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Material properties of cold-formed steel under subzero temperatures

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Abstract

Cold-formed steel (CFS) structures are becoming increasingly prominent in many construction scenarios because of its distinct advantages, which includes light-weight, easy and low cost for stacking, transportation, and construction. One of the potential application scenarios of CFS is the use under subzero temperature, including being utilized in circumpolar latitude area and functioning as storage racks in industrial freezers. Although recent researchers have made many efforts on knowing the material properties of CFS in ambient and high-temperature scenarios, the existing data on the performance of CFS under subzero temperature condition is still highly limited. In this study, from material prospective, a series of tensile coupon tests were designed and carried out on specimens made of CFS sheet with a nominal yield strength of 400 MPa at different temperatures from ambient to -60°C. Test results, including stress-strain relationships, elastic modulus, upper yield strength, yield strength, ultimate strength, and ductility, at different target temperature and their changing tendency along temperature change are thoroughly discussed. The test results from the experimental study provide essential data for developing better design guidelines for CFS structures, such as storage racks, in low temperature scenario.

1. Introduction

In recent years, because of the rapid climate change happening globally, a growing amount of human activities are taking place in circumpolar latitude areas, including Arctic, Antarctic, and the north edge of Canada, Russia, Greenland, and Northern Europe. The seafloors and subterranean lands of these areas contain abundant natural resources, including methane, petroleum, fishery resources, and rare earths that attract people for exploitation. Besides, these areas own unique geographic features and nourish special species which can be observed only in these area. The uniqueness brings an increasing number of scientists and tourists to live in these areas intermittently. The rapid expanding of these human activities objectively increases the demand on infrastructures in the circumpolar latitude areas. Nevertheless, due to the low temperature and relatively underdeveloped transportation conditions, conventional construction materials commonly used in low and middle latitude areas, like concrete and hot-rolled steel, are not appropriate options for the circumpolar latitude areas. On the other hand, the light gauge cold-formed steel (CFS) structures are more cost-efficient, in terms of time, money, and labor, for shipment and construction given its thin-walled geometry under the limitations in these areas. Similarly, owing to these advantages of CFS, it also functions as storage racks in industrial freezers under subzero temperatures. Therefore, as a potential and promising construction material for subzero temperature scenarios, including in industrial freezers and circumpolar latitude areas, the material properties of the CFS under low temperature condition are desired to be understood.

Although this topic is emerging in recent years considering the rapid development of global climate, some researchers have conducted studies on this topic. Filiatrault and Holleran [1] investigated the material properties of reinforcing steel bars made of CSA G30.16 reinforcing steel with a nominal yield strength of 400 MPa at 20°C, -20°C, and -40°C. The focus of their study was the combined impact on material properties resulting from loading strain rate and low temperature. It was found that the yield strength and the ultimate strength increased when the test temperature decreased, while the elastic modulus and the ultimate strain did not change significantly. Yan et al [2] studied the material properties of hot-rolled mild steel and hot-rolled high strength steel at different temperatures from ambient to -80°C. They found the elastic modulus, yield strength, and ultimate strength increased when the test temperature decreased. Additionally, this trend was more obvious for average mild steel than the high-strength steel. Although there was a subtle trend that the fracture strain increased when test

