

Application of the DIC System to Build a Forming Limit Diagram (FLD) of Multilayer Materials

Paulina Lisiecka-Graca^{1,a*}, Marcin Kwiecień^{1,b}, Łukasz Madej^{1,c},
Janusz Majta^{1,d}, Krzysztof Muszka^{1,e}

¹AGH University of Science and Technology, Faculty of Metals Engineering and Industrial Computer Science, Mickiewicza 30, 30-059, Krakow, Poland

^agraca@agh.edu.pl; ^bmkwiecie@agh.edu.pl; ^clmadej@agh.edu.pl; ^dmajta@metal.agh.edu.pl;
^emuszka@agh.edu.pl

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Abstract. The extraordinary combination of strength and ductility of multilayered materials makes them attractive in the various applications and industries (military, aerospace, energy industry etc.). In the present work, the investigated materials were joined into multilayered sheet using the explosive welding method. The three-layer material was made of two titanium sheets and one Armco iron sheet in between. Materials produced by explosive welding can easily be used in a simple deformation process, but more complex processes that employ a more complex mechanical state are still not sufficiently studied. The presented study analyzes the possibilities of using Ti - Armco - Ti sheet for the deep drawing process. For this purpose, the forming limit diagram (FLD) has been constructed and verified. FLD is one of the most important tools in the analysis of sheet metal forming processes. In the presented work the non-standard method (Erichsen test) coupled with Digital Image Correlation analysis was used. The obtained results confirmed that the method of producing the tested sheet and the morphology of the microstructure created have a direct impact on the deformation mechanisms.

Introduction

One of the most important processes to join metal sheet employing extremely high energy generated by the detonation is explosive welding process [1]. Additional advantage of this process is the possibility to produce multilayer composite from similar and dissimilar materials that cannot be joined through any other methods. Materials produced by this technique are widely used in the various applications and industries because of extraordinary combination of mechanical and physical properties [2-5]. The multilayered metal-to-metal composite, produced by the explosive welding process can be easily deformed under simple deformation processes such as rolling or bending. However, when this material is subjected to more complex deformation processes, the problem of proper rheology analysis becomes more complex. The presented work focuses on the possibility of performing a detailed analysis of the mechanical response of the multilayer Ti - Armco iron - Ti composite and its experimental verification.

In the conducted research, a complex mechanical state was created in deep drawing processes (Erichsen stamping test). The most common method of assessing the suitability of a selected material for the deep drawing process is the use of the Forming Limits Diagram. Forming limit diagram based on the forming limit curve (FLC) is a graphical representation of the material forming limits. The FLD can be generated by mapping the major and minor strains where the failure occurs at the beginning of necking [6-8]. In the presented work, FLC was prepared for materials before and after the process of joining into a multilayer system using the non-standard Erichsen method coupled with Digital Image Correlation analysis (DIC) [9-10].

In the recent years the DIC method has been replacing the conventional surface circle etching method for the strain measurement in the FLD determination. The DIC method is one of the optical techniques of full, non-contact measurement of the displacement field in order to obtain an accurate distribution of strain and deformation [11]. Recently, many methods for determining FLD using DIC have been proposed [12-13]. These methods can be divided into two basic groups [13], those dependent on time

and those described as a function of position. The latter group is the most widespread and is regarded as the ISO standard method [14]. In the case of the position - dependent method, the strains are estimated based on the strains map distribution when the fracture occurred. Along the line perpendicular to the fracture direction, the major and minor strains are plotted and the inverse parabola is constructed. The strain value in FLC is defined by the extremum in these curves. In the presented work the position - dependent method was adopted to multilayered, explosively cladded materials.

