Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 20
ISSUES 1-2
January-February
2007

# Effect of forming rate on the impact tensile properties of the steels under crash test

**E. Bayraktar [a,*], M. Grumbach [b], D. Kaplan [b]**
[a] Supmeca/LISMMA-Paris, School of Mechanical and Manufacturing Engineering, EA 2336, St-Ouen, France
[b] ARCELOR Group, Paris-France
* Corresponding author: E-mail address: bayraktar@supmeca.fr

Received 02.11.2006; accepted in revised form 15.11.2006

Properties

## ABSTRACT

**Purpose:** The main objective of this study is to examine the mechanical and metallurgical behaviour of the tailored blanks and base metals for thin sheet steels used in the car industry by using a new type of crash test/impact (ITT). It exposes the effect of forming rate on the toughness of thin welded joints (tailored blanks) for Interstitial Free (IFS) steels used in the automotive industry.

**Design/methodology/approach:** A special crash test device is used in different temperature and the simulated crash tests are performed at a constant speed of 5.52 m/s (strain rate about 250 $s^{-1}$).

**Findings:** The specimen is submitted to impact tensile test at different temperatures. According to testing temperature, fracture mode varies: At low temperatures, brittle fracture occurs: Due to stress concentration, fracture always occurs in the notched section. At high temperatures, the specimen fails by ductile fracture. Toughness of the steel sheets (base metals, BM or tailored blanks, TBs) after forming at certain levels is well compared at different materials and test conditions.

**Practical implications:** This study gives very useful data for the crash test. This is a new conception of specimen and of the impact/crash machine. It is easily used in automotive industry for practical and economic reason to give rapid answers to designer and also steel makers for ranking the materials.

**Originality/value:** This research used a new developed test called simplified crash test for evaluating the effect of forming rate on the toughness of thin welded joints (tailored blanks) / mechanical assemblies in high formability steel sheets for stamping submitted to dynamic loads such as experienced in real crash tests.

**Keywords:** Mechanical properties; Crash test; Tailored blanks; Forming; Interstitial Free Steel

## 1. Introduction

Interstitial Free (none commercialised IFS) steels with very low C and N contents are successfully used in many specific or complex deep drawing operations in the automotive industry. Most important expansion of tailored blanks, TBs, by means of LASER welding and the general application of LASER welding in this area has also arisen.

The behaviour of welded structures during car crash is of major importance for automotive designers. On the other hand, steelmakers need simpler dynamic testing for the evaluation of the steels characteristics, particularly of welds (spot or LASER joints). Furthermore, mechanically effective tests which are sensitive to microstructural gradients should be preferred. Constitutive laws will be derived from these tests for incorporation to Finite Element codes for predicting car behaviour during crash situations.

These remarks make the objectives of the proposed research here: A methodology is being developed in the frame of a research project which is going on for the testing of thin specimens (Base metal or tailored welded Blanks) to be able to characterize and understand the behaviour of steels themselves and thin welds/mechanical assemblies of different steels submitted to dynamic loads such as those experienced in automotive crash tests and also, through a simple simulated crash test, the influence of various joining parameters and microstructural features on the mechanical behaviour are examined.

Certain grades of IF steel are particularly suitable for ultra deep drawing operations due to high “r” values (Lankford ratio). However they can present some brittleness after forming. The desired behaviour can be obtained through an optimisation of the design of the part, and through the intrinsic quality of the base materials and their welds. These simultaneous evolution of materials and of the joining techniques need adapted tests for assessing the dynamic behaviour of the structures [1-18]. An experimental study has been carried out in order to identify the impact behaviour of the certain grades of IFS after forming operations. First part of this paper will describe the methodology developed for pre shearing varying from 0% to 50% for base metals (BM) and also for the tailored blanks up to 20% and second part will discuss the impact/crash test results to explain the effect of pre-forming on the impact behaviour of the certain grades of IFS sheets. The intention was on the fractography analysis for the tested specimens by means of the scanning electron microscopy (SEM).

## 2. Experimental conditions

### 2.1. Materials, tests and analysis

Different grades of high formability steel sheets (IFS) for stamping were used in this study. They are cold rolled steel grades. The carbon and manganese contents vary from $1.4\times10^{-3}$ to $5\times10^{-3}$ wt% and from $100\times10^{-3}$ to $650\times10^{-3}$ wt%, respectively. Thickness of blanks varies from 0.9 to 2,5 mm. The laser welding processes for TWBs of the thickness ratio of 1 were performed with $CO_2$ laser ($\eta \approx 15\%$) with 0.95 kJ/cm of linear energy.