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temperature decreased, the authors thought their correlation was too weak to make any conclusion on the low temperature effect. Yan and Xie [3] conducted experiments on hot-rolled steel bars under cryogenic temperatures from ambient to -165°C. Steel reinforcement bars made of HRB335, HRB400, and special low temperature steel (SLTS) were studied. From the results, the variation of elastic modulus did not show strong relationship when temperature decreased. Both the yield strength and the ultimate strength increased when the temperatures decreased. The increments of both strengths for three steels were from 14% to 23% when temperature decreased from ambient to -165°C. The ductility for all steels decreased rapidly when temperature decreased. Also, it was found -80°C was the threshold that the steel failure mode switched from ductile to brittle. Azhari et al [4] led a research on the material properties of Grade 1200 CFS at -40°C and -80°C. The results showed that various strengths discussed in the study increased up to 8% when tested at -40°C and increased up to 12% at -80°C. For the ductility, at both sub-zero temperatures, the elongation decreased significantly, which were illustrated by various methods. Rokilan and Mahendran [5] studied the material properties of G300 and G550 CFS specimens with different thicknesses at various temperatures from ambient down to -70°C. The results showed that accompanying the decrease of test temperature, the yield strength, upper yield strength, ultimate strength, and 2% strain stress increased. For fracture strains of most cases, results showed the elongation did not change substantially down to -50°C, while reduced considerably starting from -70°C.

The available data in existing literature for the material properties of CFS at subzero temperatures is limited. There are a large amount of data vacancies in terms of strength, thickness, and steel type for CFS under this topic. This paper introduces an experimental study on CFS at subzero temperature and it aims at providing more data for the development of this topic. This study uses specimens made of 1.8 mm thick cold-formed low-carbon mild steel with a nominal yield strength of 400 MPa. A series of tests is carried out from ambient condition to -60°C. The stress-strain behaviors, elastic modulus, essential strengths, and ductility of the steel at different test temperatures are presented and discussed in detail.

2. Experimental Study

2.1 Test material and specimen

The steel being studied in this paper was manufactured by Steel Dynamics, Inc. The uncoated steel sheet had a nominal thickness of 1.80 mm and a nominal yield strength of 400 MPa. The chemical composition of the steel sheet is provided in Table 1. The nominal dimension of the tensile specimen was designed per ASTM E8 [6] as shown in Figure 1. The nominal length of the reduced parallel section was selected as 57.15 mm (2.25 inch), which meets the minimum length allowed by ASTM E8. The steel sheet had obvious curvature along its rolling direction, therefore the specimens were cut along the transverse direction of the steel sheet to ensure the specimens were generally flat along specimen length. Some researchers studied the influence on material properties of CFS from different directions along the steel sheet, for example [7], and no significant difference of strengths and elongation were observed. The specimens are labeled as *LTXX-Y* hereinafter, where *LT* stands low temperature test, *XX* is the target temperature for the test, and *Y* is the number of the test. For example, *LT-30-1* is the first test at -30°C. 20°C is regarded as the temperature for the ambient case and is denoted as “A” in the specimen label. The target temperatures for the tests include ambient (20°C or 68°F), 0°C (32°F), -20°C (-4°F), -30°C (-22°F), -40°C (-40°F), and -60°C (-76°F). One test for each target temperature was carried out, while one additional test for each of the ambient case and the -20°C case were performed to guarantee the test was repeatable. Therefore, a total of 8 tensile coupon tests were conducted. Before the tests, the actual dimensions of each specimen was measured. The width of the reduced parallel section was measured by a digital caliper and the thickness of the specimen was measured by a digital micrometer. The cross section area of the reduced parallel section for each specimen was then calculated as the product of the measured width and thickness, and was used in engineering stress calculation when plotting the stress-strain curves in the data-processing stage.

Table 1: Chemical composition of the steel sheet

C	Mn	P	S	Si	Al	Cu
0.04	0.65	0.015	0.003	0.02	0.025	0.09
Ni	Cr	Mo	Sn	N	V	Nb
0.03	0.07	0.01	0.005	0.008	0.002	0.017
Ti	B	Ca	Pb	Zr		
0.001	0.000	0.002	0.000	0.0006		

*Values are in mass percentage.

