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EXPERIMENTAL INVESTIGATION ON FORMING LIMIT CURVE AT ELEVATED TEMPERATURE THROUGH DOME AND BIAXIAL TEST

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ABSTRACT

The characteristics of metal and materials are very important to design any component so that it should not fail in the life of the service. The properties of the materials are also an important consideration while setting the manufacturing parameters which deforms the raw material to give the design shape without providing any defect or fracture. For centuries the commonly used method to characterize the material is the traditional uniaxial tension test. The standard has been created for this test by American Standard for Testing Materials (ASTM) – E8. This specimen is traditionally been used to test the materials and extract the properties needed for designing and manufacturing. It should be noted that the uniaxial tension test uses one axis to test the material i.e., the material is pulled in one direction to extract the properties. The data acquired from this test found enough for manufacturing operations of simple forming where one axis stretching is dominant. Recently a sudden increase in the usage of automotive vehicles results in sudden increases in fuel consumption which results in an increase in air pollution. To cope up with this challenge federal government is implying the stricter environmental regulation to decrease air pollution. To save from the environmental regulation penalty vehicle industry is researching innovation which would reduce vehicle weight and decrease fuel consumption. Thus, the innovation related to light-weighting is not only an option anymore but became a mandatory necessity to decrease fuel consumption. To achieve this target, the industry has been looking at fabricating components from high strength to ultra-high strength steels or lightweight materials. This need is driven by the requirement of 54 miles per gallon by 2025. In addition, the complexity in design increased where multiple individual parts are eliminated. This integrated complex part needs the complex manufacturing forming operation as well as the process like warm or hot forming for maximum formability. The complex forming process will induce the multi-axial stress states in the part, which is found difficult to predict using conventional tools like tension test material characterization. In many pieces of literature limiting dome height and bulge tests were suggested analyzing these multi-axial stress states. However, these tests limit the possibilities of applying multi-axial loading and resulting stress patterns due to contact surfaces. Thus, a test machine called biaxial test is devised which would provide the capability to test the specimen in multi-axial stress states with varying load. In this paper, two processes, limiting dome test and biaxial test were experimented to plot the forming limit curve. The forming limit curve serves the tool for the design of die for manufacturing operation. For experiments, the cruciform test specimens were used in both limiting dome test and biaxial test and tested at elevated temperatures. The forming limit curve from both tests was plotted and compared. In addition, the strain path, forming, and formability was investigated and the difference between the tests was provided.

Keywords: Biaxial Test, Dome Test, Forming Limit Curve, Elevated Temperature, Sheet Metal Forming, Pressurization

INTRODUCTION

From decades automobile and aerospace industries are dependent on millions and millions of vehicle metal parts through conventional metal working technology and is still showing a continuous increase in demand of these manufacturing processes. These millions of metal parts which goes in the assembly of the vehicle shows the increase in the vehicle weight and brings the concerns in-relation to the fuel economy as well as the financial benefits. On other side the federal government forces the restrictions on the air pollution for better environment. These conditions have left no choice to these profit-making companies to come up with the novel manufacturing as well as the material innovation to save any penalty over the air pollution. To increase the fuel efficiency and reduce the air pollution, the vehicle needs to be lower weight. Two possible ways can be considered to reduce the weight of the vehicle: first use the same dense material but reduce the gage by using the higher strength material or second use the lower dense material. In any case, the question would be how to completely use the material. The answer could be understanding the material limits, so to use the material till that limit. Thus, the material characteristics is an important tool for finalizing the design.

Material deformation when taking the shape of any design, it goes through various deformation modes. To understand the mechanics and deformation modes, forming limit curve or strains of that material would be an important tool to predict the failure or safe, so to take an appropriate action to stop the failure or completely use the material. The forming limit diagram or curve (FLC) is the graph of major and minor strains of a section of the sheet metal which can be focused section or critical area. This FLC and the deformation path provides the indication on how, when and where the material will reach to failure and prevention technique to stop the deformation. Keeler [1] was the one who proposed the concept of forming limit curve on the major and minor axis of strain i.e., strain plane. This was further experimented on sheet metal during various stamping modes [2]. The FLC provides the curve between the uniaxial strain to equal biaxial strain mode [3]. It was identified in these literature [4-13] that this envelope is very sensitive to these parameters a) planar and normal anisotropy value "r-values", b) strain hardening exponent "n-value", c) strain rate "ε/sec-value", d) size of grain at start of deformation, e) prestrain, f) tool geometry, g) coefficient of friction between sheet metal and tool, and h) blank holding force. Traditionally hemispherical dome test was used to identify the limits of the material in various deformation modes. However, in this method the punch was in contact with the sheet metal and deformation plane was also not remained on the plane. This contact condition can come in the form of either pressure or friction [14-15]. Friction is an unwanted variable that can cause variations during testing and data collection [16-18]. Pressure is the other contact condition that can cause the sample to fail at higher forces or time because of how the pressure makes the material behave while under stress [19].