Experimental Procedure

The presented work concerned the study of the deformability of the three-layer material in terms of the possibility of using it in the deep drawing process. The experiments were performed on three - layered composite consisting of Titanium Grade 1- Armco iron- Titanium Grade 1 system. The chemical compositions of the starting materials are presented in the Table 1. In the present tests, each of the sheets before the joining process had the same thickness, equal to 1 mm. The titanium and Armco iron used in the tested multilayer material are characterized by a different crystallographic lattice, which in turn causes their different mechanical responses during the deep drawing process. Therefore, before the joining process, the mechanical properties of the particular sheets were determined using a tensile test. The tests were performed on the Zwick 250 testing machine using flat specimens. The tensile tests were carried out at room temperature under quasi-static conditions. During the tests, changes in forces and resulting elongations were recorded. Based on the recorded data, the true stress - true strain curves were determined. The obtained mechanical properties of both tested sheets (titanium and iron Armco) are shown in Fig. 1.

Table 1. Basic chemical composition of the material before explosive welding process in wt.%.

	Ti	Fe	C	N	O	Mn
Ti (Grade 1) sheet	99.9	0.03	0.01	0.01	0.04	-
Armco iron sheet	-	99.8	0.01	0.006	-	0.1

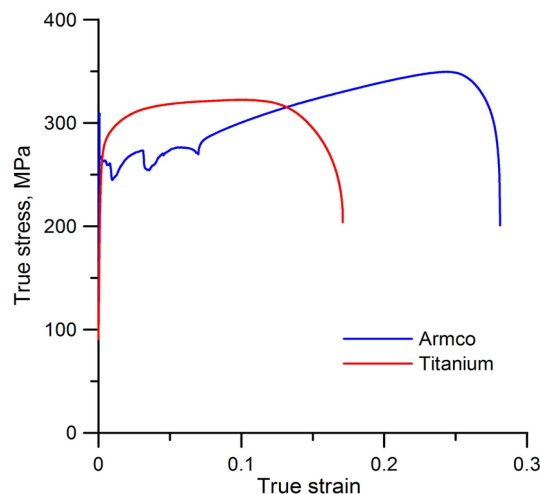


Fig. 1. True stress – true strain curve for the plates before joining process.

The tested multi-layer material was produced by the ZTW "Explomet" company. The velocity used in the bonding process was equal 2100 m/s. After the explosion, the flyer plate collapsed onto the base plate and between two metal plates the high velocity jet is formed. The high pressure, temperature and the shear strains produced near the collision surface in a very short time is caused by the high velocity oblique collision. The most important parameter is the pressure. The sufficiently high pressure produces the interatomic bonding in a short time. The explosive welding process consists of two stages: loading and unloading. After the explosive bonding process, the surface of the wave joint can be observed in the material structure. The morphology of the wave surface in a joint can be divided into wave, straight and melted layers.

The present study was focused on the possibilities to use explosively clad material in deep drawing process. In order to study the deep-drawability of these materials, identification of the forming limit diagram is necessary. In the present work, FLD for the multilayered sheet was created using nonstandard method (Erichsen cupping test) coupled with Digital Image Correlation analysis. Additionally, the Erichsen test used in the experimental procedure allowed to estimate the susceptibility of multi-layer metal sheets to plastic deformation under a complex deformation state. In the work, the FLD test was designed with the use of six different geometries of samples presented in Fig. 2 a - f. Such geometries were proposed to ensure the proper deformation state (minimize the risk of drawing the edges of sheets into deformation zone). The test was performed on a MTL-10G testing machine, the geometry of the tools is presented in Fig. 2g. The Erichsen test was carried out at room temperature with a constant punch speed of 15 mm / min. The pressing force was 10 kN. The performed test was coupled with the Digital Image Correlation measurement. First, the surface of each sample was painted with a stochastic pattern. Maintaining high-quality images during deformation is critical to obtaining good-quality correlation results. For DIC analysis, two high-resolution CCD cameras were used to track the position of the same physical point shown in the reference and deformed image. The three dimensional DIC algorithm based on the tracking of the grey value pattern in small local neighborhoods was used. In the correlation the face size equal 25 px and the grid spacing of 19 px was applied. The image resolution was 0.004 mm/px.

