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Analysis of the metal sheets formability at single point incremental forming process

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Abstract. Although research on incremental forming process began a few decades ago, it is still a process in development phase. Single point incremental forming is a simple process and the deformation of the sheet blank is done with the help of a punch that follows a known toolpath.

In the case of this process, one important aspect is the prediction of material failure. To achieve this with the help of a finite element analysis, a series of experiments were performed to determine the forming limit diagram. In this paper, an attempt has been made to determine the forming limit diagram for the AA1050 aluminum alloy. The experiments were performed with the help of an industrial robot, KUKA KR 210-2, thus the part can be measured with an optical measuring instrument obtaining the major and minor strain from forming limit diagram.

Keywords: single point incremental forming, sheet metal, formability.

1 Introduction

Incremental sheet forming process has seen one of the highest increases in diversity in the last years. Single point incremental forming (SPIF) has become more attractive due to multiple benefits it possesses over other conventional cold forming processes such as deep-drawing. However, the process has yet to arise in the large-scale industrial implementation because of its drawbacks such as high production time and low accuracy, which lead to prototype production. In recent years, behavior of ductile metallic materials has been studied in order to grasp the limits of the materials formability.

Nowadays, industrial engineers are generally focused on geometric accuracy of parts manufactured through different plastic deformation processes or if there are residual stresses in the material. An important aspect is represented by dimensional accuracy of the final product after it undergone springback. Modern industry requires great credibility and delicacy, so now, due to the advanced level of technology, one can predict the material behavior during plastic deformation processes as well as of the final product, the moment when plastic strains occurs or even the material failure. The prediction of material behavior is based on a proper knowledge of their chemical-physical properties that occurs at different levels such as: micro-mechanical, molecular or atomic. Researchers that study materials help to define mechanical characteristics such as: Young modulus, tensile strength, ductility, etc. which help to predict material behavior under certain loads.

In order to study material formability, one can take into account three main categories: formability characterization methods such as forming limit diagram (FLD), study process parameters on process formability and the prediction of failure by means of finite element analysis methods [1]. The concept of FLD was introduced a long time ago by Keeler and Backofen (1963) [2] and Marciniak and Kuczynski (1967) [3]. Pandivelan et al. [4] performed straight grove and cupping tests on AA6061 blanks from which the major and minor strain were plotted in order to obtain FLD diagram. As showed by many researchers and Mugendiran et al. [5] the FLD for incremental forming very much differs from the conventional limit diagram used in deep-drawing process. Other researchers like Jeswiet et al. [6] utilized 5 distinct shapes in order to define the FLD: a hemisphere, a straight-sided cone, a hyperbolic-sided cone, a frustum pyramid and a five lobs shape.

However, it should be noted that the conventional FLD has the shape of a "V" while in the case of incremental forming has the shape of a straight line with a negative slope, defined as a relationship between minor and major strains as can be seen in Figure 1.

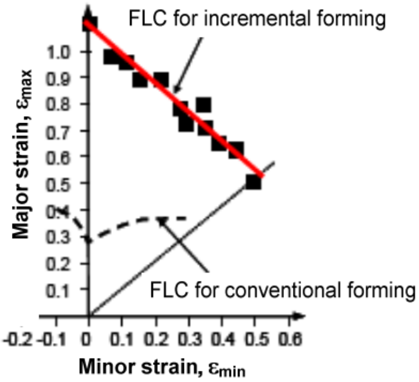


Fig. 1. Comparison between conventional forming limit diagram and single point incremental forming [7].

Mezher et al. [8] has studied the formability of AA1050 and DC04 sheet blanks by frustum cone products through maximum forming angle which was obtained without failure: 75° for steel and 72° for aluminum alloy. However, in 2020 Buffa et al. [9] presented a method to produce without failure 90° square cup from 1050 aluminum alloy through a multi-step strategy. This strategy involves a new concept with different forming directions differentiation such that multiple workpieces are obtained prior to final part in order to facilitate the material flow for the multi-step strategy. Regarding the study of the influence of temperature on the deformability of materials, Vanhove and collaborators [10] chose to apply a cryogenic treatment on sheets made of different aluminum alloys. Their studies have shown that the studied temperatures have a negative influence on the deformability of the aluminum alloy AA1050-H24, and on the AA5083-H111 there is a stability for the studied temperature range. For 1060 and 2024 aluminum alloys the fracture occurs due to material instability for the first case, respectively upon reaching forming limit for the second alloy when frustrum cone parts were manufactured with varying wall angle, as indicated by Xu et al [11].

