

Characterization of the formability limits for copper sheets

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Abstract

The commanding rhythm of production of the current industry requires efficient forming technologies with the capability to produce high quality products with lower costs at higher velocities. Knowledge of the mechanical properties and formability limits of necking and fracture became, thus, essential to evaluate the capabilities of the material regarding these new forming processes. The present work aims to characterize copper mechanically and determine the Forming Limit Curve (FLC), the Fracture Forming Limit Line (FFL) and in-plane Shear Forming Limit Line (SFFL) for the material.

The mechanical characterization of copper will be achieved by means of tensile and bulge test, subsequently the results for fracture toughness will be presented resulting from double notched, staggered and shear specimens tested under tensile strength. In order to determine copper formability nakajima test were also performed. The results obtained from conventional tests were then compared with the results obtained from three SPIF geometries, with the intent of validating the aptitude of the last ones in characterizing the formability limits.

This work shows copper mechanical characterization and presents the results obtained by means of conventional test and reveals a comparison and conformity with the results obtained by means of SPIF processes.

Keywords: Copper, Formability, Forming, Fracture, Fracture modes, Single point incremental forming (SPIF)

1. Introduction

Copper is found as one of the most utilized non-ferrous materials at the moment its use is most recognized in the production of customized or small series parts for decoration and kitchenware. Hence this necessity of characterizing this material, the production of small batches represents a necessity of cost and wastes reductions that are possible to achieve when the formability limits of the materials are known.

Formability is the term used to characterize the maximum plastic deformation that can be achieved during a technological process without the occurrence of necking or fracture. There two formability limits: a formability limit by necking, characterizes by a "V-shaped" curve which is designated as the forming limit curve (FLC) and a formability limit by fracture consisting of two curve, the fracture forming limit (FFL) and the shear fracture forming limit (SFFL). Atkins [1] proposed the FFL's graphical representation in the principal strain plane as a straight line with a slope equal to "-1" (figure 1) associated with the critical thickness reduction at failure caused by tension (mode I of fracture mechanics). Isik et al. [2] presented the SFFL and represented it in the forming limit diagram as straight curve, perpendicular to the FFL (figure 1) in agreement with the condition of critical distortion at fracture induced by the in-plane shear (mode II of fracture mechanics). The determination of FLC and FFL is done by means of conventional formability tests whereas SFFL is achieved by convention torsion and plane shear tests. The aforementioned tests are known to experience plastic localization before failure by fracture. However, Isik et al [2] show that SPIF truncated conical and pyramidal geometries are able to provide fracture strain pairs in order to characterize the FFL. Due to the incremental nature of

the deformation mechanism, significantly higher strains can be achieved in SPIF when compared to conventional forming.

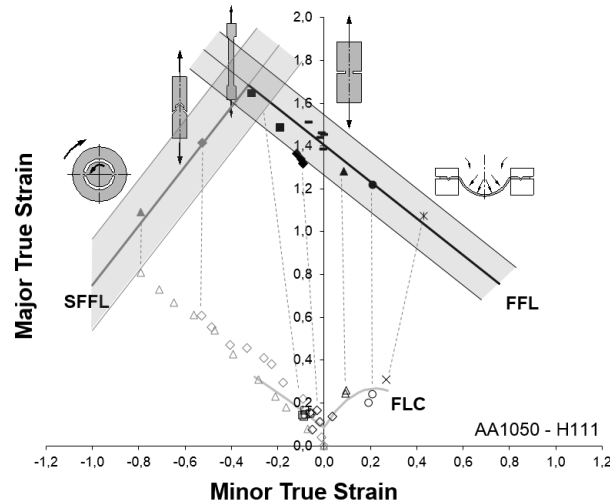


Figure 1 – Results obtained Isik et al. (2014)

This process facilitates the determination of the FFL for SPIF test can ensure linear strain paths and failure by fracture with the suppression of necking, unlike formability tests [3]. Soeiro et al. [4], [5] proposed a new geometry produced by SPIF that was capable of providing the fracture strain pairs for plotting the SFLL and facilitate its determination when compared with the method of “gauge length strains” measuring still in use.