Due to these challenges a new testing method called biaxial test was devised, which can deform the material in various modes similar to traditional method with elimination of contact conditions. For this study the experiments were performed on the National Science Foundation funded Penn State Behrend's newly developed high-capacity biaxial machine at two elevated temperature. Also, tests were performed on hemispherical dome test at elevated temperature. To fill the gap data were taken from the literature and compared. The results were analyzed between both tests and discussed.

MATERIAL

The material considered for this study is aluminum alloy AA5083. This is magnesium-based strain hardening aluminum alloy. The material was annealed at 500°C for 5 minutes due to lack of ductility at room temperature which doesn't provide enough deformation to measure the strains before failure [20-21]. The material was tested in a MTS machine with a pulling speed of 5mm/min in rolling direction and Figure 1 provides the true stress-strain curve along with the fitted curve using Holloman-Ludwik equation also called as power law to determine the strength coefficient "K" and strain hardening exponent "n". The mechanical properties of this annealed AA5083 material are given in Table 1.

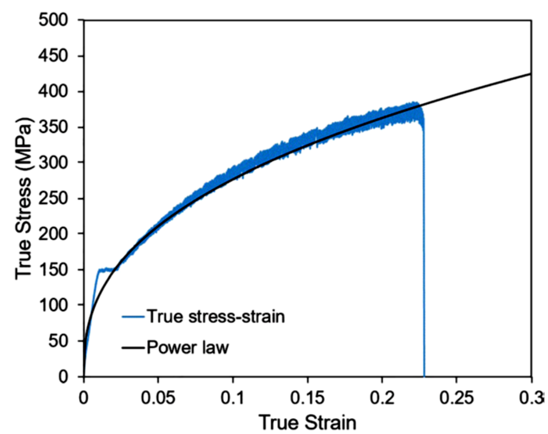


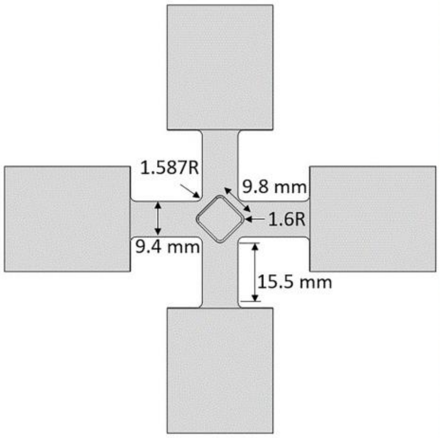
FIGURE 1-Aluminum alloy AA5083 true stress-strain curve after annealing at 500°C for 5 minutes [20-21]

TABLE 1-Aluminum alloy AA5083 true stress-strain curve after annealing at 500°C for 5 minutes [20-21]

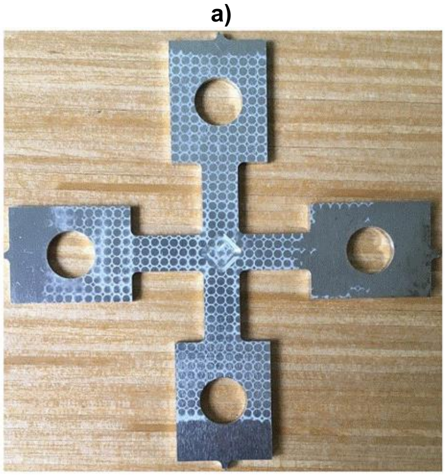
Engineering Yield Stress (MPa)	Engineering Tensile Stress (MPa)	Elongation (%)	K (MPa)	n
150	290	26	680	0.39