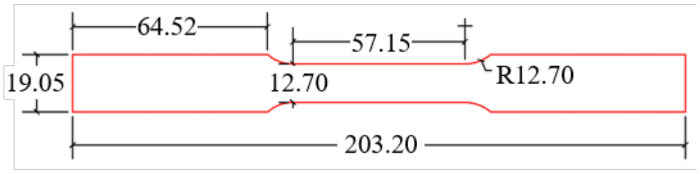

Figure 1: Nominal dimension of the tensile specimen (unit: mm)

2.2 Test equipment and process

The test was carried out in the Manufacturing and Mechanics Lab. The cooling process of the specimen was performed in ADMET F-280DT Environmental Test Chamber using liquid nitrogen. The chamber is capable to provide stable subzero temperature condition down to -80°C. The cooling process

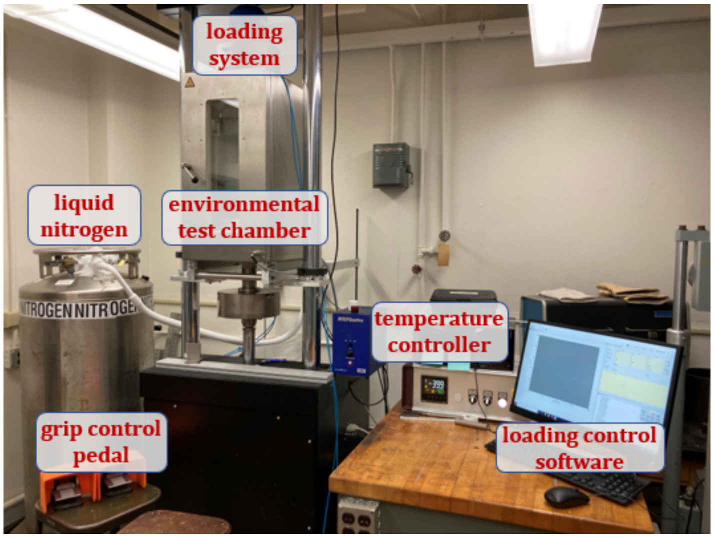

Figure 2: Test apparatus setup in Ductility Lab at UW-Madison

was controlled by a Omron temperature controller. The tensile test was conducted by ADMET eXpert 1600 Series loading system with a capacity of 100 kN. The process of the tensile test was controlled by ADMET MTESTQuattro Material Testing Software. A photo of the experiment setup is shown in Figure 2.The applied load on each specimen was directly measured by the loading system and the strain on the reduced parallel section of the specimen was measured by a customized low-temperature resistant extensometer. The original extensometer was MTS Model 632.128-20 with a gauge length of 25.4 mm (1 inch) and a maximum displacement range of 12.7 mm (0.5 inch), therefore it originally had a maximum measurement range of 50%. A customized 1-inch extension was fixed onto the original model. This customization was designed to guarantee the fracture of the specimen with a 57.15 mm (2.25 inch) gauge length would generally be captured by the extensometer if it had a 50.8 mm (2 inch) gauge length. However, because the extension was fixed and the displacement range was still 12.7 mm, the maximum measurement range of the extensometer was changed to 25%.

The test process was divided into two stages. The first stage was to obtain the stress-strain relationship of the steel under tension load at target subzero temperature condition. At the beginning of the test, the extensometer was fixed at the center of the specimen. The specimen was clamped by the bottom grip of the loading system, while the other end of the specimen was free to shrink during the cooling process due to the thermal change. Then the cooling process started at a constant cooling rate of -5°C/min until achieving the target subzero temperature. An additional 20 min conditioning was waited after the temperature stabilized to ensure a uniform distribution of the target temperature within the specimen. The free end of the specimen was then clamped by the top grip of the loading system, and tension load was applied on the specimen until the specimen fractured or the extensometer achieved the 25% limit. If the specimen fractured when the extensometer reading was smaller than the 25% limit, then the test process was fully accomplished; otherwise, there was a second stage of the test to measure the ductility of the steel. Before the test, extra-thin straight lines perpendicular to specimen length were drawn by Nalgene Cryoware marker, whose maker was able to not fade under ultra-low temperatures. The lines were distributed on the entire reduced parallel section with a uniform spacing of 2.5 mm and there was a total of 22 grids for each specimen. When the extensometer reading achieved its limit, the loading process was automatically stopped by a predefined program to protect the extensometer. In this case, the extensometer was quickly detached from the specimen and the chamber was cooled and conditioned again in a same manner as the first stage. After a 20 min conditioning, the tension load was applied to the specimen until fracture. The spacing between grids were measured by the digital caliper to determine the local, uniform, and overall elongation for the steel specimen at the target temperature.

