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Temperature Dependence of Plastic Flow, Anisotropy and Ductile Fracture

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Abstract

As one of the most common extrinsic features, temperature has an essential impact on the mechanical properties as well as the controlling mechanisms of materials. Therefore, it is aimed in this study to investigate the effect of temperature on the mechanical properties of several steels in an extensive temperature range from -150 °C to 300 °C. Three basic and essential mechanical properties are considered, the plastic flow behavior, anisotropy, and ductile fracture behavior. The temperature influence on plastic flow behavior has been well studied in the literature. With this broad temperature range in the current study, we intend to create a large database to characterize the material behavior as well as to reveal the deformation mechanism change from low to high temperatures. Except for the typical dislocation slipping, the other possible involved mechanisms are twinning and dynamic strain aging. In addition to this, we are particularly focusing on the temperature effect on anisotropy, which has been not covered yet by the existing literature. Based on the experimental results for two pipeline steels, it is shown that the temperature effect on anisotropy could be negligible or significant, depending on the materials. There have been also many investigations of the effect of strain rates on the ductile fracture; however, the temperature effect has not received obvious attention yet. In this study, we set the scope to quasi-static loading condition but vary the loading temperature from -50 °C to 300 °C. The stress-state influence under these temperatures is also considered by employing various sample geometries. Two automotive steel sheets are employed for this study and the results show that a strong temperature effect on the ductile fracture exists for the elevated temperature mainly due to the dynamic strain aging effect, while the less pronounced but non-negligible effect of the temperature is revealed for the lowered temperatures.

Keywords: Dynamic strain aging; Blue brittleness; Pipeline steels; Dual-phase steels; Stress state dependency

1. Introduction

The deformation temperature and rate are two major extrinsic variables for any material deformation involved manufacturing processes or in-service loading conditions. Therefore, it has been always a focus in the materials and mechanics fields to investigate the influence of strain rates and temperatures on the deformation behavior of materials. Concerning the metal materials, the classical work goes back to the study done by Johnson and Cook [1]. They provided a large experimental program for various metals focusing on both strain rates and temperatures. Subsequently, many studies continued to investigate the effects of strain rates and temperature on mechanical behavior, especially on the flow stresses. Correspondingly, many constitutive models have also been proposed to describe the flow stress variation with respect to these two factors in different ranges [2-7]. Zooming into the studies, it can be concluded that on the strain rate effect side, much effort was dedicated to the experimental facility design to reach higher strain rate deformation. Although nowadays many good testing devices have been created, there are still several challenges in this research field, including i) to reach a constant strain rate in the plastic deformation region instead of a constant loading speed; ii) to accurately capture the isothermal flow

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stresses instead of the ones influenced by adiabatic heating. Good solutions to resolve these challenges are still missing. In the field of the temperature influence, the studies have fewer technological challenges as the tests are much easier to control especially under quasi-static conditions. Therefore, in addition to proposing and calibrating constitutive models, the studies have also focused on the activation of various thermal-induced mechanisms, such as the typical thermal softening, deformation mechanism change from slipping to twinning and the dynamic strain aging (DSA) effects.

In this study, it is therefore aimed to investigate only the temperature influence on the flow stress behavior and we focus on its influence on the stress anisotropy, which has not been systematically examined for steels. In addition, with a large deformation temperature range, from -150 °C to 300 °C (combining various steels), it is also aimed to investigate the mechanisms including both thermal softening and DSA.

