

Effect of Temperature and Strain Rate on Formability of Titanium Alloy KS1.2ASN

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Abstract. Titanium alloys are widely used in aerospace and automotive industries due to their excellent mechanical properties, however, the formability is limited, which is an issue during forming. In the present study, the effect of temperature and strain rate on the tensile properties of the titanium α -alloy KS1.2ASN was investigated. It was observed that there is initially no gain in ductility with increase in temperature until 400 °C, however, maximum formability is reached at maximum tested temperature of 600 °C. EBSD analysis revealed that twinning is the main deformation mechanism at room temperature, however, deformation becomes more pronounced with increasing temperature. An increase in strain rate leads to a decrease in elongation, but the influence is less pronounced compared to temperature.

Introduction

Titanium alloys offer a number of advantages over other materials, such as high strength-to-weight ratio, corrosion resistance, and high operating temperature [1]. Despite this, forming of titanium alloys is challenging due to the limited formability [2]. The formability is usually affected by many factors such as temperature, strain rate, etc. Typically, an increase in formability can be gained with higher temperature. However, at certain temperatures, the formation of an oxide layer is inevitable, also called α -case, which is hard and less ductile, what can lead to the formation of surface cracks under tension [1]. In connection with the growing demand for titanium alloys, the number of studies on this topic has increased in recent decades. The formability of conventional titanium alloys was addressed by many authors. For instance, Chen and Chiu [3] studied the formability of commercially pure (CP) titanium at various temperatures and strain rates using tensile tests, forming limit tests, V-bend tests, and deep drawing tests. It was concluded that CP titanium has limited formability at room temperature, however, it can be applied for forming some small, simple parts. With increasing the temperature the technological feasibility of forming operations is simplified and improved. Odenberger et al. [4] used numerical and experimental approaches to study the forming behavior of Ti-6Al-4V sheets at 700°C. The main focus of the work was on springback and stress relaxation. The authors managed to successfully produce a double-curved part and avoid the formation of an oxide layer by controlling the holding time.

The Ti KS1.2ASN alloy studied in this work has not attracted much attention from researchers until recently. However, it has promising properties in terms of mechanical and fatigue strength as well as fracture resistance [5]. Nawaya et al. [6] studied the tensile properties of α -titanium alloys (including Ti KS1.2ASN) at elevated temperatures and it was observed that the alloys reach the maximum formability in a certain temperature range (in the paper it was approx. 600-650 °C), where

a further increase leads to a reduction of formability. In spite of that, it can be concluded that the formability of Ti KS1.2ASN is far from being understood.

Another open question is the relationship between deformation and microstructure in titanium alloys. Hao et al. [7] investigated the tensile deformation behavior of near- α alloy Ti-6Al-2Zr-1Mo-1V at various temperatures. By means of EBSD analysis it was figured out that until 400°C dislocation slip and tensile twinning are dominant, at temperatures higher than 600°C globularization and dynamic recrystallization are pronounced. Zeng et al. [8] studied the effect of deformation conditions on the texture and microstructure evolution in commercially pure titanium, employing hot compression tests and EBSD analysis. It was observed that every slip system, with the exception of the basal plane, has a significant impact on the texture evolution at the beginning of the deformation. During the deformation process the dominant deformation mechanisms change to the basal, first- and second-order slip systems.

Taking into account the research gaps described above, the present paper has the following two objectives. The first one is to estimate the influence of temperature and strain rate on the tensile properties of titanium alloy KS1.2ASN, and the second one is to connect them with the corresponding microstructure evolution.

Material

In the present study, titanium alloy KS1.2ASN as sheet material with a thickness of 0.9 mm is investigated. Its chemical composition is presented in Table 1. This α -alloy was developed to be applied in the automotive and aerospace industries. It is commonly applied in exhaust and tube systems. In [5] it was shown that the alloy has well-balanced properties in terms of mechanical strength, fatigue strength and fracture resistance, therefore the alloy is valuable for industry and can replace conventional titanium alloys such as Ti Grade 2 and Ti Grade 4.