3. Discussion on test results

3.1 Stress-strain relationships

The stress-strain relationship up to a strain limit of 25% at target temperatures is shown in Figure 3. For all stress-strain relationship, they show a typical sharp yielding mode, which can be illustrated by Figure 4. The first part of the curve is generally linear from the origin to the upper yield strength. Then the curve drops from the upper yield strength, usually not perfectly elastic, to some certain point and experiences a yield plateau, where stress does not change clearly but has some degree of fluctuation. When the plateau ends, the stress experiences strain hardening and increases nonlinearly until the ultimate, and then decreases nonlinearly until fracture. For tests at different target temperatures, the strength increases at 0°C compared with the ambient case; while the strength at -20°C and -30°C are close to the strength at 0°C; the strength at -40°C is higher than the strength at -30°C; the strength at -60°C is generally the same as the strength at -40°C. The curves for all different target temperatures achieve the upper yield strength, the start of the yield plateau, and the start of the nonlinear strain hardening stage at similar strain levels. The curve for -30°C has a more rapid strain softening rate than that of 0°C and -20°C cases after passing the ultimate point; similarly, the curve for -60°C also has more rapid strain softening rate than that of -40°C after the ultimate. All stress-strain curves from the test using the extensometer do not achieve the fracture, so the ductility of the steel need to be evaluated by grid method described in Section 3.4.

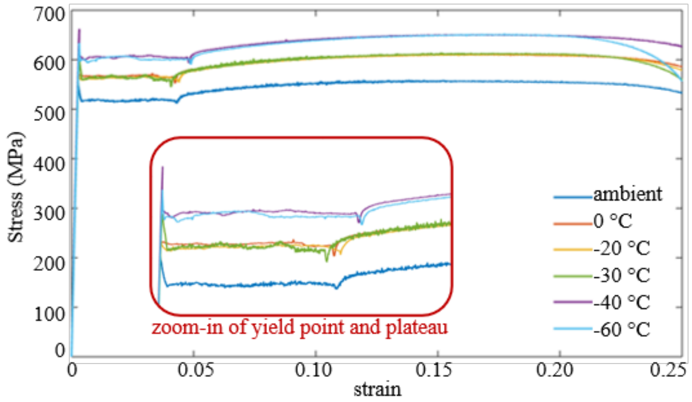

Figure 3: Representative stress-strain relationship up to 25% total strain at target subzero temperatures