2 Materials and Methods

In this section the test procedures used to carry out the research about material formability are presented in detail. Our aim is to analyze the behavior of the aluminum alloy AA1050 under characteristic stresses of incremental forming.

The specimens investigated in this study were made from commercial aluminum alloy AA1050 with the thickness of 0.8mm. The chemical properties (nominal chemical composition in weight %) for aluminum alloy according to EN573-3:2009 standard are shown in Table 1.

Table 1. Chemical composition of aluminum alloy AA1050 material.

Composition	Al	Mn	Fe	Cu	Mg	Si	Zn	Ti
Wt %	99,5	0,05	0,4	0,05	0,05	0,25	0,05	0,03

2.1 Uniaxial tensile test

In order to study material formability and fracture mechanism in SPIF, it was necessary to determine the stress-strain curve. For this we used the tensile test machine Instron 5587 which facilitates determination of mechanical properties of different materials. This test machine has a maximum test force of 300kN allowing automatic recognition and calibration of force, displacement and deformation transducers. It operates with the help of Bluehill 2 software which allows real-time results visualization and can save the results as conventional stress-strain curves. Due to the sheet's anisotropy, we produced specimens sets of 6 pieces for uniaxial tensile test for each of the three different angles in regard with the rolling direction of the sheet blank: 0°, 45° respectively 90°. Thus, 18 specimens were tested which were produced according to European standard SR EN 10002-1:2002. The proportional specimens had a rectangular cross section with calibrated length of 75mm, width of 12.5mm and the thickness was as mentioned above 0.8mm.

2.2 Single point incremental forming

In order to perform the tests, KUKA KR 210-2, a robotic arm with 6 degrees of freedom (DOF) was used. This robot has a 210kg payload which implies a maximum deformation force at about 2kN. The setup was done in such a way that the sheet blanks were fixed in a vertical plane. On one side of the supporting frame was the robotic arm which manufactured the parts and on the other side there was mounted a 3d optical measuring system Aramis used for digital image correlation. With the help of this system, major and minor strains are measured during the process. The test procedure involved the deformation of sheet blanks until failure occurred, thus the forming limit diagram was determined.

The size of the sheet blanks used was 250 mm x 250 mm and they were deformed with the help of 10 mm hemispherical punch. To study the behavior of material failure under different stress conditions, a line and a cross shape were programmed with the help of Sprutcam software. For both shapes a 1 mm depth step was used, wall angle of 90° and the total depth was established by the moment of material failure.

3 Results and discussions

In order to know as accurately as possible, the material behavior, several experiments are required to determine the material characteristics. One of the most common experiments to determine some of the characteristics of the material is the tensile test, so parameters such as: E modulus, Tensile stress at Yield, Strain hardening exponents, Maximum tensile stress and Tensile Strain at break are determined. In the case of the analyzed material, all this information was obtained by the tensile test of 6 specimens taken from each rolling direction. The results obtained are presented in Table 2.

Table 2. Mean values of AA1050 uniaxial test.

Rolling direction	E modulus (MPa)	Tensile stress at Yield (MPa)	Strain hardening exponent	Maximum tensile stress (MPa)	Tensile strain at break (%)
0°	31229.8	82.7	0.05	89.1	5
45°	29436.7	84.1	0.05	90	3
90°	30731.8	89.1	0.06	95.3	3

It can be seen that the specimens cut in the rolling direction have the highest Young's modulus, while those at 45 ° have the lowest value. On the other hand, Tensile stress at Yield and maximum tensile stress have the lowest value at 0 ° and the highest value at 90 °. The value of strain hardening exponent has approximately the same value for all three directions. Figure 2 presents the engineering stress-strain curves obtained from uniaxial tensile test with the specimens debited on the rolling directions.

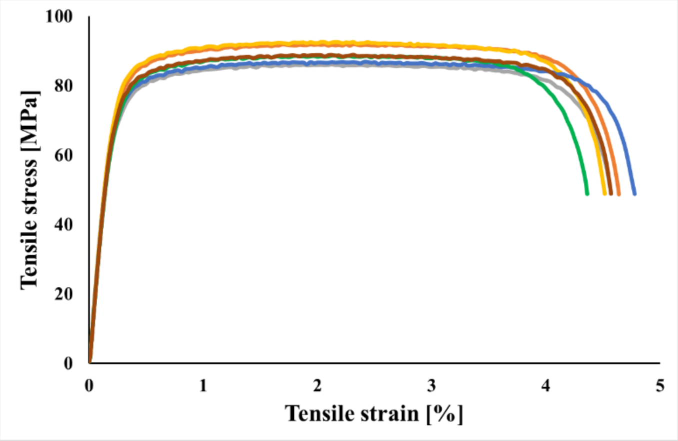


Fig. 2. The engineering stress-strain curves form specimens collected at 0°.