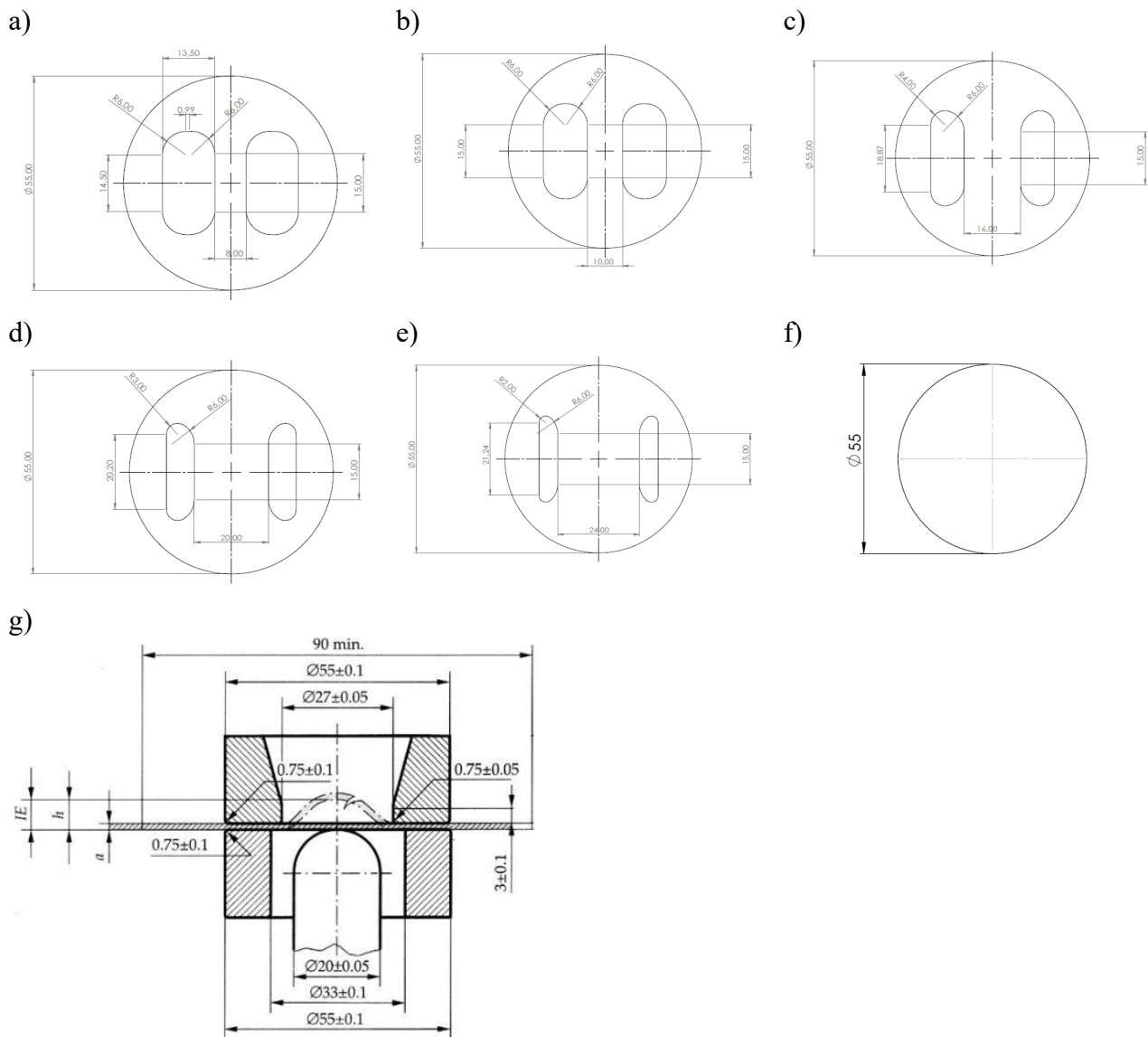


Fig. 2. The specimen geometry using to the FLD test – a) -f); scheme of the Erichsen cupping test [15].