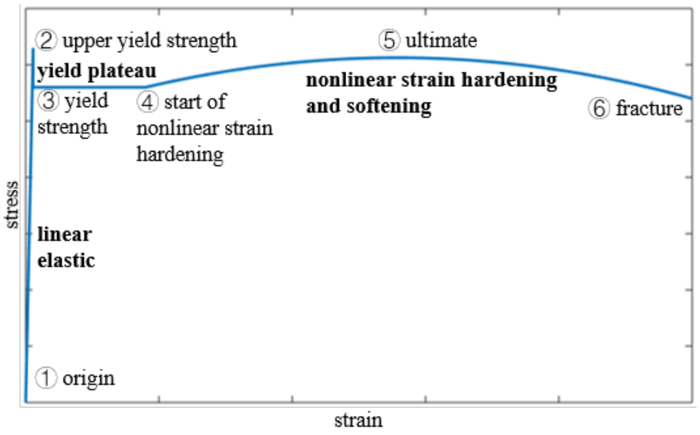

Figure 4: Schematic diagram of stress-strain relationship with sharp yielding

Table 2: Elastic modulus and strengths of specimens

specimen	E GPa	σ_u MPa	σ_{yu} MPa	$\sigma_{0.2}$ MPa	$\sigma_{2.0}$ MPa
LT-A-1	226.6	559.1	555.9	514.4	516.2
LT-A-2	255.1	549.4	547.3	507.7	505.1
LT-0-1	218.0	611.1	591.2	566.8	567.4
LT-20-1	215.8	611.3	599.6	559.4	562.7
LT-20-2	231.6	621.8	626.0	575.7	576.0
LT-30-1	207.9	614.5	603.8	559.5	564.2
LT-40-1	220.9	651.2	662.3	601.7	605.9
LT-60-1	211.3	652.7	633.7	599.9	606.3

3.2 Elastic modulus

Elastic modulus is one of the most important material properties both in structural design and simulation analysis. Theoretically, it can be determined as the slope of the linear part between the origin and the upper yield strength. Nevertheless, in practice, not all data points within this range are guaranteed in the same line, particularly around the beginning and the end of this range. To determine accurate elastic modulus, alternative methods were adopted in research [8]. In this paper, the slope of linear regression in the region between two points with stresses of 20% and 45% nominal yield strength (400 MPa for the ambient case) was calculated as elastic modulus. For cases at subzero temperatures, the nominal yield strength was amplified by the ratio between its ultimate strength and the ultimate strength at ambient. The linear regression was achieved by using first order polynomial curve fitting function in Matlab and for any case R^2 is larger than 0.9996, which proves the selected data range for elastic modulus calculation is strictly linear and therefore the calculation is accurate. The calculated elastic modulus at each target temperature is shown in Table 2. The results show the elastic modulus at ambient is larger than the case at subzero temperatures, while the elastic modulus at different subzero temperatures are close to each other.

3.3 Strengths

Multiple strengths that are essential in depicting the material properties of the steel at target subzero temperatures are defined and extracted from the corresponding stress-strain curves. These strengths include the upper yield strength, the yield strength, the stress at strain of 2.0%, and the ultimate strength. In theory, the upper yield strength σ_{yu} defines the end of the linear behavior before the yielding of the steel and it is mathematically defined from the stress-strain curve as the maximum stress before the appearance of the yield plateau. For stress-strain curves with sharp yielding, the yield strength is commonly defined as the stress of the yield plateau. However, for many cases from actual experiments, the stress fluctuation along the yield plateau is not negligible. For example, in Figure 3, the stress fluctuation along the yield plateau for test at -30°C is up to 14 MPa. Therefore,

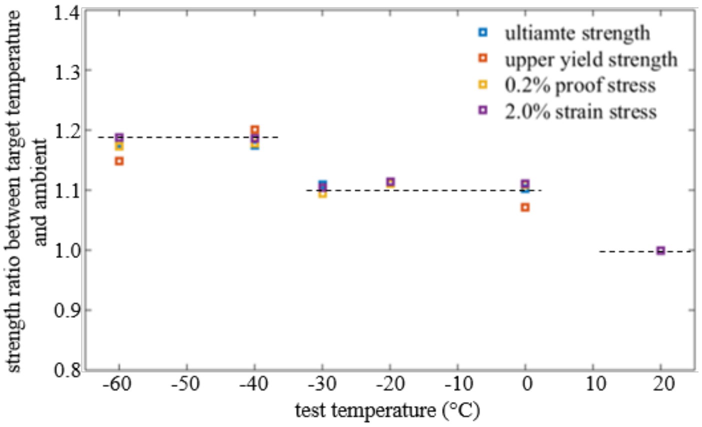

Figure 5: Ratio between strength at test temperature and at ambient

the 0.2% proof stress (or 0.2% offset yield strength) $\sigma_{0.2}$ (the stress that will result in 0.2% plastic strain) is used to calculate the yield strength. However, one characteristic of $\sigma_{0.2}$ is it depends on the elastic modulus E. To eliminate any potential inaccuracy of the calculation on elastic modulus E, the stress at 2.0% strain $\sigma_{2.0}$, which is independent on the elastic modulus, is also provided. $\sigma_{2.0}$ is widely used in the fire research area and has been adopted into the subzero studies (e.g. [5]) as a compensation of $\sigma_{0.2}$. The ultimate strength σ_u shows the upper limit of the material strength and it was captured as the maximum stress at the strain hardening and strain softening phase.