Following the tensile test, the material behavior at uniaxial loads was determined, but we must keep in mind that in the case of SPIF process, the material undergoes complex stresses. Therefore, in order to deepen the knowledge of SPIF failure mechanism, 4 parts will be manufactured by means of SPIF: a line, a cross, a frustrum cone with 70° wall angle and also variable angle (VWA). For the line test, the toolpath follows a line that intends at each end with a step of 1mm, and in the case of variable wall angle part, the start angle was 40° up to 75° .

In the case of line specimen, the maximum depth reached before failure was 14 mm as presented in Figure 3 a). Figure 3 b) shows the crack at the bottom of the cross specimen at a depth of 15 mm. After this test, an attempt to manufacture the VWA part was made, and it formed until the end without any crack, but due to the bottom of the part where the wall angle exceeded 70° the optical measuring system ARAMIS was unable to measure the strains (Figure 3 c). Thus, a fixed 70° wall angle part was produced which failed at 20 mm depth as in Figure 3d).

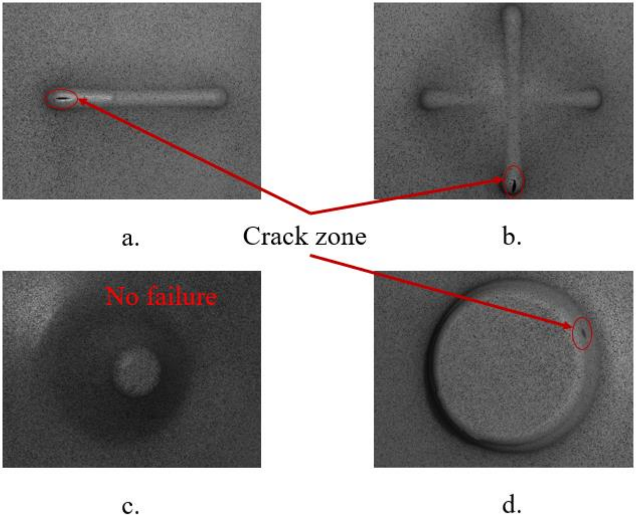


Fig. 3. a) Line specimen; b) Cross specimen; c) VWA frustrum cone; d) Frustum cone with 70° wall angle;

After failure, the test was stopped and the major and minor strains were extracted from the last image processed by the 3d measuring system Aramis. Figure 4 presents the major and minor strain extract from Aramis.