Table 1. Chemical composition of Ti KS1.2ASN (wt. %) [5].

H₂ (max.)	O₂ (max.)	N₂ (max.)	Fe (max.)	C (max.)	Si	Al	Nb
0.0013	0.15	0.05	0.20	0.08	0.30-0.60	0.30-0.70	0.10-0.30

Experimental Procedure

According to the first objective of the present study, two series of tensile tests were carried out: tests at various (i) temperatures and (ii) strain rates. For both test series, the loading direction of the specimens was oriented in rolling direction. Three repetitions were made for each test condition.

To study the influence of temperature, the specimens with a gauge length of 22.5 mm and a width of 4.5 mm were tested using an MTS 810 universal testing machine equipped with a furnace according to DIN EN 2002-001 and DIN EN 2002-002. The temperature was controlled via three thermocouples of type K. The tensile tests were performed at a strain rate of 0.0005 1/s and at the following temperatures: room temperature (RT), 200 °C, 400 °C, and 600 °C. To study the influence of the strain rate, specimens with a gauge length of 32 mm and a width of 6 mm (according to ASTM E8/E8M-13) were tested at room temperature at three strain rates: 0.0005 1/s, 0.005 1/s, and 0.05 1/s. A 10 kN ZwickRoell testing machine was used in combination with laserXtens extensometer.

For the investigation of the underlying deformation mechanism during the tensile testing, EBSD analysis with an EDAX EBSD system equipped with DigiView 5 camera was performed at fractured as well as base material specimens. For the analysis, specimens tested at RT, 400°C, and 600°C were considered, as well as the specimens tested at different strain rates. EBSD analyses of the fractured specimens were carried out in the area at a distance of 12 mm from the fracture surface to prevent influences from the necking zone. Resulting crystal orientation maps and inverse pole figures were used to analyze the effect of microstructure on the deformation behavior in the tensile tests.

Results and Discussion

Effect of temperature on tensile behavior

The results of tensile tests at different temperatures are presented in Fig. 1 and Table 2. Yield strength and ultimate tensile strength (UTS) decrease with increasing test temperature, which is expected. However, there is no gain in elongation with increase in test temperature from RT to 400°C. Similar results were observed for commercial pure (CP) Ti [3], however, without further investigation of the deformation mechanism in the microstructure. Therefore, in the current study EBSD analysis was performed to understand the deformation behavior in relation to the microstructure further.

Table 2 – Tensile properties of Ti KS1.2ASN at different temperatures, obtained at the strain rate of 0.0005 1/s.

Temperature	Yield strength [MPa]	UTS [MPa]	Elongation [-]
RT	341 ± 2	434 ± 1	0.283 ± 0.006
200°C	192 ± 10	310 ± 5	0.269 ± 0.004
400°C	145 ± 2	258 ± 2	0.252 ± 0.019
600°C	116 ± 3	145 ± 3	0.809 ± 0.014