A summary of the strengths is listed in Table 2. All these different strengths show similar tendency when the temperature changes. When temperature changes from ambient to 0°C, the strengths increase around 10%. The strengths do not change obviously from 0°C to -20°C or -30°C, where the strength changes are all within 4% and mostly within 2%. The strengths increase around 8% when the temperature decreases from -30°C to -40°C. The strengths are relatively stable when the temperature changes from -40°C to -60°C. Figure 5 shows the ratio between each strength at test temperature and at ambient as well as its changing tendency along temperature change.

3.4 Ductility

As discussed in Section 2.2, due to the range limit of the extensometer, the maximum reading of the extensometer stopped at 25% and the elongation was therefore not measured by the extensometer. Rather, uniform distributed grids with a spacing of 2.5 mm between each two adjacent grids were drawn before the test and designed for the elongation measurement. After the experiment when the specimen fractures, the spacing between specific grids provides elongations in various gauge lengths, instead of the only gauge length of the extensometer. The method adopted in this paper is introduced by [9], which adopts the same ideas as AISI S903 [10], as shown in Figure 6. $\varepsilon_{7.5}$ and $\varepsilon_{12.5}$ are the strain within 3 and 5 grids centered at the fracture, respectively. Both are regarded as local elongation, which shows the largest displacement during the fracture, and are required to be not smaller than 20%. ε_{25} and ε_{50} are the strain within 10 and 20 grids centered at the fracture, respectively. ε_{50} is regarded as overall elongation and ε_{25} is regarded as adjusted overall elongation, both are required to be not smaller than 10%. $\varepsilon_{37.5}$ is the strain outside the 5 grids centered at the fracture and it mathematically equals to $\varepsilon_{50} - \varepsilon_{12.5}$. $\varepsilon_{37.5}$ is regarded as uniform elongation and it is required to be not less than 3%. A summary of the measurement for each discussed elongation at different test temperature is shown in Table 3 and Figure 7. The local elongation $\varepsilon_{7.5}$ has a clear drop from ambient to 0°C case, then keeps relatively stable down to -60°C. The local elongation $\varepsilon_{12.5}$, the adjusted overall elongation ε_{25}, and the overall elongation ε_{50} has a obvious drop at -30°C; while at all other test temperatures, these elongations are close. The uniform elongation $\varepsilon_{37.5}$ is similar for all different test temperatures. Generally, it is observed that the change of ductility of the specimens being tested due to the change of temperature is very small and the material does not become less ductile when it is used at subzero temperature down to -60°C. A photo comparing the elongation of specimens being tested at different temperatures when they fractured, which is shown in Figure 8, also supports this observation.

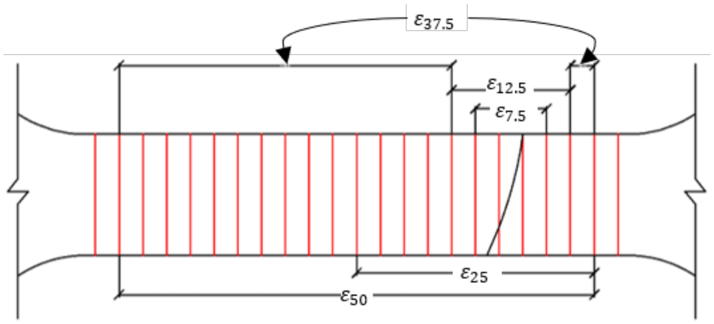

Figure 6: Definition of elongation with different gauge lengths (ref.: [9])