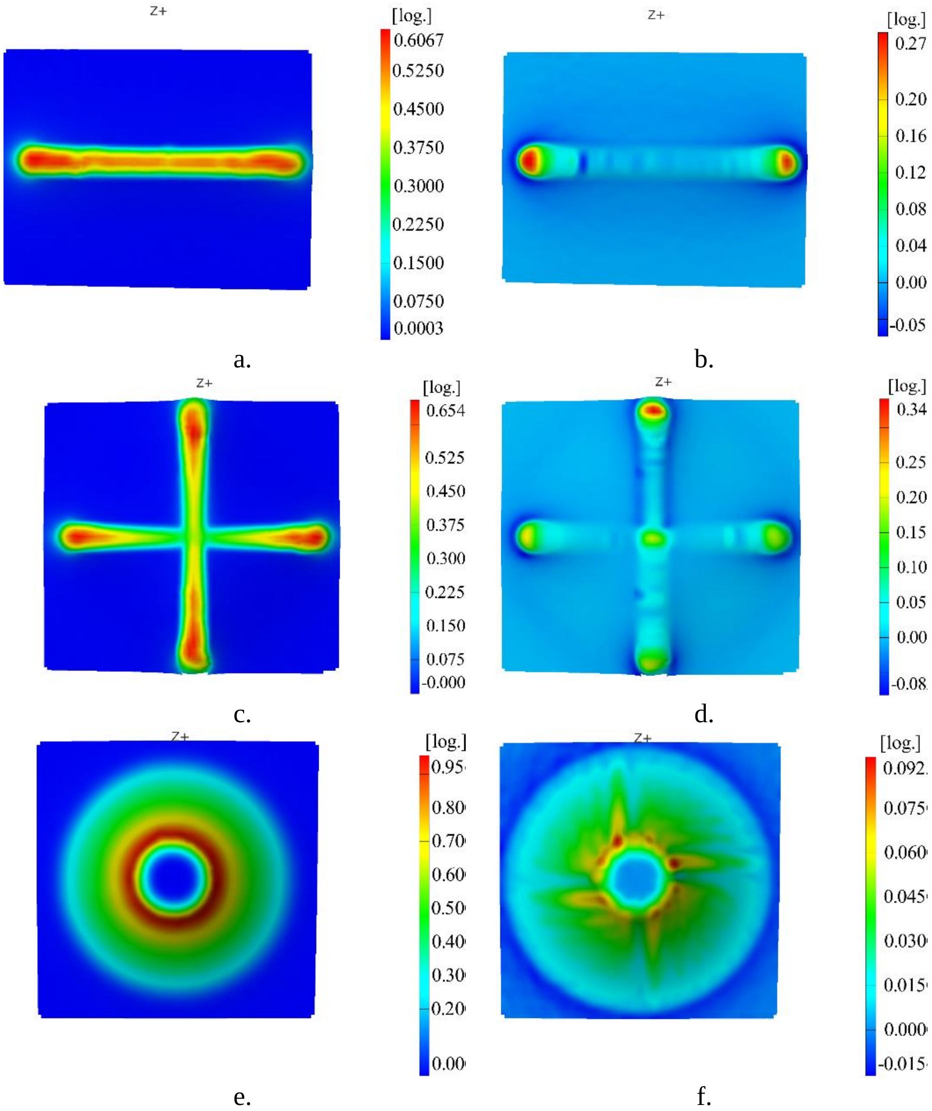
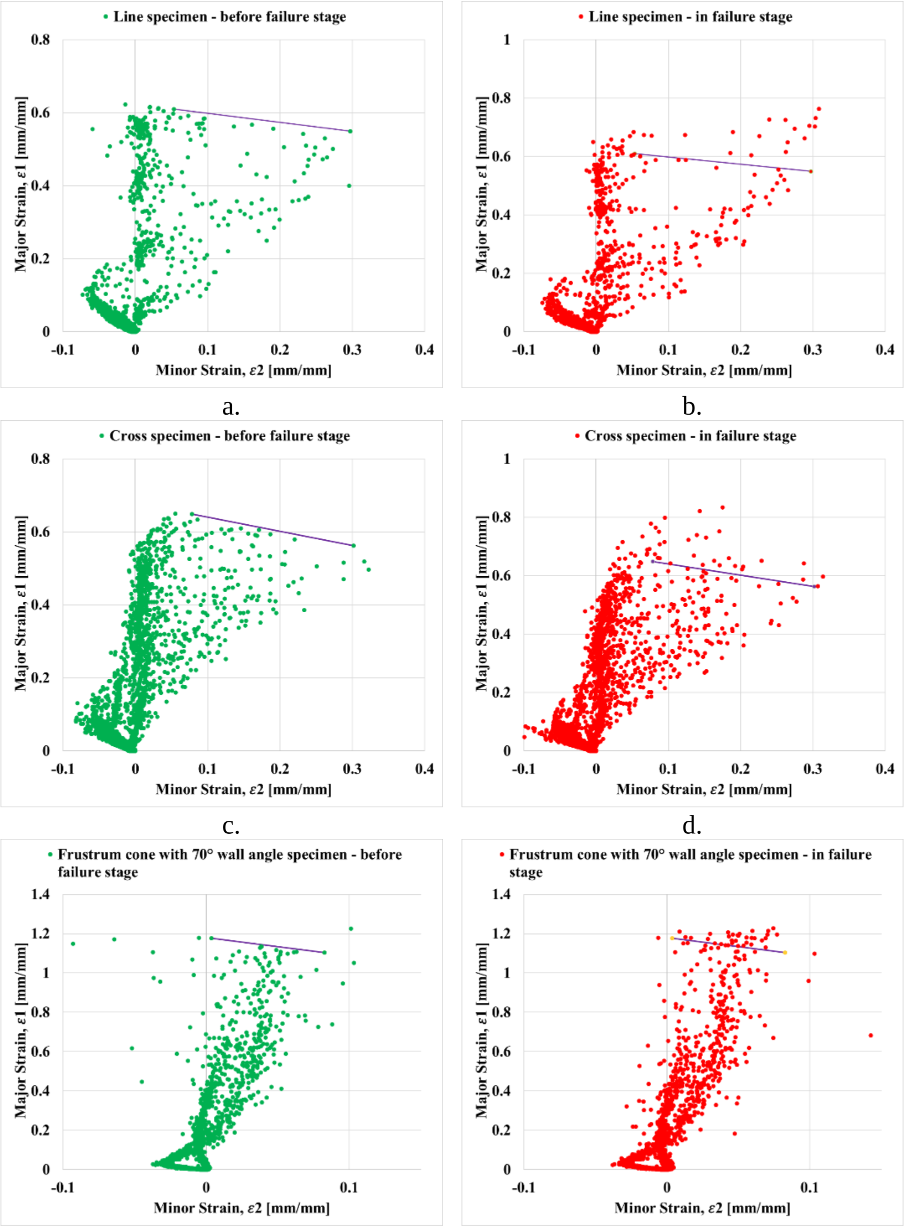