The aim of this paper is to determine copper mechanical characteristics and the formability limits of the material. This paper's aims also to verify the reliability of the geometries produced by SPIF test in the determination of the fracture forming limit curves by comparing the results obtained from these with the results obtained for copper specimens from the conventional tests such as tensile tests, double notch tensile test, in-plane shear test and bulge and Nakajima tests.

2. Experimentation

The investigation concerns the mechanical and formability characterization of copper using specimens with 0.8 mm in thickness. Tensile tests were used for the mechanical characterization, as for the formability characterization it was achieved by means of tensile, double notch, in-plane shear, bulge and Nakajima test as shown in table 1.

Table 1 – Layout of Experiments for Copper

Test	Specimens Geometry	Number of Specimens
Tensile	$l_0 = 50$	15
Double Notch Tensile Test	$a = 5, 10, 15, 20$ and 25;	20
Staggered	$a = 5, 10, 15, 20, 25$	20
Shear Test	$c = 1, 2, 3, 5, 6, 8$	21
Bulge	$\varnothing 100$	3
	100:80	2
	100:64	5
Nakajima	$R = 40, 50, 57.5, 65, 72.5, 80$	12
SPIF	Cone	5
	Pyramid	5
	4lobe	5

2.1 Mechanical and Fracture Toughness characterization

The mechanical characterization of copper was performed by means of tensile tests in specimens that were cut out from the supplied sheets at 0°, 45° and 90° with respect to the rolling direction. The modulus of elasticity E , the yield strength, σ_y , the ultimate tensile strength, σ_{UTS} , the normal anisotropy coefficient, \bar{r} , and the planar anisotropy coefficient, Δr and the elongation at break, A were calculated for each of the directions. The material law was obtained from the stress-strain curve resulting from the tensile tests approximated by Ludwik-Holloman equation.

With the objective of characterizing the fracture toughness of copper, double notch specimens were used in a tensile test, supplied from sheets at 0° and 90° with respect to the rolling direction. For each of the tested specimens a strength-displacement curve was obtained and the total energy was calculated by integrating the evolution of the force with the displacement. Assuming the total energy is to be split into the sum of a term associated to the energy of plastic deformation W_p and a term related to the energy that is needed to form new surfaces, W_s , the total energy per unit of area can be express as follows:

$$w = \frac{W}{A} = \frac{W_p}{A} + \frac{W_s}{A} = \frac{W_s}{A} + R \quad (1)$$

Where $A = a \times t$ is the area of the ligament and R is the fracture toughness defined as the amount of energy per unit of area that is required to create a new surface. The value of R correspond to the y-interception of a straight line with slope equal to α that contains the total energy per unit area w of all the experiments performed with double notched specimens having different lengths c of the ligaments (figure 2).