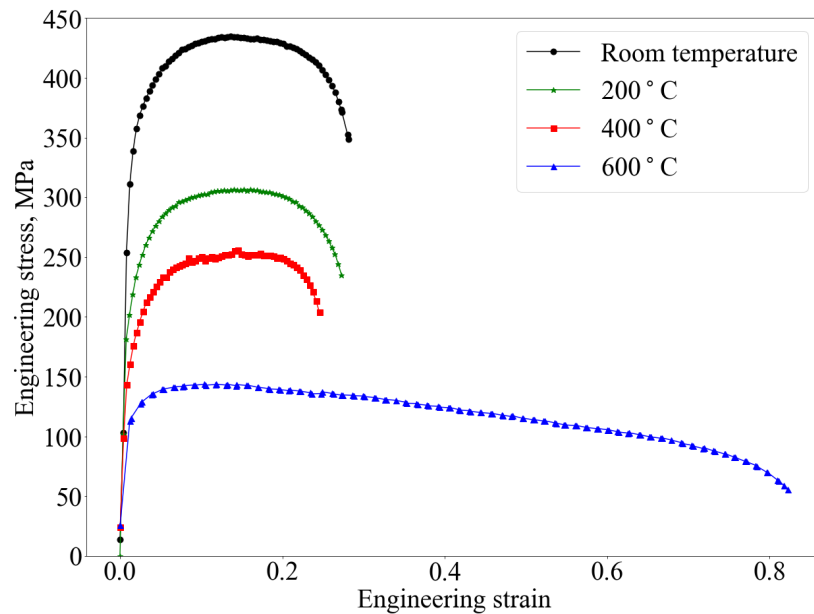


Fig. 1 – Engineering stress-strain curves of the specimens tested at different temperatures at the strain rate of 0.0005 1/s.

The initial microstructure of Ti KS1.2ASN is presented in Fig. 2. A distinct texture can be observed. The material shows a recrystallized structure with grains of globular shape. The microtexture of the initial state can be described as $(0\ 0\ 0\ 1) \pm 30^\circ - \pm 35^\circ \rightarrow \text{TD}$, $[1\ 0\ -1\ 0]//\text{RD}$. The orientation band lies on the TD axis of $(0\ 0\ 0\ 1)$ pole figure.

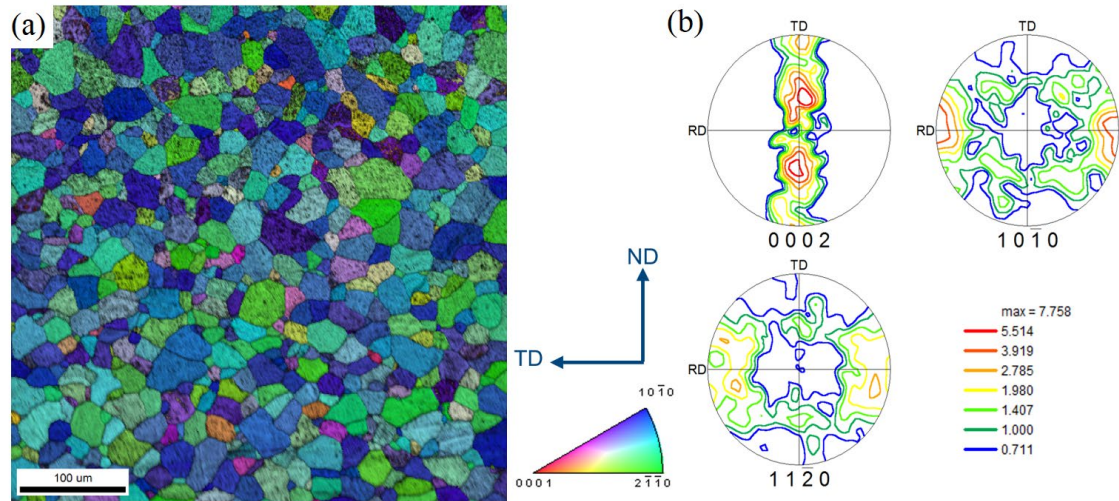


Fig. 2 – Initial microstructure of Ti KS1.2ASN. (a) Crystal orientation map (TD – transverse direction of the specimen, ND – normal direction). (b) Initial pole figures (RD – rolling direction).

The pole figures of the deformed specimens tested at different temperatures are presented in Fig. 3. The crystal orientation maps of the deformed specimens tested at RT, 400 °C, and 600 °C are shown in Fig. 4. At RT, the maximum grain size is $d_{max}^{RT} = 14.0 \pm 5.6 \mu\text{m}$, the minimum grain size is $d_{min}^{RT} = 6.7 \pm 3.3 \mu\text{m}$, the mean misorientation angle $\Delta\omega = 0.83^\circ \pm 0.56^\circ$, and the maximum measured pole density is $P_{max}^{RT} = 7.5$ m.r.d. (multiple of random distribution). At 400°C, the grain size is larger than at RT: $d_{max}^{400^\circ\text{C}} = 15.8 \pm 5.5 \mu\text{m}$ and $d_{min}^{400^\circ\text{C}} = 8.5 \pm 3.4 \mu\text{m}$. The maximum measured pole density, with $P_{max}^{400^\circ\text{C}} = 8.9$ m.r.d., is also higher. The mean misorientation angle, $\Delta\omega = 0.76^\circ \pm 0.51^\circ$, is slightly less than that at RT. At 600°C, the grain size is the lowest: $d_{max}^{600^\circ\text{C}} = 13.3 \pm 8.1 \mu\text{m}$ and $d_{min}^{600^\circ\text{C}} = 5.1 \pm 3.1 \mu\text{m}$. At 600°C, the texture is stronger than that at 400°C: $P_{max}^{600^\circ\text{C}} = 9.4$ m.r.d. The mean misorientation angle at 600°C is the highest: $\Delta\omega = 1.04^\circ \pm 0.67^\circ$.