In terms of the strain rate and temperature dependence of ductile fracture, the initial and complete investigation is still the classical work by Johnson and Cook [1]. On the strain rate side, the same challenges raised before still exist and it is even exaggerated because the fracture is mostly accompanied by localized necking, which makes the constant strain rate at the fracture point from the beginning of plastic deformation to final fracture nearly impossible at very high strain rates. However, neglecting these challenging points, still, several studies have been performed to fine-tune the ductile fracture dependence on strain rates [8-10]. Surprisingly, the follow-up studies that focus only on the influence of temperature on ductile fracture are not many, especially for steels. In the classical work by Johnson and Cook [1], a testing program on the Hopkinson bar with various temperatures was conducted and compared with the tests under quasi-static and room temperature. It is discovered that with elevated temperatures, the ductility of materials has been enhanced. This conclusion has been confirmed by also a few more studies. Derpeński, et al. [11] studied the ductile fracture of an aluminum alloy from room temperature up to 300 °C and the same conclusions were drawn. He, et al. [12] investigated this topic with ultra-super-critical rotor steel at a very high temperature from 950 °C to 1300 °C. A consistent conclusion is drawn up to 1150 °C and for even higher temperatures a decrease of the ductility was found as it was too close to the melting temperature. Yang, et al. [13] tested the TA15 titanium alloy in the range of 750 °C–850 °C and the increase of ductility with temperature was found for various strain rates. It is obvious that the conclusions are consistent. However, it is also noticed that for the most investigated temperature range, the thermal softening is the main mechanism. In addition, the temperature is always elevated from room temperature. The influence of temperature on the ductile fracture with different mechanisms and temperature range below room temperature remains unclear.

Therefore, in this study, it is also aimed to investigate the temperature influence for two automotive steel sheets in the range from -25 °C to 300 °C. In addition to the normal uniaxial tensile tests, other fracture specimens with different stress states are also investigated to reveal the stress-state influences on the temperature sensitivity of ductile fracture.

2. Experimental program

In this study, both the plasticity and fracture behavior of high-strength steels are investigated with respect to their response to the deformation temperature. The experimental testing program is shown in Fig. 1. The smooth dog-bone (SDB) specimens are used for the characterization of plasticity in the uniaxial tensile tests, and the rest are referred to as the fracture specimens, with various features to create a variety in their stress states. The central-hole (CH) specimens feature a uniaxial tension stress state at the critical fracture spot through the deformation history. The notched dog-bone (NDB) specimens show a stress state between the uniaxial tension and plane-strain tension. The plane-strain (PS) specimens basically follow a generalized plane-strain condition under enhanced stress triaxiality with smaller notch radii. The shear (SH) specimens exhibit a simple shear stress state at the fracture point. All the specimens are loaded on a universal tensile test machine. Their specific geometries shall be optimally designed to create a proportional loading history, i.e. the stress state at the fracture spot keeps a constant as desired during the entire deformation history till fracture to eliminate the loading history influence on ductile fracture. More details can be found in Liu, et al. [14]. Depending on the investigation goals, various steels are used in this study; however, the geometry of them always follows the illustrated program.

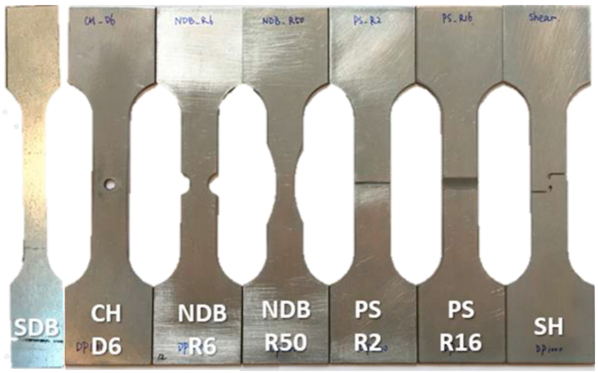

Fig. 1 The sample geometries for the testing program. (Adapted from Liu, et al. [14]).

3. Results and discussion

3.1. Temperature dependence of flow stress and anisotropy

For the anisotropy study, two bainitic-ferritic pipeline steels (X70-A and -B) are chosen. Tensile tests with the SDB geometry in Fig. 1 along three directions, rolling direction (0°), diagonal direction (45°) and transverse direction (90°) were performed. The testing condition was set to be quasi-static with a strain rate of 1×10^{-4} s^{-1}. The temperature range of the test was from -150 °C to room temperature (25 °C). The two steels have similar thermal-mechanical treatment history; however, they differ slightly from the chemical composition and the final finishing thickness after rolling. The X70-A has a thickness of 22 mm, while for X70-B it is 14 mm. The results in terms of true stress–strain curves are shown in Fig. 2.