The principle of the impact tensile testing has been well explained formerly [1, 2, 4, 7, 8]. All of details on this new methodology have been published in [1, 4, 8]. Briefly, this test is based on the use of a specially designed two-body tensile specimen, including a smooth part and a notched section. This specimen is mounted in a special device called crash simulation device and the whole setting is brought to the desired testing temperature by means of a cooling system (in liquid nitrogen).

Afterwards, this set is rapidly placed in a pendulum device having a quick locking system where special housing has been arranged (<3 s) and fractured. Figure 1a shows a typical deep drawing simulation test device developed by Arcelor-Irsid. This test allows obtaining a pure sheared zone (25-50%) that can be sampled for crash test simulations (Figure 1b). These special geometries of the specimen to be tested is composed of two different parts, a smooth and a notch section adapted to welds and base metals.

The new impact tensile test measures the total energy absorbed in fractured testing parts. The instrumentation of the test enables to obtain stress-strain laws in dynamic testing. With the help of photo-deposited grids prior testing, it is possible to derive local strain rates in the welds. According to test temperatures, strain rates vary. Thus, changing testing temperature in this test is a convenient way for obtaining a whole range of strain-rates, similar to the ones obtained in crash testing [4].

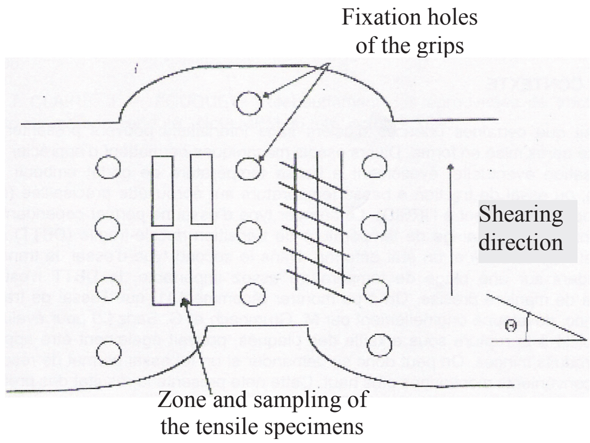



Fig. 1a. Schematic of specimen device containing a homogenous sheared zone allowing the sampling for crash test

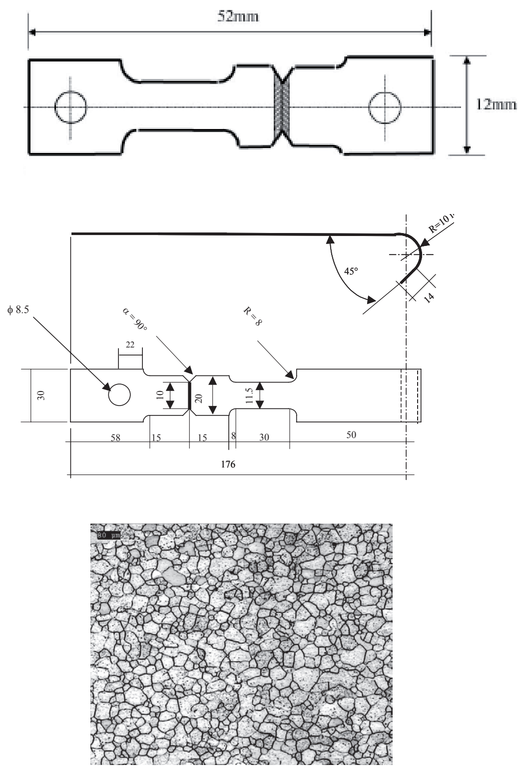



Fig. 1b. Sample geometries and microstructure of IFS used in simulated crash test applications

As it possible to design specimens with areas differing in the notched and the smooth section, the degree of "**matching**" can be finely adjusted: Then after, tests are carried out either in the "**undermatching**" situation (load capacity under simple tensile effort) of the section under the notch is inferior to the one of the smooth section) or with "**overmatching**".

Simulated crash test installation of the assembly with a capacity of 650J are shown in the Figure 1c.

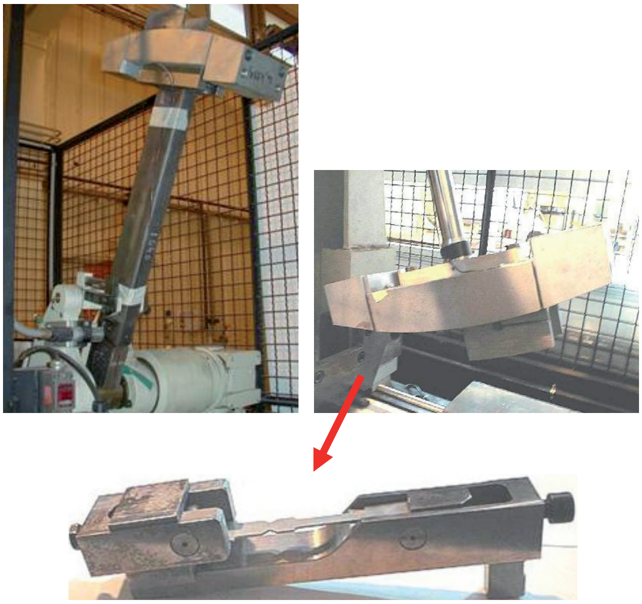


Fig. 1c. Simulated crash test installation of the assembly with hammer and support adapted to the double cutter and specimen for the testing of the steels (capacity of the assembly: 650J)