Results and Discussions

The forming limit diagram based on the forming limit curve (FLC) is one of the most important tools in the analysis of sheet metal forming processes. Proper analysis of the deformation process and comparison of the obtained experimental data with FLC ensure a reliable assessment of the mechanical states in sheet metal forming processes. Identifying the conditions of plastic flow instability is particularly important in the case of deep drawing with the use of multi-layer materials. As already mentioned, the FLC for the multilayer sheet was created using a custom method (Erichsen test) combined with DIC analysis. During the DIC analysis the position - dependent method based on the ISO standard was adopted.

In the first step of the work, the as-received materials (before explosive welding) were analyzed. The DIC measurements were made according to the ISO 12004-2:2008 standard. After recording images, the data processing was performed using Istra4D software. The obtained maps of the main strain distributions made it possible to draw a line along each sample. Based on the data recorded in the correlation analysis, parabolas and equations describing them were determined (Fig. 3).

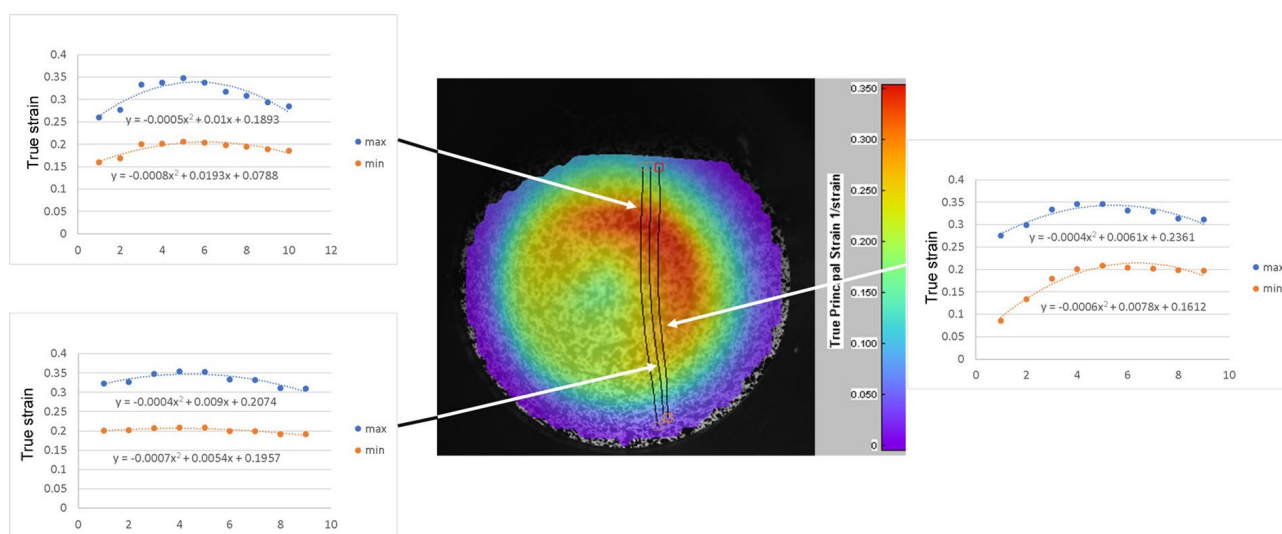


Fig. 3. Strain distribution maps for the specimen represent equibiaxial tension with the constructed parabolas for three lines.

In the presented work three lines for each specimen were chosen. Those lines were marked in the strain concentration area where the crack occurred after deformation process. The determined parabolas for the marked lines were the basis for determining the values of the major and minor strains.

