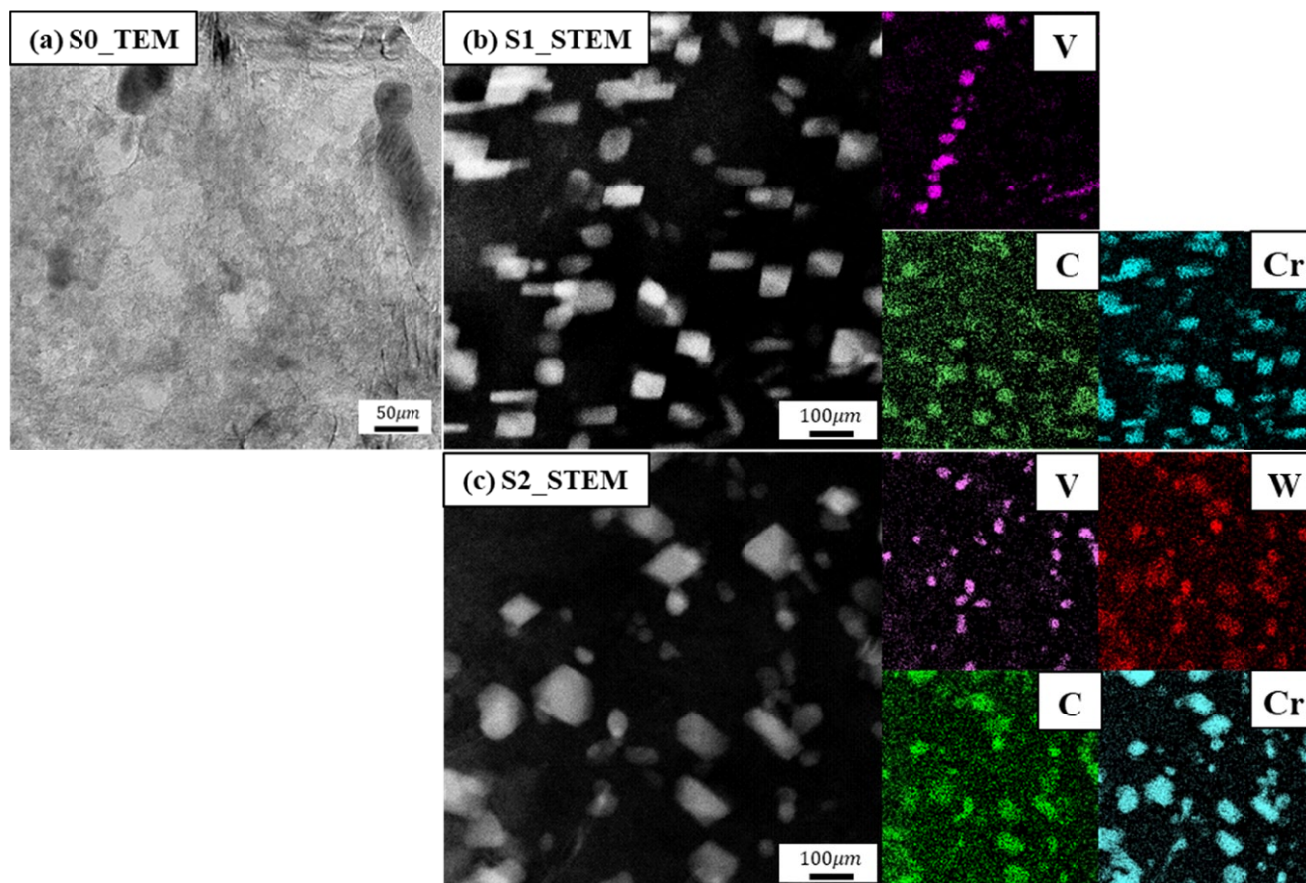


Fig. 4. TEM-EDS analysis results of S0, S1, and S2; (a) S0, (b) S1 and (c) S2

properties through grain refinement [4,6]. Notably, W carbides play a crucial role in maintaining strength under these conditions by significantly enhancing phase stability at high temperatures. The dispersed W carbides within the S2 matrix provide additional resistance to high-temperature softening, directly contributing to S2's excellent high-temperature strength, as observed in Fig. 3. The combination of Cr, V, and especially W carbides in S2 indicates that these elements are key factors in achieving the highest high-temperature strength among the tested materials, and W is instrumental in improving the alloy's thermal stability and overall mechanical performance.