Fig. 4. a) Major strain on line specimen; b) Minor strain on line specimen; c) Major strain on cross specimen; d) Minor strain on cross specimen; e) Major strain on VWA frustrum cone specimen; b) Minor strain on VWA frustrum cone specimen;

The points presented in Figure 5 represents the major and minor strains from which we can predict the forming limit of AA1050 sheet blanks during single point incremental forming process.



a.

b.

c.

d.

e.

f.

Fig. 5. Forming limit diagram obtain from: a. line specimen in the stage before failure; b. line specimen in the failure stage; c. cross specimen in the stage before failure; b. cross specimen in the failure stage; e. frustrum cone with 70° wall angle specimen in the stage before failure; f. frustrum cone with 70° wall angle specimen in the failure stage;

4 Conclusions

In this paper, the material behavior of AA1050 sheet blanks was investigated. In the first steps the uniaxial tensile test was performed to obtain the material characteristics. In addition, a line, a cross, a VWA frustrum cone and a fixed 70° frustrum cone were manufactured. All specimen showed failure, at 14 and 15mm for line and cross test, at 20 mm for fixed wall angle frustrum cone, with the exception VWA part which was formed successfully. After extracting the major and minor strains, FLD was plotted from the failed specimens.

For line and cross tests, we observed a maximum major strain of 0.8mm/mm and a minor strain above 0.3mm/mm, whereas in case of frustrum cone the major strain exceeded 1.2mm/mm but the minor strain was lower than 0.1mm/mm. This shows the complexity of the forming mechanism of SPIF process and one must take note that line and cross test are not accurate in describing the material behavior in the case of incremental forming process. For complex stresses such as in incremental forming, more research must be done for a better understating of the failure phenome.

References

1. Guzmán, C.F. Yuan, S., Duchêne, L., Saavedra Flores, E.I., Habraken, A.M: Damage prediction in single point incremental forming using an extended Gurson model. Int. J. Solids Struct. 151, 45-56 (2018).
2. Keeler, S. P., Backofen, W. A.: Plastic instability and fracture in sheets stretched over rigid punches. Trans. Am. Soc. Met. 56, 25–28 (1963).
3. Marciniak, Z., Kuczynski, K.: Limit strains in the processes of stretch-forming sheet metal. Int. J. 845 Mech. Sci. 9 (9), 609–620 (1967).
4. Pandivelan, C., Jeevanantham, A.K.: Formability evaluation of AA 6061 alloy sheets on single point incremental forming using CNC vertical milling machine. In: J. Mater. Environ. Sci. 6, 1343-1353 (2015).
5. Mugendiran, V., Gnanavelbabu, A.: Comparison of FLD and thickness distribution on AA5052 aluminium alloy formed parts by incremental forming process. In: Procedia Engineering 97, 1983-1990 (2014).
6. Jeswiet, J., Young, D.: Forming limit diagrams for single-point incremental forming of aluminium sheet. In: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 219, 359-364 (2005).
7. Krállics, G., Agena, A. S.: Investigation of Ductile Fracture of Nanostructured Al 6082 Material. In: Periodica Politechnica, Ser. C. Mech. Eng., 50, 89-97 (2004).
8. Mezher, M.T., Barrak, O.S., Nama, S.A., Shakir, R.A.: Predication of Forming Limit Diagram and Spring-back during SPIF process of AA1050 and DC04 Sheet Metals. In: Journal of Mechanical Engineering Research and Developments 44, 337-345 (2021).
9. Buffa, G., Gucciardi, M., Fratini, L., Micari, F.: Multi-directional vs. mono-directional multi-step strategies for single point incremental forming of non-axisymmetric components. In: J. Manuf. Processes 55, 22-30 (2020).
10. Vanhove, H., Mohammadi, A. Duflou, J.R.: Incremental forming of aluminium alloys in cryogenic environment. In: AIP Conference Proceedings 1769, 070020 (2016).

11. Xu, Q., Yang, M., Yao, Z.: Influence of Tool-Sheet Contact Conditions on Fracture Behavior in Single Point Incremental Forming. In: IOP Conf. Ser. Mater. Sci. Eng. 394 (2018).