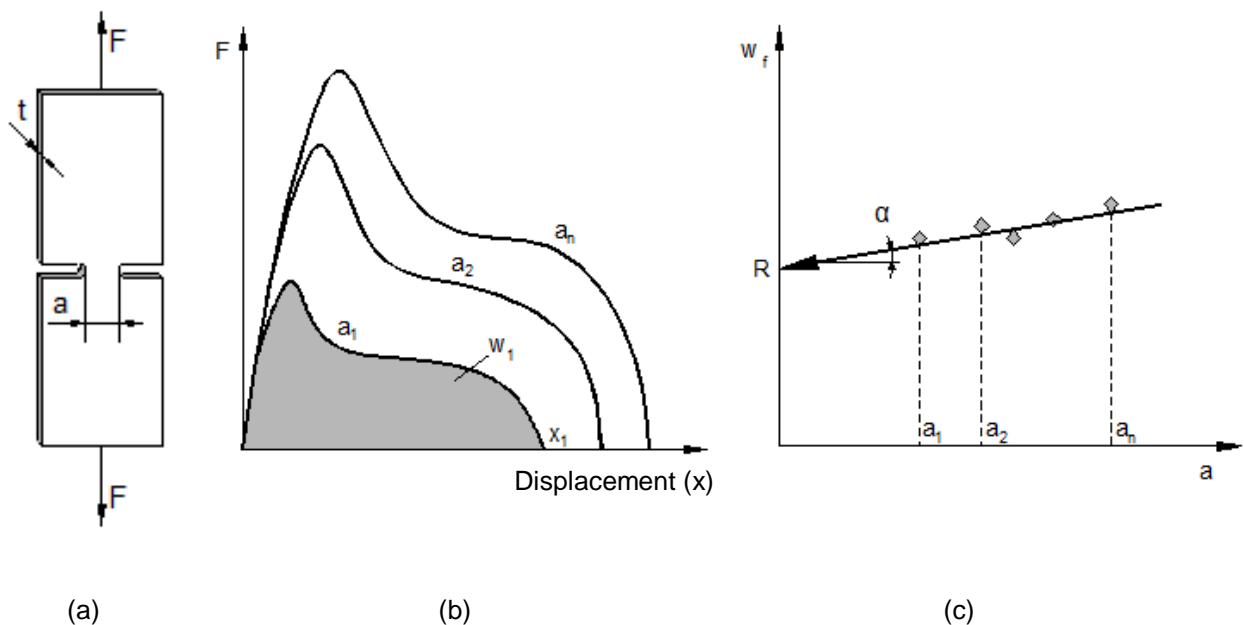


Figure 2- Method and procedure used for determining fracture toughness R . a) Schematic representation of double edge notched test specimen loaded in tension. B) Schematic evolution of the tensile force with displacement for test specimens with different ligaments c. c) Determining fracture toughness R from extrapolation of the amount of energy per unit of area w that is needed to create a new surface

2.2 Formability characterization

The methodology used for determining the FLC was based upon measuring the in-plane strains ($\varepsilon_1, \varepsilon_2$) at grid points along predefined directions that crossed the crack region perpendicularly. The in-plane strains at the grid points were obtained as follows,

$$\varepsilon_1 = \ln\left(\frac{a}{d}\right) \qquad \varepsilon_2 = \ln\left(\frac{b}{d}\right) \qquad (2)$$

Where a and b are the lengths of the major and minor axes of the ellipses that resulted from plastic deformation of the original grid of tangent circles during sheet formability test.

The methodology used to determine the FFL and the SFFL was based upon measuring the thickness of the specimens before and after the fracture at several locations along the crack in order to obtain the “gauge length” strains. However, to obtain the trajectories of deformation in the SPIF geometries the methodology to determine the FLC was used in order to understand if this methodology could be applied to substitute the aforementioned one.

3 Results and Discussion

3.1 Mechanical Characterization

The mechanical characterization of copper was performed by means of tensile tests, at room temperature, the stress-strain curve was approximated by the Ludwik- Hollomon equation:

$$\sigma = 427.56 \varepsilon^{0.17} \qquad (3)$$

Table 2 presents the main properties obtained from the tensile tests performed for copper for 0°, 45° and 90° with respect to the rolling direction

Table 2 – Mechanical Properties for Copper

Rolling direction	Modulus of elasticity, E (GPa)	Yield strength, σ_e (MPa)	Ultimate tensile strength, σ_r (MPa)	Elongation at break, A (%)	Normal anisotropy coefficient	Planar anisotropy coefficient
0° DL	109.43	213.24	343.52	24.17	0.79	$\Delta r = -0.43$
45° DL	109.49	207.62	327.49	27.11	1.19	
90° DL	128.96	207.06	326.77	28.20	0.74	
Valor médio	141.3	208.89	331.32	26.65	$\bar{r} = 0.98$	

3.2 Fracture Toughness in mode I

The procedure to determine the fracture toughness in crack opening mode I makes use of double notched specimens loaded in tension. The specimens presented different ligaments $a = 5, 10, 15, 20, 25$ mm and the results for the evolution of force with displacement are shown in figure 2.