4. Conclusions

In this study, the effect of adding Cr and W to AISI 4140 alloy steel and adjusting tempering temperatures on improving high-temperature strength was confirmed. In particular, the S2 alloy exhibited significant improvements in phase stability and strength at high temperatures due to the formation of WC carbides resulting from the addition of W. Although the strength decreased as the tempering temperature increased, the S2 alloy, with added W, maintained a high level of strength, suggesting enhanced applicability in high-temperature environments. These findings provide valuable data for the potential application of AISI 4140 Mod. alloys in various industries requiring high strength and stability at elevated temperatures.

Acknowledgments

This study was supported by the International joint technology development project (P155500021, Development of eco-friendly high-performance forged parts manufacturing technology based on AI intelligent plastic processing system) and additionally by the Materials/Parts Technology Development Program (RS-2024-00444679, Development of test evaluation, standardization and filed engineering technology for high-pressure hydrogen pipe).

References

- [1] A. Meysami, R. Ghasemzadeh, S. Seyedein, M. Aboutalebi, *Mater. Design* **31** (3), 1570-1575 (2010).
- [2] M.K. Sanij, S.G. Banadkouki, A. Mashregi, M. Moshrefifar, *Mater. Design* **42**, 339-346 (2012).
- [3] L. Zheng, D. Zheng, L. Zhao, L. Wang, K. Zhang, *Met. Mater. Int.* **19**, 1373-1376 (2013).
- [4] W.D. Klopp, J. Less-Common. Met. **42** (3), 261-278 (1975).
- [5] M. Lee, *Metall. Trans. A* **14**, 1625-1629 (1983).
- [6] N.V. Luzginova, L. Zhao, J. Sietsma, *Metall. Mater. Trans. A* **39**, 513-521 (2008).
- [7] D.T. Pierce, G. Muralidharan, A. Trofimov, J. Torres, H. Wang, J.A. Haynes, K. Sebeck, E. Gingrich, G. Byrd, M. Tess, *Mater. Des.* **214**, 110373 (2022).
- [8] B.R. Antoun, C. Alleman, J. Sugar, *Thermomechanics & Infrared Imaging, Inverse Problem Methodologies and Mechanics of Additive & Advanced Manufactured Materials* **7**, 27-32 (2021).
- [9] S.G. Hong, S.B. Lee, *Trans. Korean Soc. Mech. Eng. A*, **27** (8), 1398-1408 (2003).
- [10] B.R. Antoun, R.S. Chambers, J.M. Emery, A.A. Brown, *Challenges in Mechanics of Time Dependent Materials* **7**, 141-148 (2017).
- [11] R. Gao, X.-X. Ye, S. Yan, Y. Lu, L. Jiang, Z. Li, et al., *Corros. Sci.* **149**, 87-99 (2019).
- [12] S. Jung, C. Jeon, Y.H. Jo, W.-M. Choi, B.-J. Lee, Y.-J. Oh, et al., *Mater. Sci. Eng. A* **656**, 190-199 (2016).
- [13] V. Pod'yachev, M. Gavriluk, *Strength Mater.* **7**, 1514-1516 (1975).
- [14] H.S. Kim, M. Kang, M. Park, B.J. Kim, B. Kim, Y.S. Ahn, *Arch. Metall. Mater.* **69** (1), 61-65 (2024).
- [15] H. Bhadeshia, R. Honeycombe, *Steels: microstructure and properties*, Oxford 2017.
- [16] D.H. Kou, J.H. Yoon, S.J. Park, J.M. Kim, H.J. Kang, J.H. Sung, *J. Korean Heat Treat. Soc.* **24** (4), 187-192 (2011).
- [17] B. Hwang, D.-W. Suh, *Korean J. Mater. Res.* **23** (10), 555-561 (2013).