EXPERIMENTAL PROCEDURE

To analyze the differences between the material forming limit curve at elevated temperature (250°C and 450°C) from hemispherical dome test and biaxial test, tests were conducted with both test set-up. The specimen geometry utilized for this work is the cruciform geometry as shown in Figure 2a. Figure 2a provides the detail geometry of the specimen. To concentrate the strain at the center of the specimen, a diamond section with reduce thickness was used. The material stock thickness used was 2mm. The center diamond section (gage area) was machined from front as well as back so that the center diamond thickness of 0.762mm was remained. This thickness is much lower than the material stock thickness of 2mm and during test, the strain concentrates in this gage area and material fail in this section. To determine the induced strain during deformation, circle of 2.54mm diameter were etched with electrochemical etching process. The electrochemical etched specimen is shown in Figure 2b.



a)



b)

FIGURE 2-Biaxial cruciform specimen a) specimen dimension, and b) electrochemical etched specimen [21]

BIAXIAL TEST

Figure 3 shows the National Science Foundation funded machine at Penn State Behrend. This machine was used to test the cruciform specimens at 250ºC and 450ºC. The machine consists of two axes; horizontal and vertical which independently move in tension as well as in compression. With the help of four holes in the specimen, the specimen is mounted in the four tabs in the vertical as well as the horizontal axis. For test at elevated temperature, the biaxial built furnace at Penn State Behrend was used (not shown in the image). The furnace stands on the railing and goes back when the furnace is not required for testing and can bring in front if the elevated temperature test is needed. To accommodate the four jaws to hold the specimen, the furnace has four open access two on side walls for horizontal axis and two on top and bottom wall for vertical axis. To reduce the heat loss, after the jaws were inserted, the furnace access openings were covered by the insulated material provided by the Onex, Inc furnace company at Erie, PA. Once the specimen was mounted the front door of furnace was closed. The vertical and horizontal axis were manually moved in tension so that a 133N of tensile preload was applied on the specimen to make sure that the pins are in complete contact with the arm holes. Then the furnace was heated to a desired temperature. Due to heat the specimen expands and the increase in force was noted, which was then manually bring back to 133N. Once the furnace is set to desired test temperature, the loading was started by applying the desired speed of each axis. The speed of each axis is shown in Table 2 depending on which deformation mode the specimen was tested. Five deformation modes were tested: uniaxial, between uniaxial as plane-strain, plane-strain, between plane-strain and equi-biaxial, and equi-biaxial. At each condition 2-3 tests were performed.

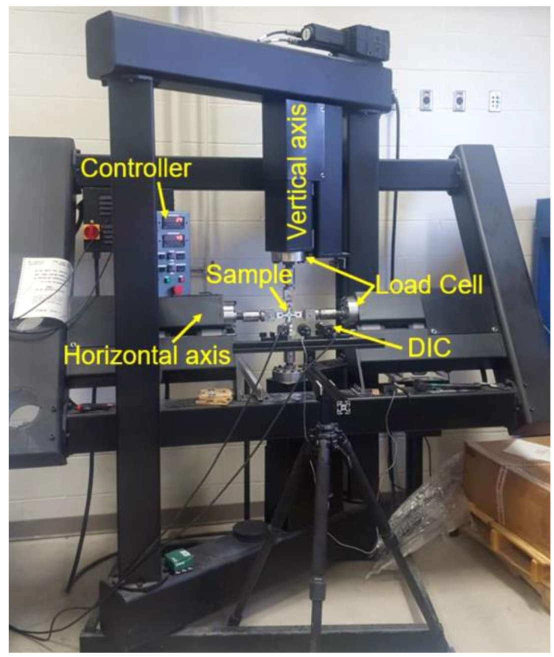


FIGURE 3-Biaxial test machine with cruciform sample mount [21]

TABLE 2-Biaxial specimen test condition to capture uniaxial to equi-biaxial deformation modes

Strain mode	Vertical axis pulling speed (mm/min)	Horizontal axis pulling speed (mm/min)
Uniaxial	5	Free (Specimen not mounted on this axis)
Between Uniaxial and Plane strain	5	-1
Plane-strain	5	0
Between Plane and equibiaxial strain	5	2.6
Equibiaxial strain	5	5