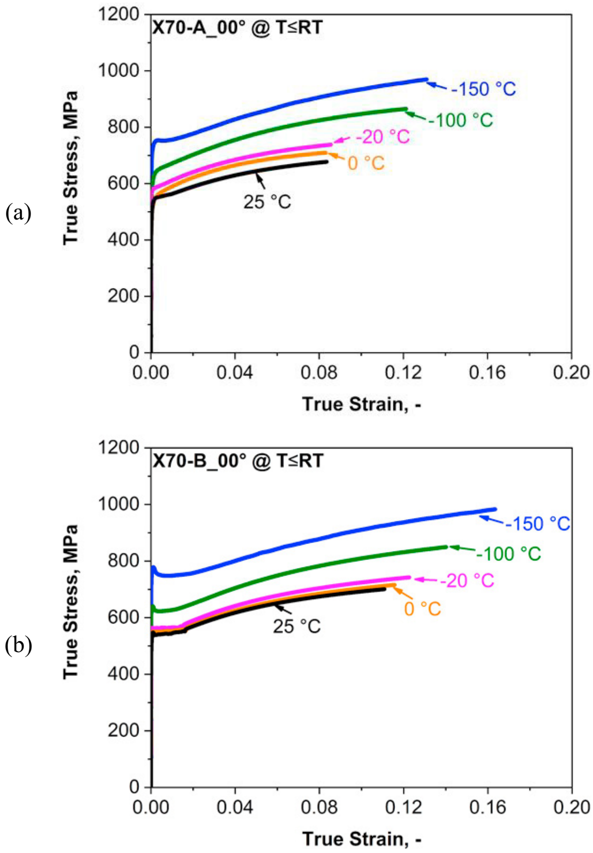

Fig. 2. The true stress–strain curves of X70-A (a) and X70-B (b) along the rolling direction under different deformation temperatures from room temperature to -150 °C.

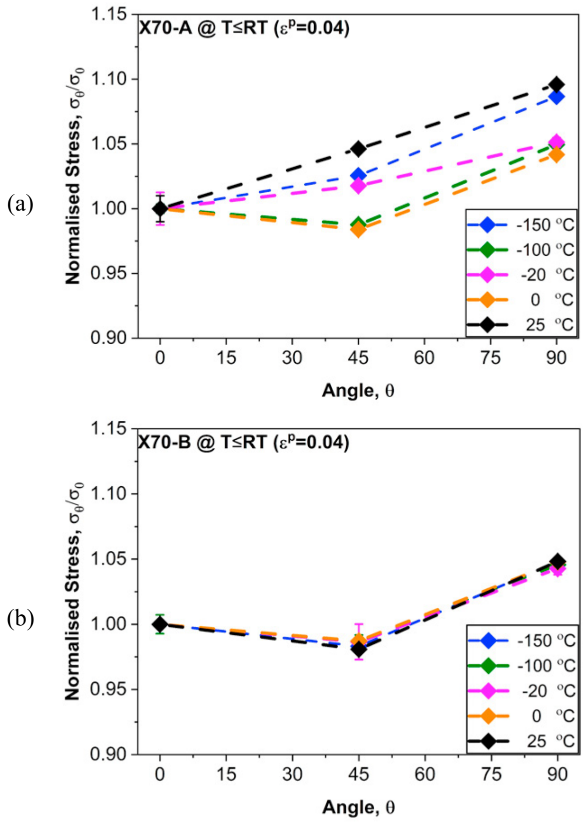

Fig. 3. The stress directionality of the X70-A (a) and X70-B (b) at the plastic strain of 0.04 at different deformation temperatures.

Due to the limit of space, only the results along the rolling direction is given. A much more detailed study that shows the complete results are being prepared by Shen, et al. [15]. From these results, it is clear that both steels show a strong thermal softening effect, i.e. with decreasing the deformation temperature, the flow stress gets significantly increased. What is also noticeable is that in addition to the flow stress, the strain hardening rate has also got an increase, which is reflected clearly by the larger uniform strain at lower temperatures. It shall also be pointed out that for this type of steels, although the deformation temperature has decreased to quite low, -150 °C, surprisingly, the cleavage fracture did not show at the early stage of the deformation. Instead, the plastic deformation has gone a larger range than the test at room temperature.