All impact tensile tests (ITT) in different temperature are performed at a constant speed of 5.52 m/s (strain rate about 250 $s^{-1}$). The SEM photomicrographs were carried out in a 435 VP – LEO-2003 model scanning electron microscopy (SEM).

## 3. Results and discussion

The ductile-brittle transition (DBTT) curves of fracture mode obtained by simulated (impact) crash test (ductile fracture in the smooth part and brittle fracture in the notched part) are given in the Figures 2a (0% forming), 2b (ε=27%) and 1c (ε=52%). Two modes of failure are observed:

At high temperatures, the specimens fail in the smooth part and at low temperatures, the fracture occurs in the notch with little energy. Fracture energy levels vary between 8 J (in the notched part 91 J/cm²) and 33 J (in the smooth part 330 J/cm²).

Transition temperatures are found for each forming rate; -110°C (0%), -105°C (ε=27%), -105°C (ε=52%). Thus, transition temperatures are defined with very great precision, better than 5 – 10°C. Few testing specimens are needed for transition temperature determination. In our test conditions, increase in DBTT due to pre-forming is very weak.

SEM photomicrographs of fracture surfaces are shown partially in both of the Figures 2a-c and essentially in the Figures 3 at the different pre forming conditions.

The following observations are revealed: In the non preformed samples, the fracture are combining and happen partially by cleavage or intergranular types. In the case of preformed samples (forming rates, (ε=27 and 52%), fractures surfaces present also typical combined types (cleavage or intergranular types).

However, in the higher forming levels such as more than 30-50% of forming rates, very pronounced scratches (deformation lines) are observed. It is most probability the forming effect result in appearance of the slip lines, of which general direction correspond to the intersection of shearing plane and also to the fracture plane.

Here, a particular attention was given to the broken specimens that are interesting to underline these observations:

In the case of the steels that non-deformed before crash test, the fracture occurs as usually at the low temperature at the notched part. It means that fracture path follows the normal direction with respect to the solicitation direction (Figure 4a).

But, in the tests with formed samples, the principal direction of the fracture coincide roughly with the direction of forming (in the shearing direction) as seen in the Figures 4b-e. In other words, the fracture initiates at the bottom of the notch and then follows the shearing direction of the samples after that fracture deviation is observed, it means the bifurcation occurs in the part of its trajectory in order to meet again eventually in the opposite zone of the bottom of the notch.

It can be observed also a situation where two simultaneous cracks, corresponding to the part of the shearing direction, lead to a fragmentation of the specimen during the fracture.

These observations can verify well the reality that the forming of the parts (pre-deformation) lead to an embrittlement corresponding to the preferential –forming- direction under the crash test.

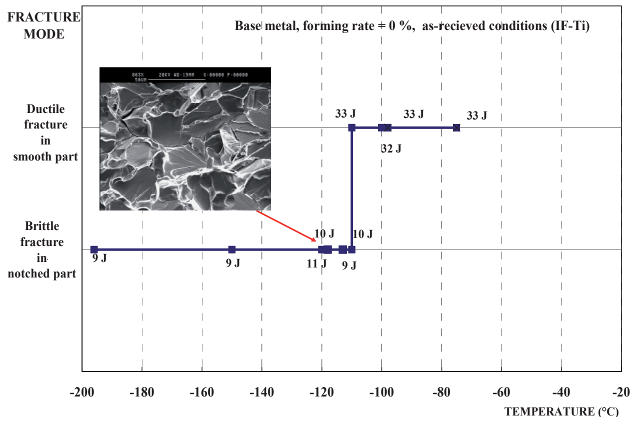



Fig. 2a. Ductile-brittle transition (DBTT) curves of fracture mode obtained by simulated crash test at the conditions of the forming rate of ε = 0 %

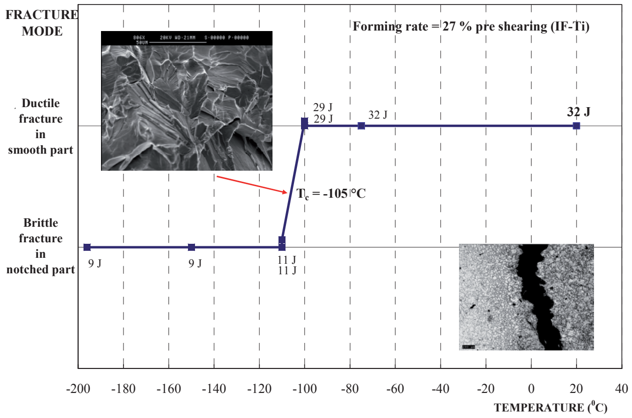



Fig. 2b. Ductile-brittle transition (DBTT) curves of fracture mode obtained by simulated crash test at the conditions of the forming rate of ε = 27 %