DOME TEST

Hemispherical dome test was utilized to determine the forming limit strains. This test was traditionally used to determine the formability and forming limit strain when biaxial machine was not common. The specimen utilized in this test are various geometrical specimens to induce various deformation modes [21]]. One of the specimens is shown in the test set-up (Figure 4). Figure 4 shows the hemispherical dome test to deform the specimen. In this test the specimen was mounted between the blank and the die. The blank and die has a lock bead which prevents the material sliding during deformation. The hemispherical punch is then displaced down to deform the specimen. In this test as the rigid hemispherical dome punch contacts the punch, a lubrication was supposed to used to reduce the friction and reduce the effect of friction on the forming limit results. The electrochemical etched side was placed towards the die side so that it would be easy to measure the strains. For test at elevated temperature, the dome test set-up was placed in the MTS machine and MTS environmental chamber was used. The test set-up is shown in [22]. The punch speed was kept constant of 5mm/min. For this work only cruciform specimens were used. To capture the uniaxial, and plane-strain modes, the arms of the specimen were chopped to induce the strain (Figure 5). The red section chop line shows for uniaxial specimen and yellow line shows for plane-strain sample. At each condition 2-3 tests were performed.

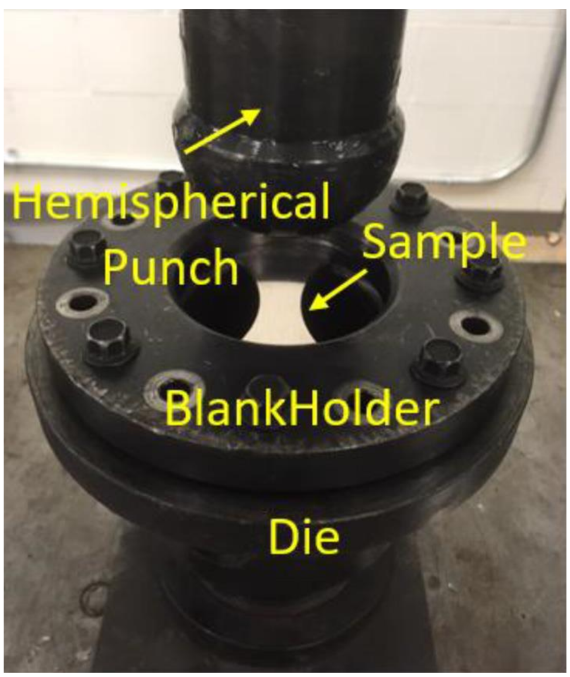


FIGURE 4-Hemispherical dome test for conventional as well as biaxial specimen

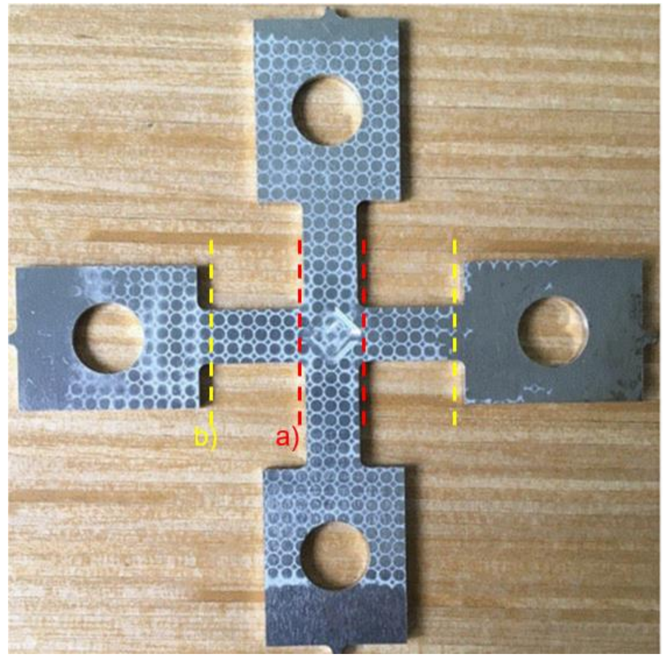


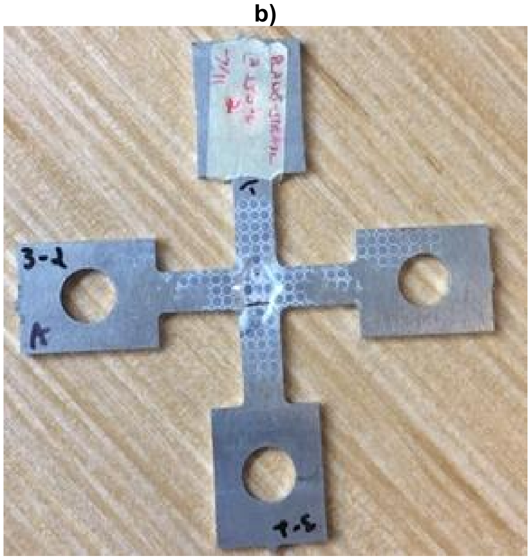
FIGURE 5-Cruciform specimen with chopped arm sections to capture a) uniaxial, and b) plain strain mode with dome test set-up