In terms of the anisotropy analysis, all the test results along different loading directions and temperatures are taken into account for both steels. As clearly shown in Fig. 2, both steels show a certain level of Lüders band at selected temperatures. Therefore, the analysis has focused on the flow stress at the equivalent plastic strain of 0.04, instead of the initial yield stress. Taking the flow stress at this particular strain along the rolling direction as the reference stress for each temperature, the flow stress directionality diagrams are shown in Fig. 3 for both steels.

It is obvious that both steels show non-negligible deformation anisotropy. For room-temperature deformation, the largest stress is along the transverse direction for both materials. For the X70-A, a large amount of about 10% higher flow stress is observed. Taking the temperature influence into account, the two steels show completely distinct responses. For X70-B, the stress anisotropy is almost completely insensitive to the deformation temperatures. However, for X70-A, a dramatic change of the stress anisotropy is shown with respect to the change of the deformation temperature. A clear pattern is not found with respect to the temperature. What is noticeable is that the stress anisotropy has become less pronounced with the decrease of the deformation temperature.

3.2. Temperature dependence of ductile fracture

The investigation of the temperature influence on the ductile fracture is presented in the following two sections. Firstly we are discussing the temperature influence for elevated temperatures from room temperature and then its influence for the temperatures below room temperature is analyzed.

Temperatures above room temperature

For this investigation, a commercial cold-rolled dual-phase steel (DP1000 with 45% martensite and 55% ferrite [16]) with a thickness of 1.5 mm is used. All the samples shown in Fig. 1

were tested. All the tests were conducted under a quasi-static condition. For SDB, a strain rate of 1×10^{-4} s^{-1} was applied. For the fracture specimens with notches or holes, a nominal strain rate of 4.4×10^{-5} s^{-1} was applied to ensure the localized deformation spots were still in a quasi-static condition. The investigated temperatures were from room temperature to 300 °C. The tensile test results are shown in Fig. 4.

(a)

(b)

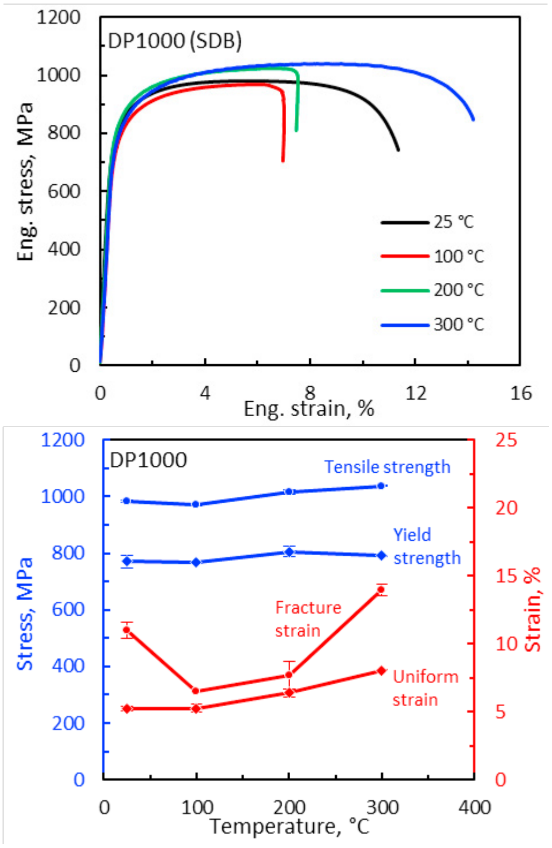

Fig. 4. (a) The engineering stress–strain curves of DP1000 along the rolling direction at different temperatures; (b) the temperature dependence of the main tensile properties.