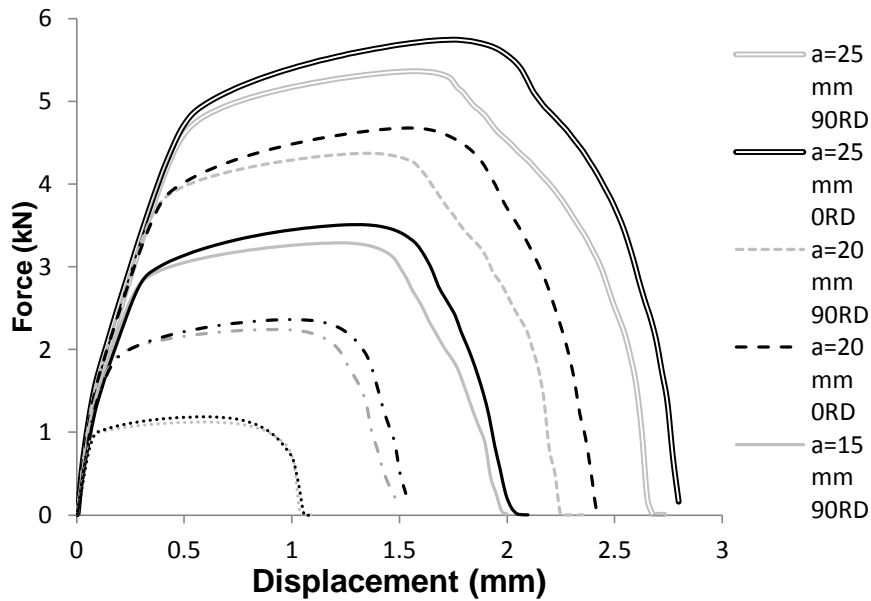


Figure 2 - Experimental evolution of the tensile force with displacement for test specimens with different ligaments that were cut out from the supplied sheets at 0° and 90° with respect to the rolling direction

Figure 3 represents the value of the specific total energy and is possible to conclude that the energy required to create a new surface (fracture toughness) is equal to $R = 197.9 \text{ kJ/m}^2$, this value is an average obtained from the specimens cut out from the supplied sheets at 0° and 90° degrees with respect to the rolling direction (refer to table 3).

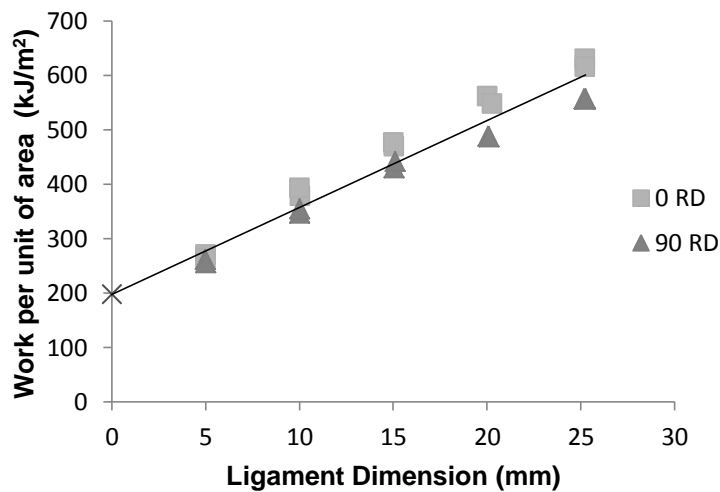


Figure 3 - Average value of fracture toughness obtained from test specimens with different ligaments that were cut out from the supplied sheets at 0° and 90° with respect to the rolling direction

Table 3 - Fracture toughness, R, obtained from double edge test specimens loaded in tension that were cut out from the supplied sheets at 0° and 90° degrees with respect to the rolling direction.

	0° RD	90° RD	Average
Fracture Toughness, R (kJ/m ²)	197.5	198.2	197.9

3.3 Fracture Toughness in mode II

In order to determine the fracture toughness in crack opening mode II we made use of shear specimens loaded in tension. The specimens presented different ligaments $c= 1, 2, 3$ mm and the results for the evolution of force with displacement are presented in figure 4.