RESULTS AND DISCUSSION

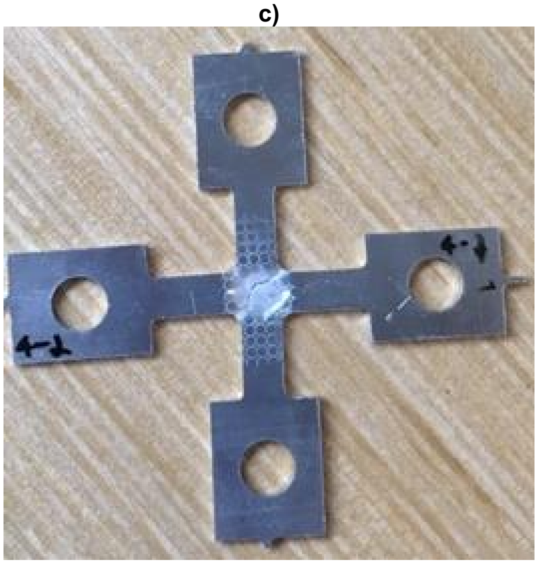
Overall in this work Biaxial test machine was used to measure the forming limit curve at two elevated temperature i.e., 250ºC and 450ºC. Hemispherical dome test was used to measure the forming limit curve at 250ºC. Biaxial test and hemispherical dome test at room temperature forming limit curve was taken from this literature [20-21]. Hemispherical dome test with conventional specimen at elevated temperature at 250ºC and 450ºC forming limit curves were taken from this literature [22].

a)

b)



c)



d)

e)

FIGURE 6-Neck or failed cruciform specimens tested with biaxial machine at 250°C

Figure 6a-e shows the neck or failed specimen at uniaxial, between uniaxial and plane-strain, plane-strain, between plane-strain and equi-biaxial, and equi-biaxial deformation mode. It can be seen that all specimens were failed or necked at the diamond section and thus failure strain can be measured. If the circle was necked, then measurements of major and minor strains were taken and named as “neck circle”. If the circle shows the crack, then strain measurements were taken and named as “failed circles”. Then measurements of strains of some safe circles near to the neck or failed circles were taken and named as “safe circles”. It can be seen that how the diamond deformed in single direction in uniaxial and the deformation modes changed and becomes bigger diamond for equi-biaxial strain mode.

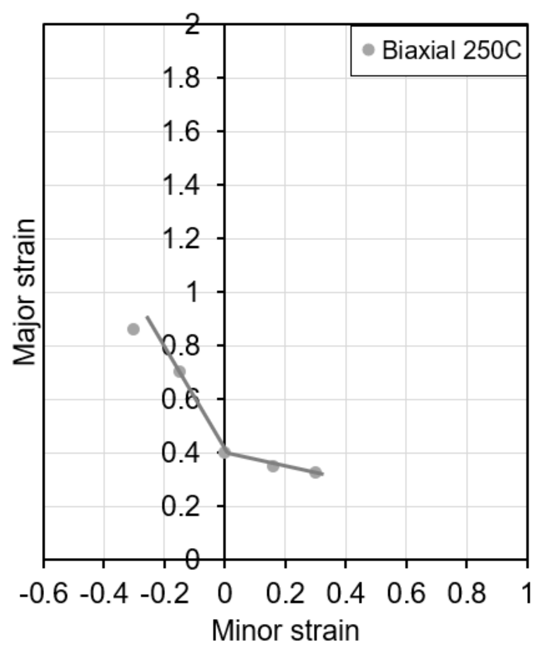


FIGURE 7-Forming limit strain points and fitted line of cruciform specimens tested with biaxial machine at 250°C

The deformed circle measurements were then plotted on the major and minor strain plot and then a best fit line was manually drawn as shown in Figure 7. It can be seen that the plane strain deformation strain or FLD_0 (Forming limit diagram at plain strain) is approximately 0.4 strain value. It can also be observed that the plain-strain deformation strain is not the lowest and keep lowering down for equibiaxial deformation mode.