Compared with the results from the previous steels studied in the range of -150 °C to room temperature, where a monotonic temperature influence on the flow stress is found, the investigated DP1000 in this temperature range shows obviously a non-monotonic dependence on the deformation temperature. As shown in Fig. 4 (b), both the yield and tensile strength only show a very minor decrease from room temperature to 100 °C, and for the rest of temperatures, a clear increase of the strength is shown, especially for the tensile strength. The abnormal behavior is caused by the DSA effect, which is dependent on the material alloying, deformation temperature and strain rate. The basic underlying mechanics is that at particular combination of temperature and strain rate, the mobility of the interstitial or substitutional elements, such as C atoms, are becoming comparable with the mobility of the dislocations, and they continuously prohibit the dislocation movement and increase the energy needed for plastic deformation, therefore leading to an increase of the strength. It shall also be pointed out that in addition to the temperature and strain rate, the effect of DSA is also dependent on the plastic strain. Comparing its effect on the yield and tensile strength, it can be seen that the yield strength shows already a decrease in increasing the temperature from 200 °C to 300 °C, while the tensile strength continues with an increase. Observing the engineering stress–strain curve, it can be seen that the two curves at 200 °C and 300 °C have an intersection at the strain around 5%. It is, therefore, important to emphasize for the modeling of this effect, it is critical to consider an evolving plasticity model [17] to precisely reflect this behavior.

Another contradictory effect to the previous materials is that for the DP1000 in this temperature range, the increase of temperature causes a higher strain hardening rate, which can be seen from the higher uniform strain with increased temperatures. This contribution is also caused by the DSA. However, this pattern does not apply to the fracture strain and at the temperature of 100 °C and 200 °C, the fracture strain shows a dramatic decrease, basically approaching the uniform strain. When the temperature comes to 300 °C, the fracture strain gets a large increase, with a similar extent of post-necking deformation to the room temperature again. This specific behavior is often referred to as the blue brittleness. It is also a phenomenon from the DSA effect, but a clear physical and quantitative explanation of it is still missing in the current literature. Its basic influence is that it strongly prohibits necking and promotes an early fracture.

To further investigate the influence of temperature on ductile fracture, tests with the fracture specimens were conducted and the results are shown in Fig. 5. As an example, the force–displacement curve of the NDB-R50 is shown here. The general trend in terms of the force response is similar to the uniaxial tensile test. However, it is also noticeable that the quantitative trend is not completely the same. The most distinct curve is the one at 300 °C. For the uniaxial tensile test, the strength of it is clearly larger than the one at room temperature, while for the NDB-R50, a lower force than the room temperature case is found at the beginning of deformation and in the end, it is only approaching the force at room temperature with very litter overshooting at the fracture point. This phenomenon clearly indicates that there is most likely a stress-state dependence of the DSA effect. It is shown for the case of NDB-R50 and for other stress states, a similar trend is also observed. Therefore, it is necessary for the modeling of the DSA effect, a stress-state dependence of it is formulated with respect to these experimental results.

In terms of the fracture displacement, a similar pattern is observed for the NDB-R50 to the uniaxial tensile test, as shown in Fig. 5 (b). It is easy to correlate because although there is a slight difference in terms of the stress state, these two geometries still share a generally similar stress state. However, when it is compared with other geometries, such as PS, CH, and SH, completely different behavior is found. The CH geometry somehow still shows a similar pattern, although its sensitivity to fracture is much less. The similarity can still be attributed to its similar stress states to NRB-R50 and uniaxial tensile tests. For both the PS and SH specimens, the Lode angle parameter for these tests is basically switched to the vicinity of zero, instead of one for the previous tests. A distinct character for these cases is that the increase of the fracture displacement at 300 °C is not as high as the previous tests. For the PS tests, an increase of the fracture displacement compared with 200 °C is still observed, but this value is already lower than the one at room temperature. For the case of SH, the fracture displacement just continues to decrease. It can be concluded that higher stress triaxiality actually promotes a higher fracture displacement at 300 °C. This also applies to the Lode angle parameter as one region, as the NDB-R50 features a higher stress triaxiality compared to the CH. However, it shall be noted that the Lode angle is also playing a role in this, as at a similar stress triaxiality, e.g. NDB-R50 and PS-R16, the fracture displacement stills shows differences. It can be also concluded that the higher Lode angle parameter tends to improve the fracture displacement at 300 °C.