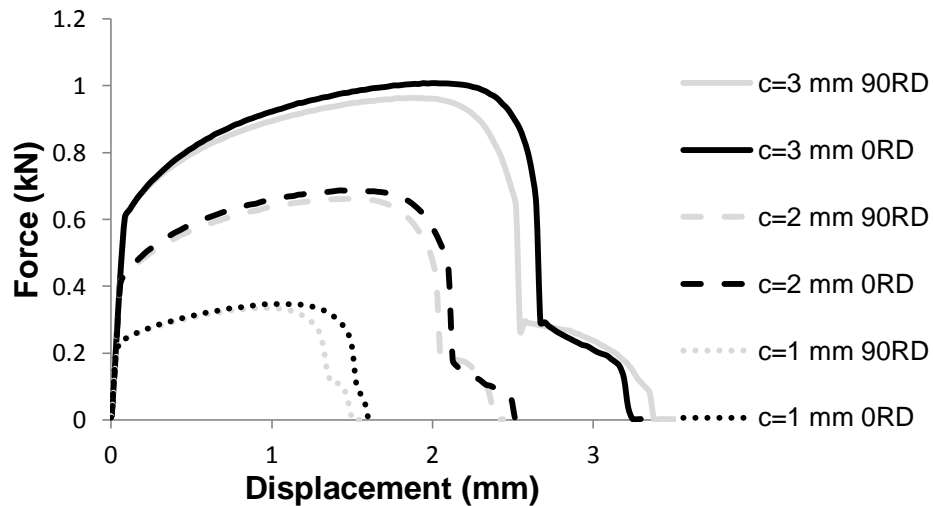


Figure 4 - Experimental evolution of the tensile force with displacement for test specimens with different ligaments that were cut out from the supplied sheets at 0° and 90° with respect to the rolling direction

In figure 5 is presented the specific work for each specimen and the average calculated by means of the linear regression function.

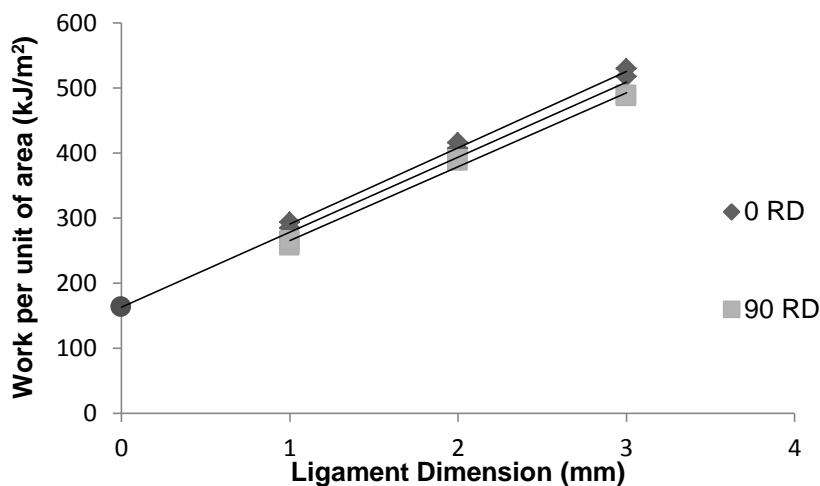


Figure 5 – Average value of fracture toughness obtained from test specimens with different ligaments that were cut out from the supplied sheets at 0° and 90° with respect to the rolling direction

The value of the specific total energy and is possible to conclude that the energy required to create a new surface (fracture toughness) is equal to $R = 162.9$ kJ/m², obtained from the

specimens cut out from the supplied sheets at 0° and 90° degrees with respect to the rolling direction (refer to table 3).

Table 4 – R, obtained from double edge test specimens loaded in tension that were cut out from the supplied sheets at 0° and 90° degrees with respect to the rolling direction.