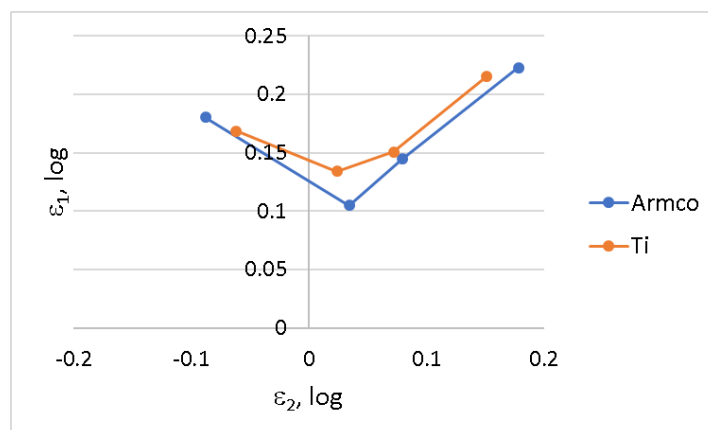


Fig. 4. The forming limit curve for the Armco iron (blue) and titanium (orange) sheets metal.

The forming limit diagram (FLC) for the both starting materials are presented in the Fig. 4. Comparing obtained results, it can be seen that the higher value of the major strain distribution was observed in the case of the titanium sheet for each of the analysis strain state. The minor strains of the specimens, representative the uniaxial tension and equibiaxial tension achieve higher value for the Armco Iron sheet.

It should be mentioned that the results obtained for the deep drawing test based on the custom Erichsen test and the tensile test show differences in the behavior of the material. The reason for this may be due to the occurrence of two different deformation states, i.e. uniaxial and three-dimensional. The second step of the presented research was focused on the Ti-Armco-Ti multilayer material. The experimental procedure was the same as in the case of the starting materials. At the beginning the tensile tests were performed. The obtained yield point was higher than for both starting materials and equal to 528MPa. Next, based on the strain distribution map analysis the forming limit curve was calculated. Obtained principal strain distribution maps from the DIC analysis are presented on the Fig. 5.

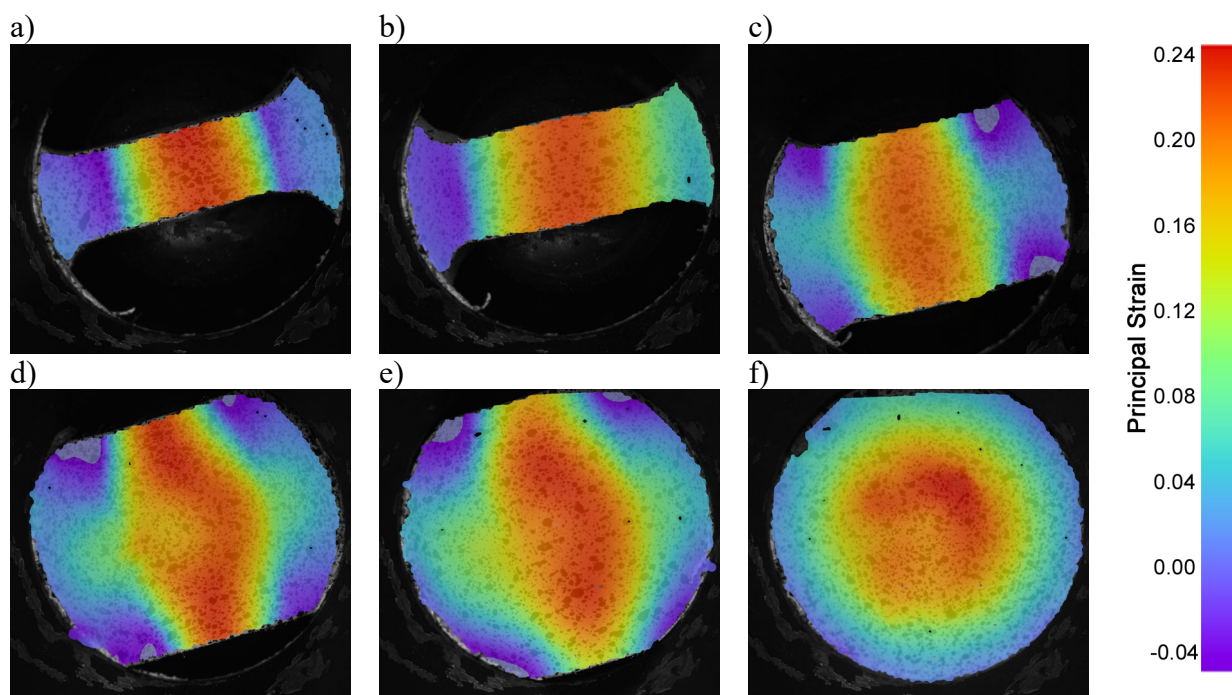


Fig. 5. Principal strain maps distribution obtained for the specimens with gauge width equal 8mm – a); 10mm – b); 16mm – c); 20mm – d); 24mm – e) and 55mm – f).