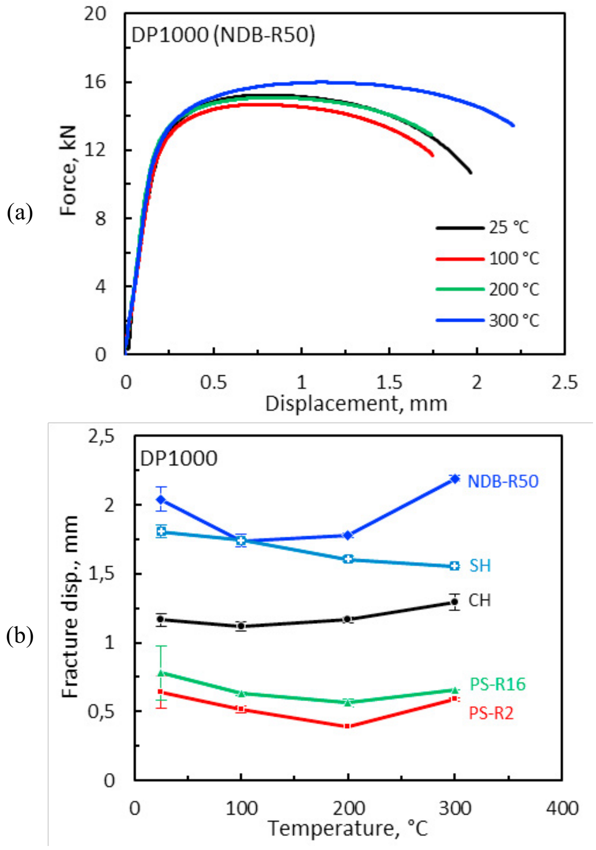

Fig. 5. (a) The force–displacement curves of the NDB-R50 samples of DP1000 at different temperatures; (b) the fracture displacement of various geometries of the DP1000 at different temperatures.

Temperatures below room temperature

Due to the existence of DSA, it is not clear from the previous study if the temperature is promoting ductile fracture for purely thermal softening effective materials or temperature ranges. Therefore, in this section, a temperature range from room temperature to -25 °C is designed, as this avoids the DSA and it ensures that the dominant fracture mode is still ductile fracture. In addition, it is also quite an effective temperature range for the automotive industry in terms of the environment variables. A cold-rolled DP600 steel sheet with a thickness of 1.5 mm is chosen for this study. All the samples from Fig. 1 were used for this study except for the PS specimens. The same deformation rate as DP1000 was also applied here to ensure quasi-static deformation.

The results from the SDB uniaxial tensile tests are shown in Fig. 6. The results are consistent with the X70 steels shown previously. With decreasing the deformation temperatures, although a rather small range, obvious stress hardening is seen, almost 100 MPa increase for the tensile strength from room temperature to -50 °C. In addition, both the uniform strain and the failure strain are increased as well with the temperature decrease. Although scatter is found for the failure strain, the trend of its increase with the temperature decrease is still clearly visible.

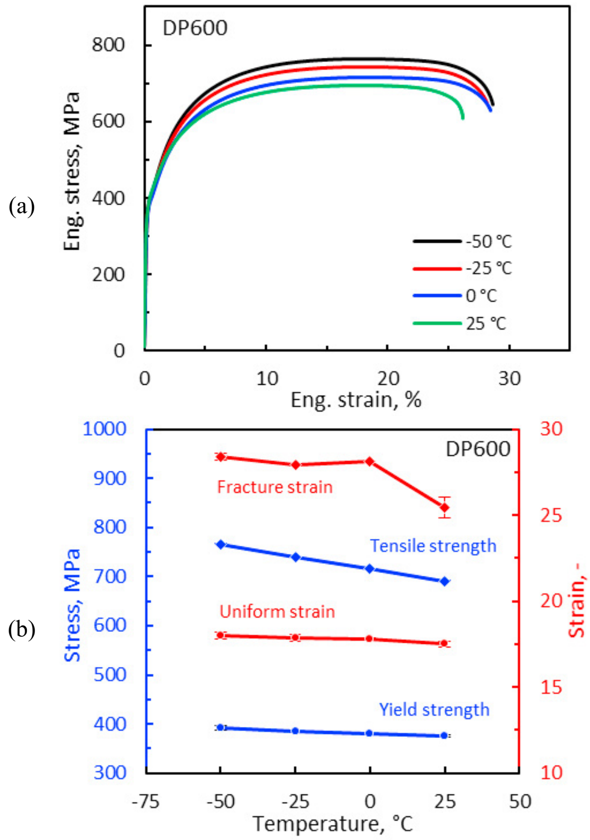

Fig. 6. (a) The engineering stress–strain curves of DP1000 along the rolling direction at different temperatures; (b) the temperature dependence of the main tensile properties.