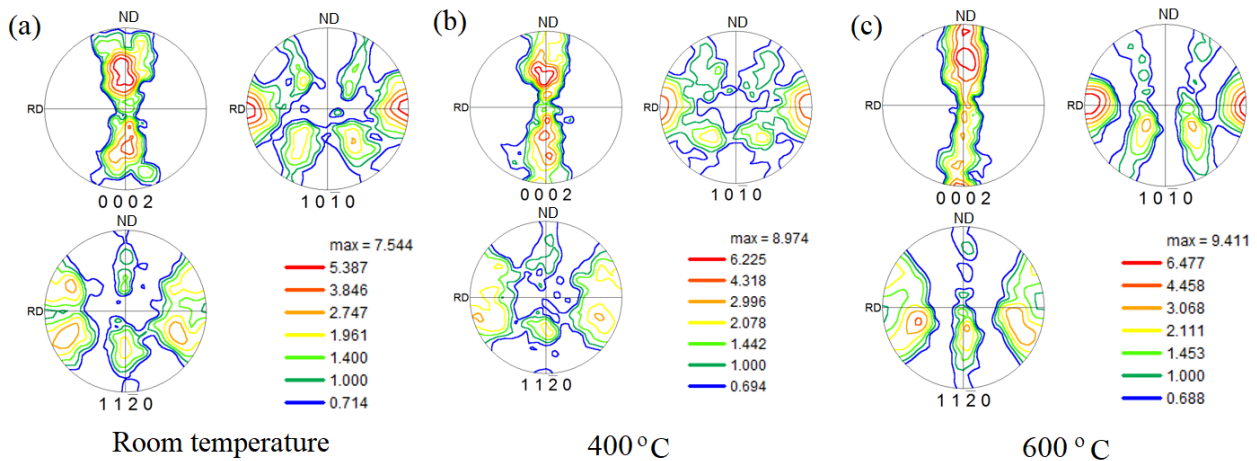


Fig. 3 – Pole figures of the deformed specimens tested at different temperatures and at a strain rate of 0.0005 1/s. (a) Room temperature. (b) 400°C. (c) 600°C.