As expected, the strain concentration was located near the center of the gauge area. The higher strain value shows that the samples represent two different strain states i.e. uniaxial tension and equibiaxial tension. The lowest value was recorded for a sample with a gauge width of 16 mm. For the remaining three samples, the obtained deformation value was similar to each other and amounted to about 0.2.

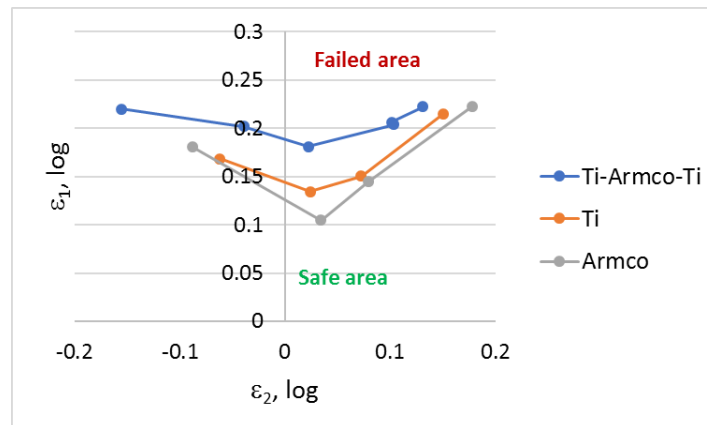


Fig. 6. The forming limit curve obtained for the multilayer material (Ti-Armco-Ti) and both starting materials.

The forming limit curve (FLC) for the three-layer material is shown in Fig. 6. Comparing the FLC for Ti-Armco-Ti with the FLC obtained for the starting materials (Fig. 4), it can be seen that the safety area in the case of the multi-layer material is greater. The multilayer material representative of the major strain was higher than that of the starting material by approx. 30%. The largest difference was recorded for the specimen with gauge width of 16 mm. The recorded main strains for samples representing equibiaxial stress for each analyzed material had a similar value. In the case of minor deformation, the comparisons between the analyzed starting materials and the material after explosive welding were smaller. Only in the sample with a thickness of 8 mm, the slight deformation for the multilayer material (-0.155) was more than twice lower compared to both starting materials (Armco iron: -0.088; Ti: -0.062).

Summary

The performed tests allowed for the characterization of the complex state of deformation and stress that occurs during a deep pressing station. For this purpose, the Digital Image Correlation System was used. An additional challenge was the deformation of the Ti - Armco - Ti multilayer material after explosive welding.

The results of the research on the component materials were taken as the starting point for the analysis of the mechanical state during the non-standard Erichsen test of the multilayer material.

Based on the DIC analysis, the forming limit curves (FLCs) were determined for the two base materials used (before the explosive welding process) and the multilayer material (after the explosive welding process). The DIC analysis was based on the position-dependent methods used in ISO 12004-2: 2008.

Based on the presented results, the following conclusions can be drawn:

- The resulting forming limit curve for the material after explosive welding shows a greater safety area than the FLC obtained for both starting materials (titanium and iron Armco sheets).
- An additional advantage of using the non-standard Erichsen test for FLC determination is lower material consumption compared to the use of standard sample geometry in the Nakazima or Marciniak tests.
- The presented results indicate that the DIC system can be successfully used to develop a graph of the formation limits of multilayer materials using a non-standard method (Erichsen test).
- Properly planned and performed deep drawing of multilayer materials can only be performed on the basis of a detailed analysis of the rheological and mechanical properties of clad sheets.

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