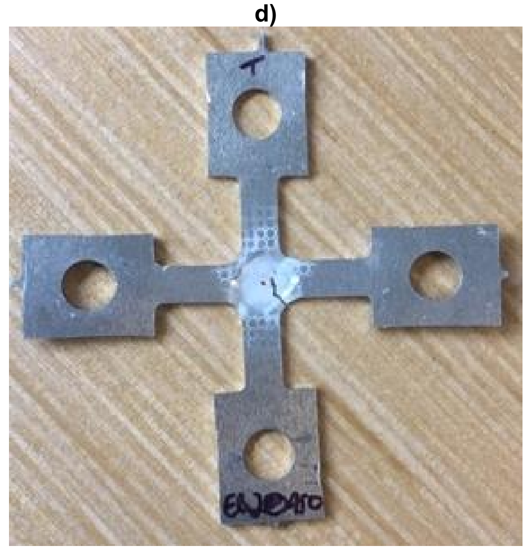
Figure 8a-e shows the neck or failed specimen in five strain deformation modes with biaxial test at 450°C.As compared to the 250°C, the 450°C specimen deformation is much higher after seeing the diamond deformation in the specimens. The material becomes super-plastic at 450°C. The fractured specimens at deformation modes of between plane-strain and equi-biaxial, and equi-biaxial specimen thickness was much lower like an aluminum foil. Again, the deformed circles in the diamond region were measured to plot the strains.

a)

b)

c)

d)



e)

FIGURE 8-Neck or failed cruciform specimens tested with biaxial machine at 450°C

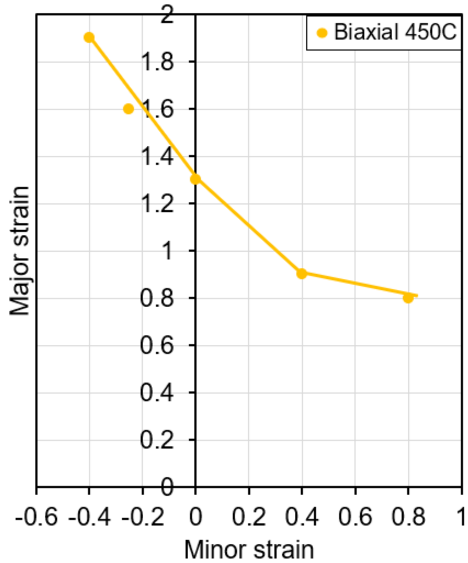
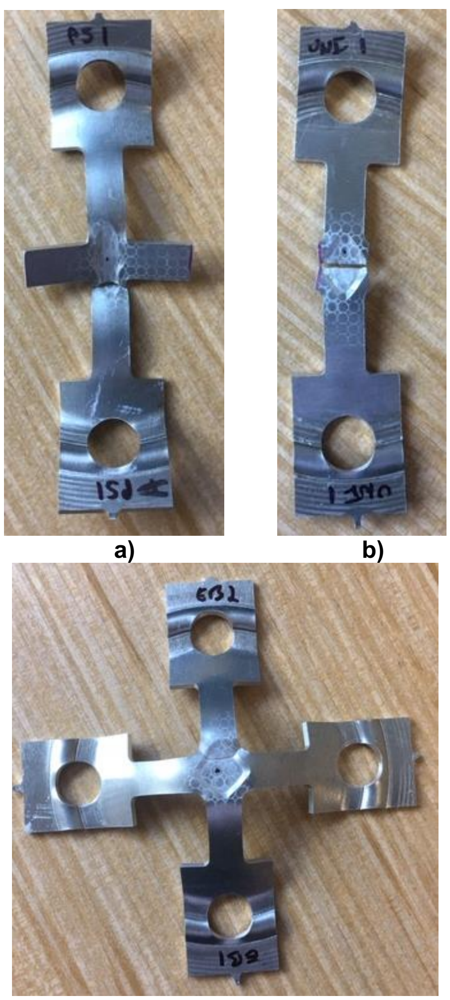


FIGURE 9-Forming limit strain points and fitted line of cruciform specimens tested with biaxial machine at 450°C



a) **b)**

c)

FIGURE 10-Neck or failed cruciform specimens tested with hemispherical dome test at 250°C

From the circle strain measurements, the forming limit curve was plotted for 450ºC as shown in Figure 9. The FLD_0 value at 450ºC is approximately 1.3. Similar observation is made that the plain strain forming limit strain is not the lowest strain and limit strain falls down till equ-biaxial deformation mode. As compared to 250ºC the 450ºC forming limit strain is much higher.