	0° RD	90° RD	Average
Fracture Toughness, R (kJ/m ²)	173.5	152.2	162.9

The layout of experiments for the shear specimen presented higher lengths of ligaments to be tests, however, due to the material hardening the fracture for specimens with ligaments higher than 3 mm did occur in the expected zone (figure 6) , therefore the fracture toughness made use only of these c lengths.

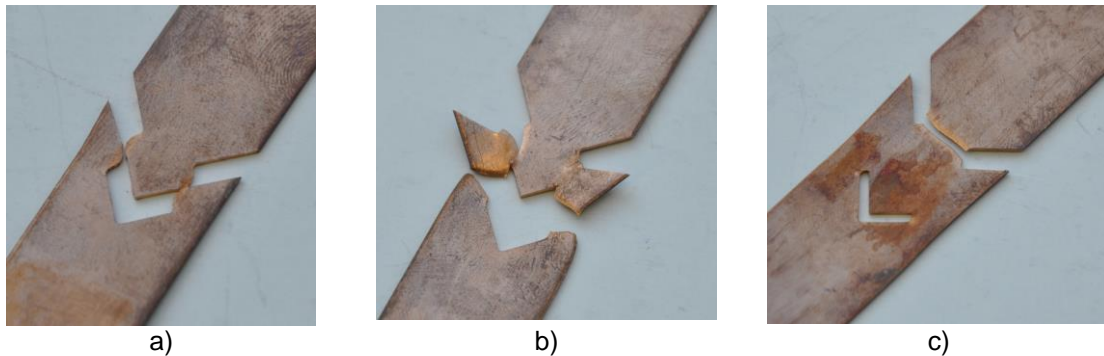


Figure 6 – Shear Specimens Tested a) Fracture occurred in the expected area, b) e c) Fracture propagation did not occur in the expected area

3.4 Fracture Toughness mode I/II

The characterization of fracture toughness in mix mode was not possible to achieve because the specimens with ligament lengths higher than 15 mm presented unexpected fracture propagation (figure 7). Therefore the calculations for the fracture toughness in this mode were not reliable but the results are presented in table 5.

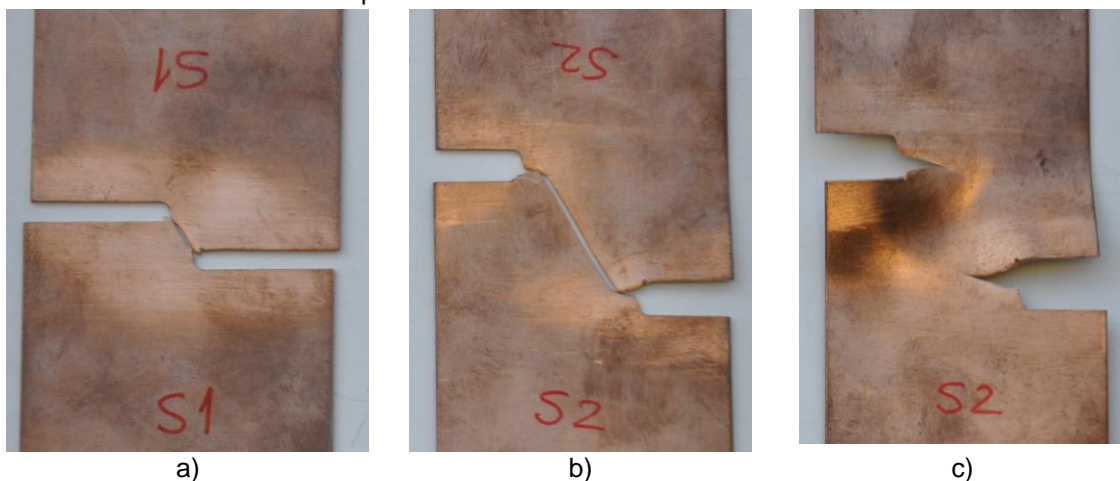


Figure 7 –Tested Staggered Specimens a) a= 5 mm, b) a = 15 mm, c) a = 20 mm

Table 5 – Results for fracture toughness in mode I/II

	0° RD	90° RD	Average
Fracture Toughness, R (kJ/m ²)	311.3	345.3	350.4

The value obtained for fracture toughness is 350 kJ/m² is very high when compared with the values obtained for fracture toughness in modes I and II.