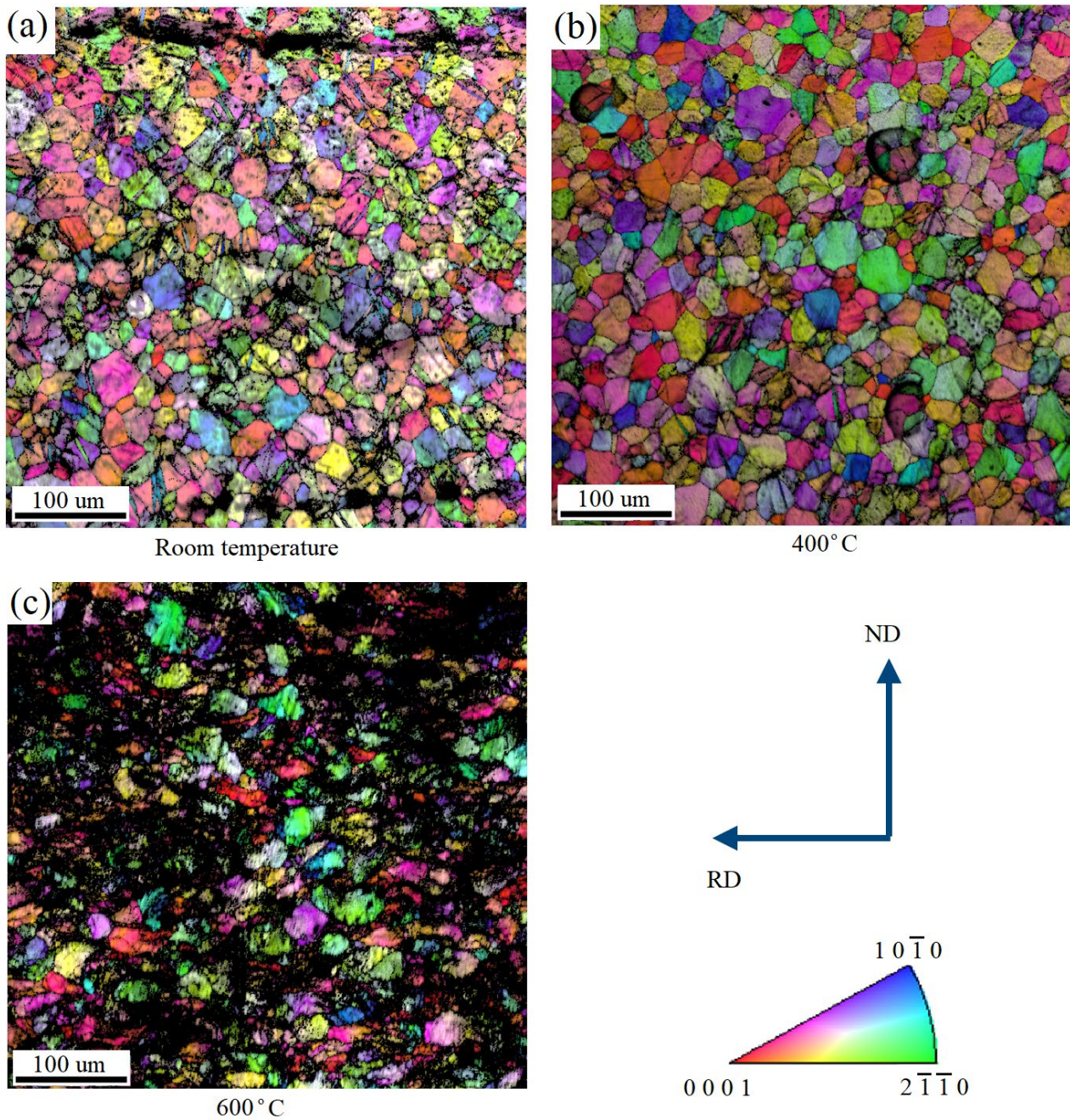


Fig. 4 – Crystal orientation maps of the deformed specimens tested at different temperatures and at a strain rate of 0.0005 1/s. (a) Room temperature. (b) 400°C. (c) 600°C.

Considering the results of the EBSD analysis, it can be concluded that the microstructure is stable regardless of the test temperature. The $\langle 1\ 0\ \bar{1}\ 0 \rangle // \text{RD}$ fiber component is pronounced during the deformation and it is most clearly expressed at 600°C. The orientation band on the TD axis shows almost no change with regard to temperature. In Fig. 3(a) it can be seen that the tensile specimen tested at RT has a large number of twins in the structure, where twinning takes place in almost every grain. Based on this, it can be concluded that the dominant deformation mechanism during the uniaxial tension at RT is twinning, which is the most common deformation mechanism in hcp alloys [9]. Considering the microstructure shown in Fig. 3(b) it is obvious that no pronounced twinning was found in the specimen tested at 400°C, however linear deformation traces are detected which can be attributed to slip deformation. In Fig. 3(c) the microstructure of the specimen tested at 600°C is presented, in which high defect densities are found. Furthermore, a large number of small grains are noticed. Again, the presence of linear deformation traces is a sign of slip deformation.