Figure 10a-c shows the specimen deformation with hemispherical dome test at 250oC for uniaxial, plane-strain and equi-biaxial strain modes as cruciform specimens were used. Generally, a conventional specimen was used in this test to find the forming limit curve, but for consistent purpose the cruciform specimen was used. Due to the nature of the specimen, the only option left was to chop the arms of the specimen to see which deformation can be obtained. Thus, multiple trials were made. When the specimen tabs were chopped (refer Figure 5b), and tested, the specimen provided the uniaxial deformation mode which was thought to be a plane-strain mode. The specimen deformation is shown in Figure 10a. When the specimen was chopped (refer Figure 5a) and deformed, the specimen provided the plane-strain mode opposite to the thinking of uniaxial mode. The specimen deformation is shown in Figure 10b. Figure 10c shows the equi-biaxial deformation as all tabs were pinched between the blankholder and die.

Figure 11 shows the forming limit strains of a material at 250ºC with hemispherical dome test. Here the FLD_0 is approximately 0.45 strain. The forming limit strains are approximately similar after plane-strain to equi-biaxial strain mode.

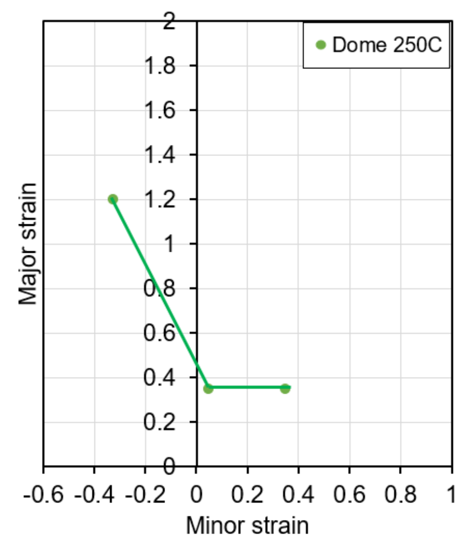


FIGURE 11-Forming limit strain points and fitted line of cruciform specimens tested with hemispherical dome test at 250°C

Figure 12 shows the forming limit strain for the same material with hemispherical dome test set-up using conventional specimens at 250ºC and 450ºC. It can be seen that there is a big jump in the forming limit strain from 250ºC to

450^{o}C. Similar observation was made with cruciform specimens with biaxial test.

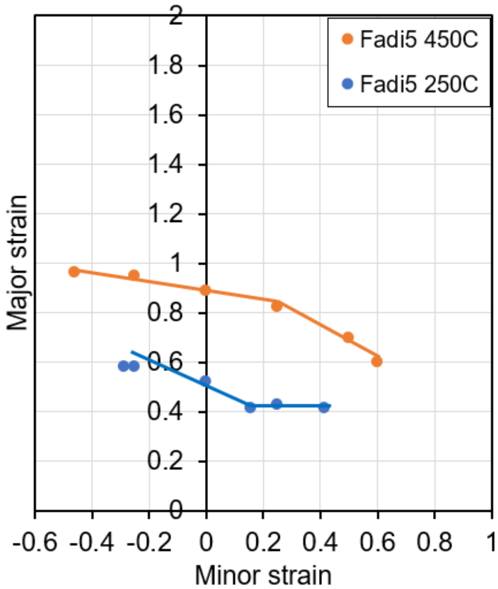


FIGURE 12-Forming limit strain points and fitted line of conventional specimens tested with hemispherical dome test at 250°C and 450°C [22]