3.4 Formability Limits

The FLC was determined combining tensile, bulge and nakajima tests. The resulting FLC is shown in figure 8. The determination of the FFL and the SFFL was made by means of the aforementioned tests and also by shear test, double notched tensile tests and SPIF tests with three different geometries (cone, pyramid and four lobes) and also shown in figure 9.

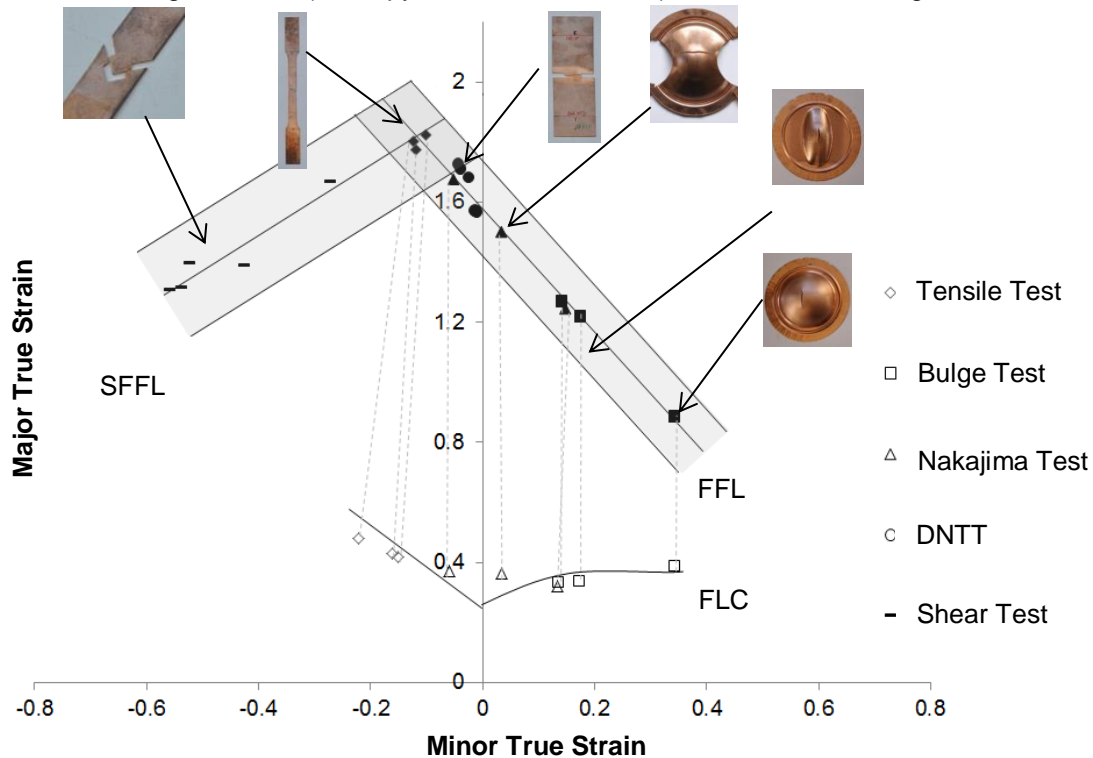


Figure 8 - Formability Limits obtained for Copper

The solid points represent the fracture point obtained from the specimens. The lines represent the evolution of the strain pairs after necking. The equation obtained for the FFL curve is:

$$\varepsilon_1 + 2.06\varepsilon_2 = 1.58 \quad (4.2)$$

And the equation obtained for the SFFL curve is:

$$\varepsilon_1 - 1.17\varepsilon_2 = 1.96 \quad (4.3)$$

From the analysis of figure 8 is possible to observe that the results obtained from SPIF geometries are in agreement with those obtained from the conventional formability tests.