Table 3: Elongation measurements of specimens at different target temperatures

	$\varepsilon_{7.5}$	$\varepsilon_{12.5}$	ε_{25}	ε_{50}	$\varepsilon_{37.5}$
20°C	75.07	57.76	42.40	31.04	22.13
0°C	62.13	50.96	36.00	26.90	18.88
-20°C	60.93	55.44	38.52	27.22	17.81
-30°C	63.60	44.16	32.16	26.04	20.00
-40°C	60.67	54.32	39.92	30.26	22.24
-60°C	65.20	53.12	35.36	26.98	18.27

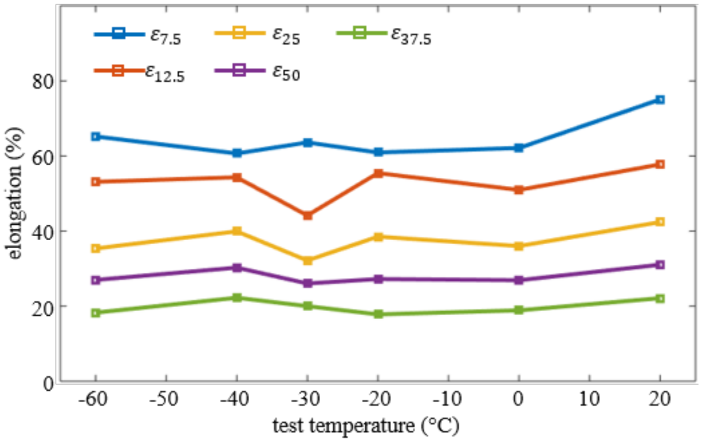

Figure 7: Elongation measurements with different gauge length along test temperature

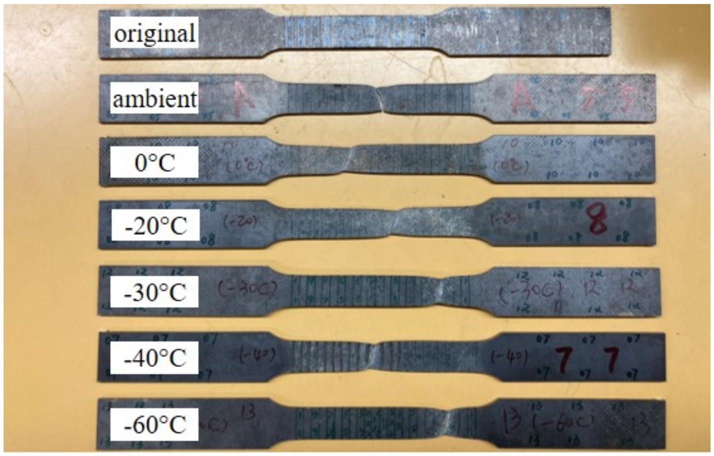

Figure 8: Photo on specimens at fracture

4. Conclusions

This paper introduces an experimental study on material properties of cold-formed steel with nominal yield strength of 400 MPa at subzero temperatures. The stress-strain behaviors measured by low-temperature resistant extensometer are discussed. For different test temperatures, the behaviors are similar and all had clear yield point and yield plateau. Important strengths, including upper yield strength, yield strength defined by proof stress or total strain stress, and ultimate strength are discussed. The strengths have similar behaviors along the temperature change. The strengths increase from ambient to 0°C and then become stable down to -30°C; the strengths increase again from -30°C to -40°C and does not change much from -40°C to -60°C. The ductility of the material is illustrated using the grid method to measure elongation with different gauge lengths. The results show the elongation only fluctuates within a reasonable range. Compared with the corresponding ambient cases, the maximum deterioration of specific elongation is around 23%, while deterioration of most cases are between 4% and 20%. Therefore, the ductility does not deteriorate significantly when the steel is used at subzero temperature down to -60°C.

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