Effect of strain rate on tensile behavior

The results of tensile tests at different strain rates are presented in Fig. 5 and summarized in Table 3. Yield strength and ultimate tensile strength increase with increasing strain rate, but elongation decrease. This behavior is common for titanium alloys, for instance for CP titanium [1] similar results were obtained. Similarly to the previous section, EBSD analysis is employed to investigate the effect of strain rate on microstructure evolution during the tensile tests.

Table 3 – Tensile properties of Ti KS1.2ASN at different strain rates, obtained at RT.

Strain rate [1/s]	Yield strength [MPa]	UTS [MPa]	Elongation [-]
0.05	363 ± 3	470 ± 2	0.269 ± 0.006
0.005	334 ± 3	456 ± 3	0.277 ± 0.010
0.0005	319 ± 3	448 ± 2	0.321 ± 0.008

The pole figures of the deformed specimens tested at 0.0005 1/s, 0.005 1/s, and 0.05 1/s are presented in Fig. 6, and the crystal orientation maps of the corresponding specimens are shown in Fig. 7. From the results of the EBSD analysis, the conclusion can be made that the microstructure is stable regardless of the strain rate. The orientation band on the TD axis remains similar for every strain rate. The $\langle 10\bar{1}0 \rangle // RD$ fiber component is observed, independent of the applied strain rate. The only noticeable difference can be highlighted in the pole figure of the specimen tested at 0.0005 1/s. It is seen that there is a clearly pronounced maximum in pole densities at $(0002) \pm 40^\circ$ to the transverse direction, which is attributed to the stronger texture than in the other test cases. It is also confirmed by the magnitudes of the maximum measured pole density: $P_{max}^{0.0005} = 13$ m.r.d for the strain rate of 0.0005 1/s, $P_{max}^{0.005} = 6.9$ m.r.d. and $P_{max}^{0.05} = 6.3$ m.r.d. for the strain rates of 0.005 1/s and 0.05 1/s, respectively. This decrease can be explained by the fact that at the low strain rate the elongation is higher and the grains have more time for alignment in a certain direction, therefore the texture is stronger. Considering the fact that stress-strain curves of specimens tested at different strain rates do not differ significantly and the microstructure of these specimens looks similar, it can be concluded that the effect of strain rate on the tensile properties of Ti KS1.2ASN is small.

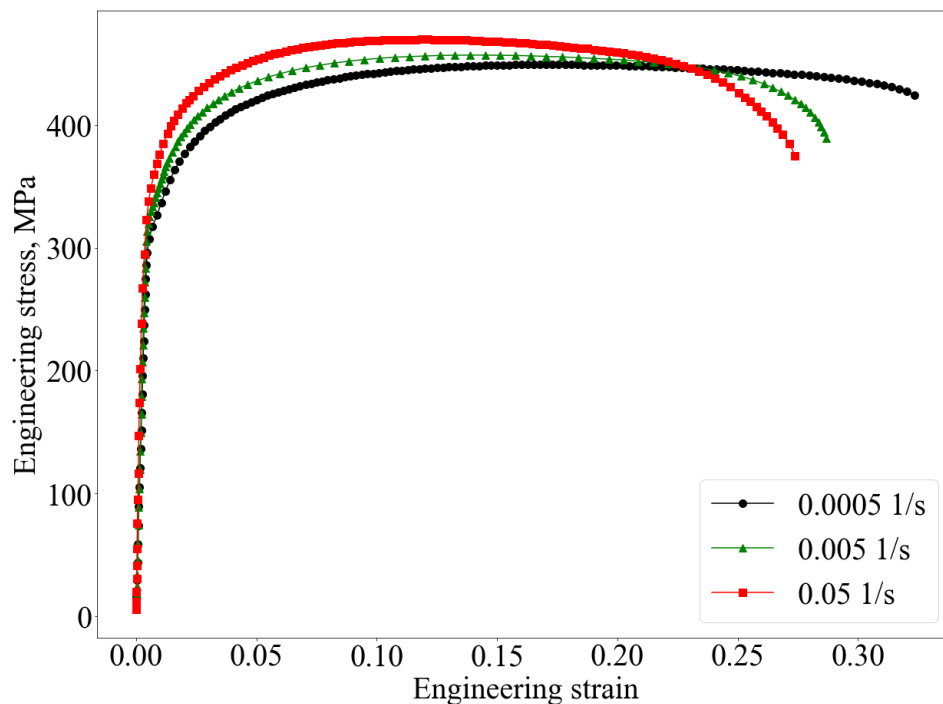


Fig. 5 – Engineering stress-strain curves of the specimens tested at different strain rates and at room temperature.