In figure 9 are presented the strain pairs trajectories obtained for the three geometries produced by SPIF.

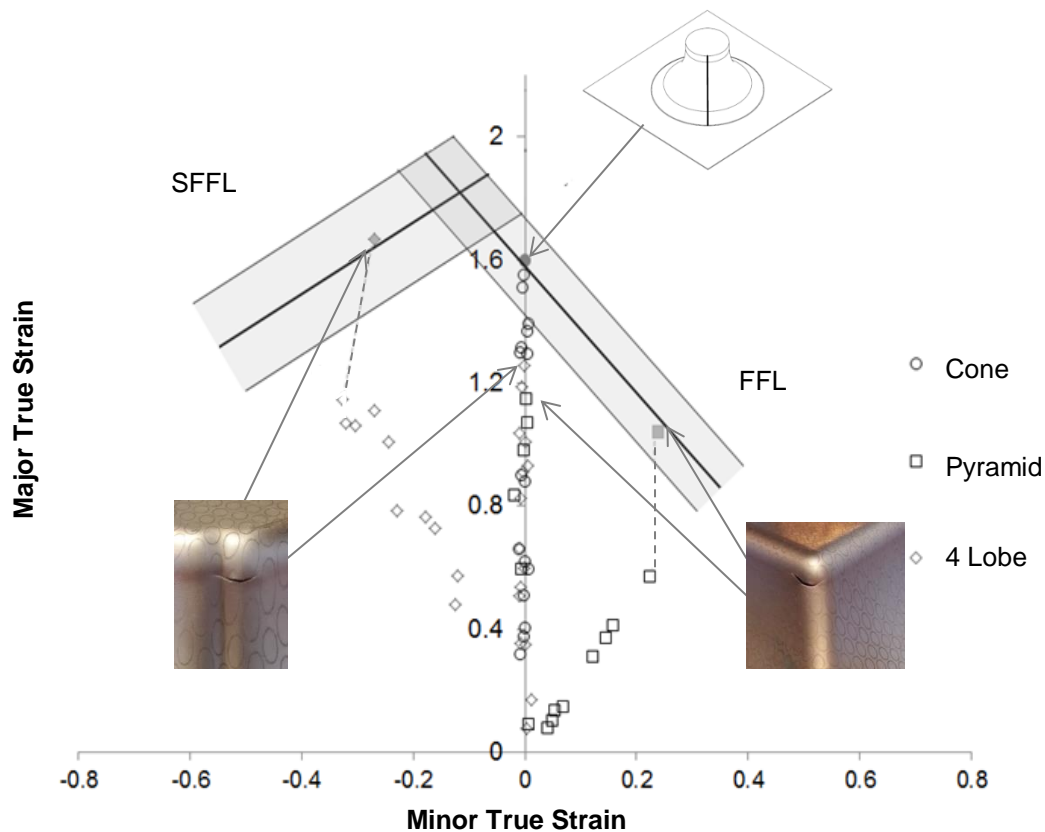


Figure 9 – Strain pairs obtained for SPIF geometries

From figure 9 is possible to observe that the values obtained from the SPIF specimens in all of the three geometries for the point that are not from fracture are very near the fracture points obtained.

4 Conclusions

This work proposes a mechanical and formability characterization for copper according to conventional formability tests as tensile tests, double notched tensile, shear, bulge and nakajima test. It was possible to calculate the fracture toughness in in crack opening mode I and II, but the results for fracture toughness in mode I/II were considered not valid because the value obtained were not in accordance with the ones obtained for mode I and mode II.

The results obtained from the SPIF with pyramid and cone geometries are in very close agreement with the FFL obtained by means of conventional test, being therefore a viable method to characterize this fracture forming limit.

The result obtained with four lobe geometry demonstrate a very approximant result with the one obtained from the shear tests performed with copper specimens therefore suggesting this geometry has a viable one to characterize the SFFL for copper.

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