In Fig. 7 (a), the force–displacement response of the NDB-R6 specimen is shown. Similar to the uniaxial tensile test, an increase of the force, as well as the fracture displacement, is observed. Due to the space limit, the results from other geometries are not shown, but similar behavior is found. Focusing on the fracture displacement for various geometries, as shown in Fig. 7 (b), it can be seen that a certain extent of stress state dependence also exists. Compared to the NDB-R50 and SH, the NDB-R6 shows clearly a stronger dependence on the temperature. This indicates that for the modeling, the fracture locus shall not only be scaled by temperature as the one proposed by Johnson and Cook [1], but the scaling factor shall also be stress-state dependent.

What has been shown in Fig. 7 is the fracture displacement. However, combining with the results of the force–displacement plot, it is easy to imagine that the entire fracture energy of the DP600 has an increasing trend with the decrease of the deformation temperature. This result is quite contradictory to the common sense from literature. In the ductile-to-brittle transition diagram, the energy is typically either not changing or decreasing significantly with respect to the decreased temperature. This study provides some findings that need further investigations to discover physical insights.

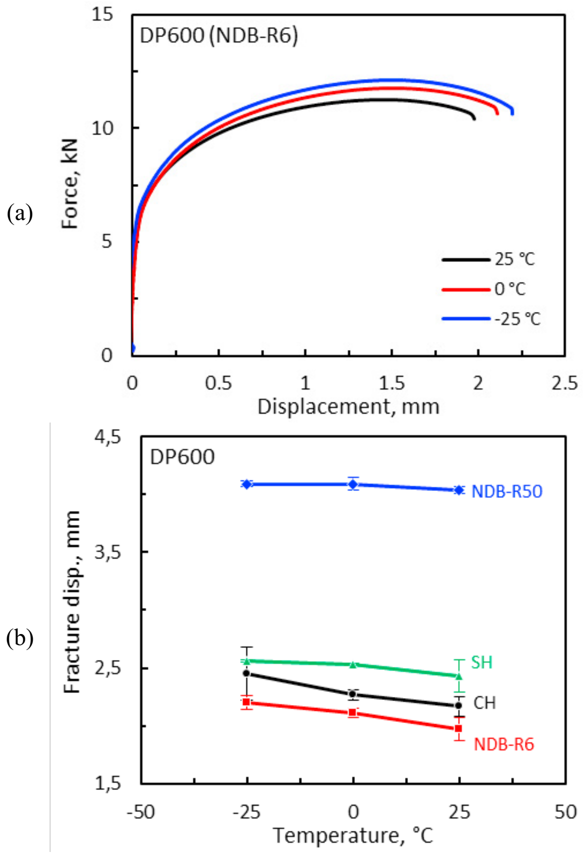

Fig. 7. ((a) The force–displacement curves of the NDB-R6 samples of DP600 at different temperatures; (b) the fracture displacement of various geometries of the DP600 at different temperatures.

4. Conclusions

With the test program in the study for two pipeline steels, it is concluded that the stress anisotropy can be either sensitive or insensitive to the temperatures. For steels with similar processing parameters, only a slight difference in chemical composition and thickness, the response can be distinct.

It is generally regarded that the temperature effect on ductile fracture shows a monotonically increasing pattern [1], and it is however discovered by the current investigation, under a quasi-static condition, two abnormal patterns appear for the commercially used dual-phase steels:

- With increasing temperature from room temperature to 300 °C, DP1000 steel shows a clear fracture dependence on temperature due to the presence of dynamic strain aging (DSA) and the fracture displacement shows a distinct decrease followed by an increase again for most of the stress states. The DSA effect on the ductile fracture owns a stress state dependency as well. The general pattern is that lower stress triaxiality seems to promote the blue brittleness range to a higher temperature.
- With decreasing the temperature from room temperature to -20 °C, the fracture displacement of DP600 steels shows a steady increasing trend. The conclusion is general for various stress states from shear to plane-strain tension, although a certain level of sensitivity of the stress state on the dependency exists.

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