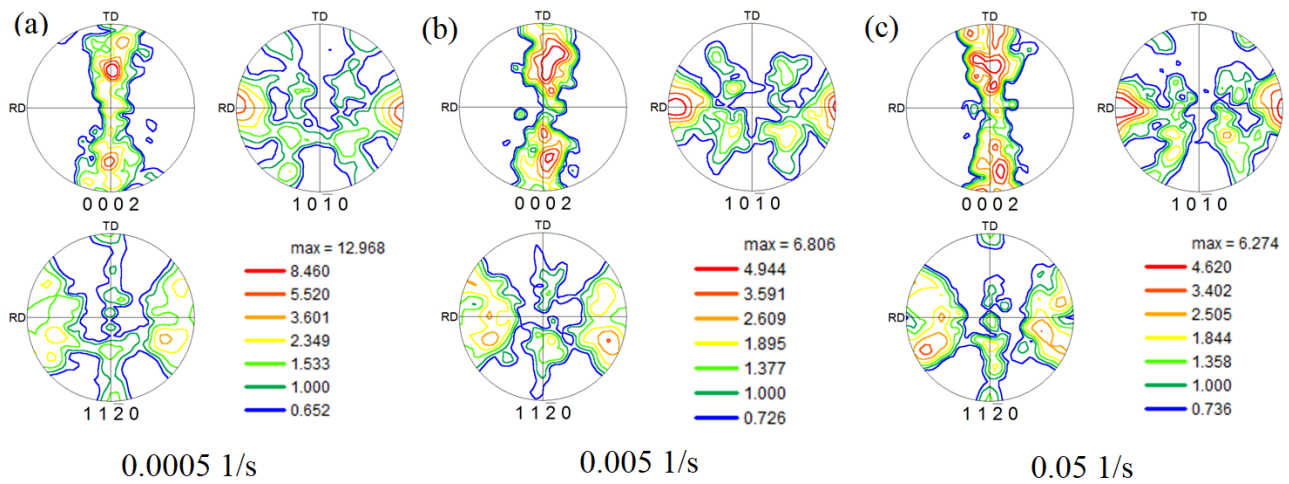


Fig. 6 – Pole figures of the deformed specimens tested at different strain rates and at room temperature. (a) 0.0005 1/s. (b) 0.005 1/s. (c) 0.05 1/s.