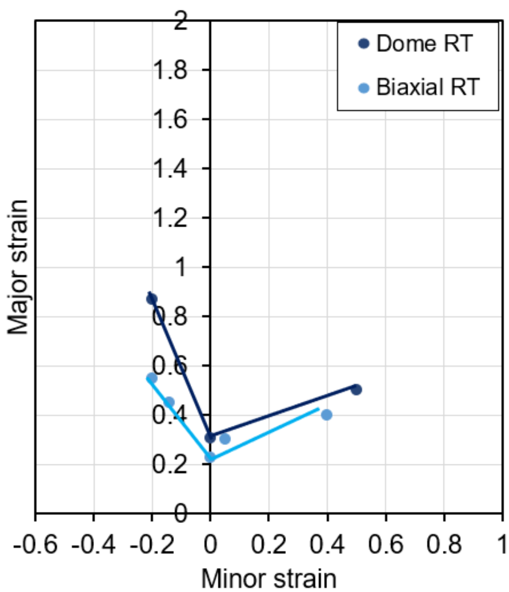


FIGURE 13-Forming limit strain points and fitted line of cruciform specimens tested with biaxial machine and conventional specimen tested with hemispherical dome test at room temperature (RT) [21]

The comparison study is also previously published by one of the authors [21] that biaxial test provides the lower limit strains as compared to the dome test. This is because no rigid tool is in contact with the specimen in the biaxial test whereas the hemispherical rigid punch is in contact with the specimen which pressurizes the specimen in contact and thus suppresses the micro voids and delays the failure. This effect is called the pressurization effect. This was not noted earlier because a similar die punch setting was used in the industry to stamp the material and limit strain would be in same agreement with the forming limit curve provided by the hemispherical dome test. The intention of the work was if it can be extended at higher temperature.

Finally, all either tested in this work or taken from literature forming limit curves for same material were plotted together for comparison purpose. As mentioned earlier that dome test provides the higher strain at room temperature than the biaxial test, a kind of similar observation can be made for 250^{o}C, however it doesn't match the complete trend. With the current test the plain-strain mode limit strain is lower for dome test as compared to the other deformation modes, however literature data shows higher in biaxial mode as compared to uniaxial deformation mode. At 450^{o}C the trend seems opposite as biaxial test shows higher limit strains. This may be because of the nature of testing in dome test, the kind of cold punch (conduction with the attachment outside of furnace) which is in contact with the center of the specimen where the strain measurements will be taken, may not have provided the actual temperature environment and decreases the limit strains.

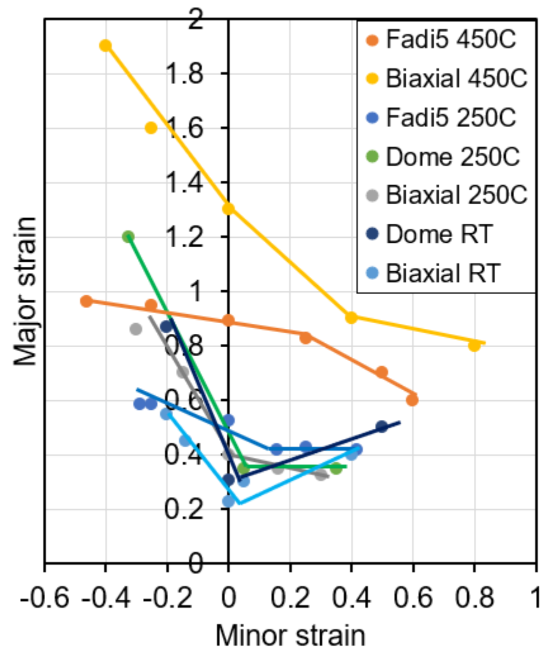


FIGURE 14-Comparison of forming limit strain of cruciform and conventional specimens at RT, 250°C, and 450°C with hemispherical dome test and biaxial machine

CONCLUSION

The paper deals with the forming limit strains differences between the testing by biaxial test and hemispherical dome test as elevated temperature. It was hypothesized that the dome test forming limit strains would be higher than the biaxial test at elevated temperature too as it was for room temperature. To find the results, biaxial tests were performed to measure the forming limit strain at two elevated temperature i.e., 250 and 450°C. Also, hemispherical dome tests were performed at 250°C. For all tests cruciform specimens were utilized. Then literature data was utilized to fill the current testing gaps. It was noted that with current testing at 250oC, the forming limit strain comparison provides lower forming limit strain at plane-strain with dome test, however when compared with the dome test literature data, the uniaxial shows the lower forming limits. At 450oC the forming limit strain comparison trend is opposite and biaxial test provides the higher strain as compare to the dome test. The reason may be the nature of the test set-up for dome test and the solid punch which comes in contact with the specimen might be colder and this provides lower strains at failure. From the results it seems that more data is needed to come to the right conclusion that if there is higher limit strains with dome test.

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