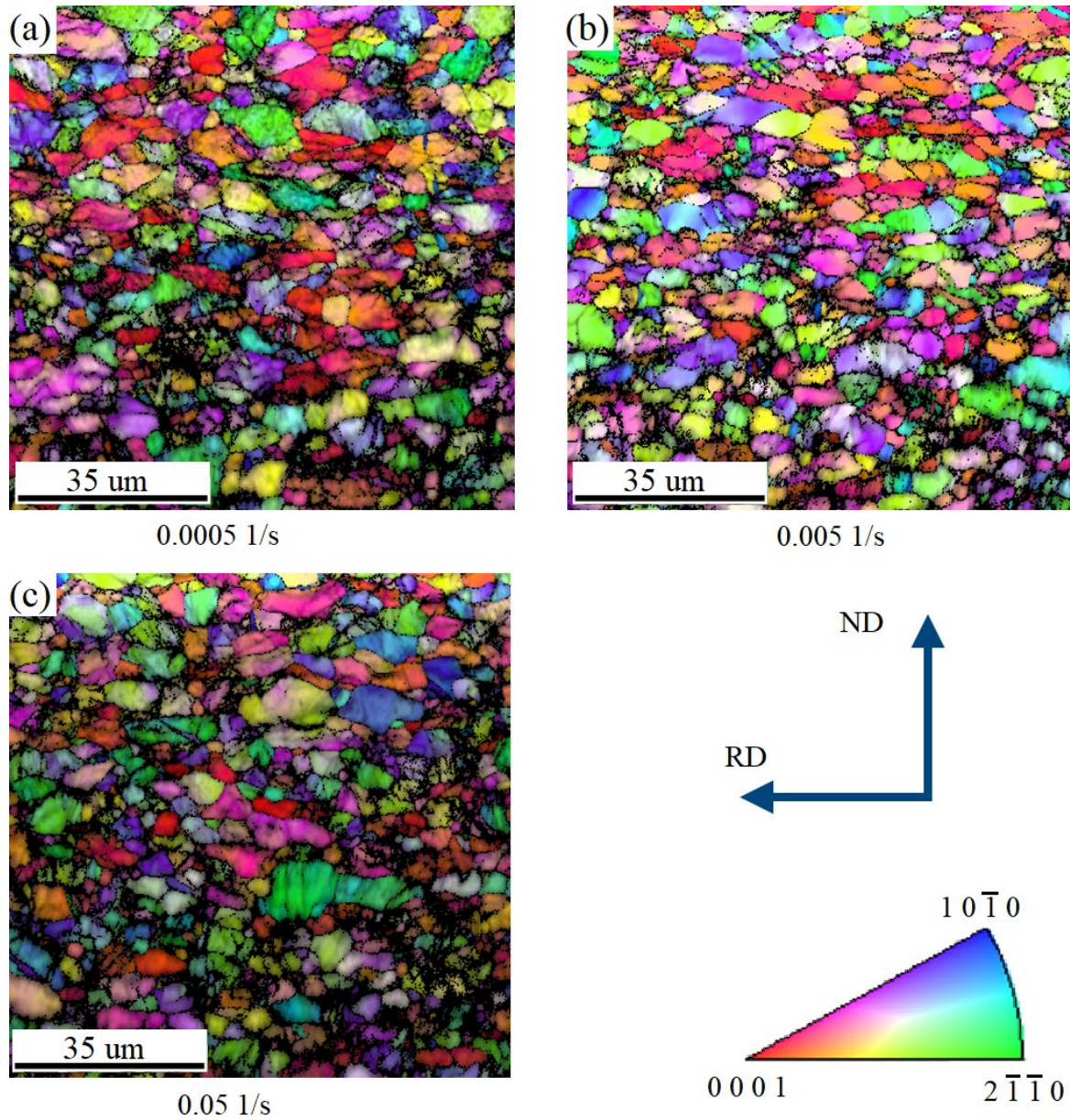


Fig. 7 – Crystal orientation maps of the deformed specimens tested at different strain rates and at room temperature. (a) 0.0005 1/s. (b) 0.005 1/s. (c) 0.05 1/s.

Conclusions

In the present work, the temperature and strain rate effect on the tensile properties of the Ti alloy KS1.2ASN was studied. Based on the experimental results, the following conclusions were made:

- Yield strength and ultimate tensile strength decrease with increasing test temperature and decreasing strain rate. The influence of temperature is very severe, where the effect of strain rate on the tensile properties is relatively small.
- A slight decrease in elongation was observed with an increase in the test temperature from RT to 400 °C. Significant gain in elongation was found at 600 °C. Therefore, a reasonable process window for forming is located in the proximity of 600 °C due to the promising formability.
- Elongation decreases from 0.32 at a strain rate of 0.0005 1/s to 0.27 at a strain rate of 0.05 1/s. In terms of formability, it can be concluded that it is desirable to perform forming of KS1.2ASN at lower speeds.
- EBSD analyses showed that the material has a distinct initial texture, where the grain microstructure does not change significantly during the applied deformation.
- Tensile twinning is the main deformation mechanism at RT, however, slip deformation becomes more pronounced with increasing temperature. No change in deformation mechanism are observed in terms of the different strain rates investigated.

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