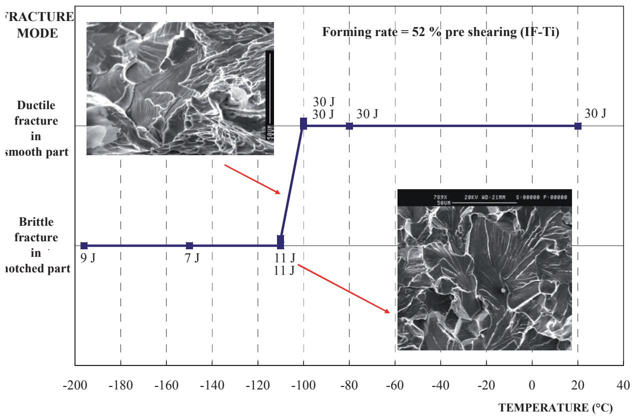



Fig. 2c. Ductile-brittle transition (DBTT) curves of fracture mode obtained by simulated crash test at the conditions of the forming rate of ε = 52 %

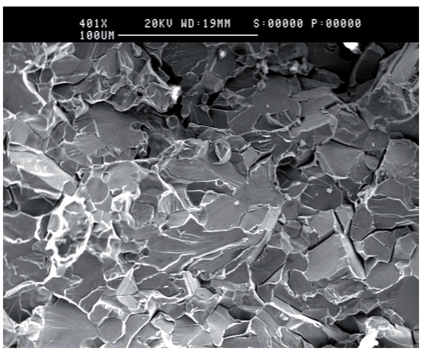



Fig. 3a. SEM microphotographs of the non-preformed a specimens under the chock (base metal), ε = 0% (test= -150°C)

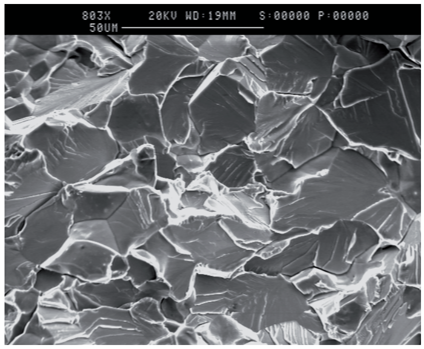
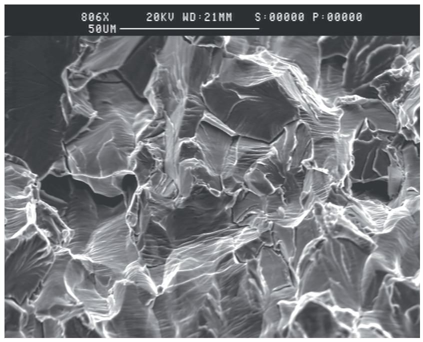
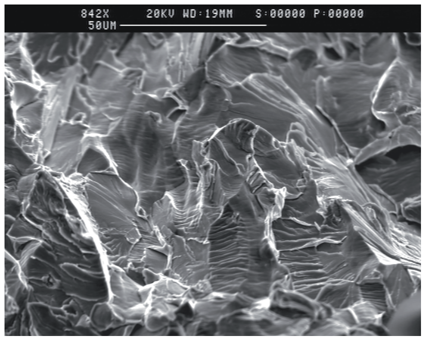



Fig. 3b. SEM microphotographs of the pre-formed specimens under the chock (base metal), ε=27% (test= -150°C)




ε = 52% (test= -140°C)




ε = 52% (test= -150°C)

Fig. 3c. SEM microphotographs of the pre-formed specimens under the chock (base metal), ε = 52%

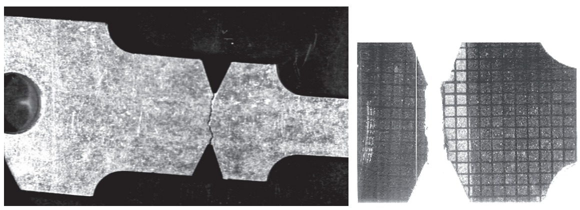
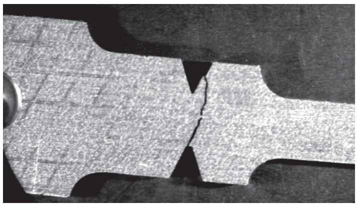
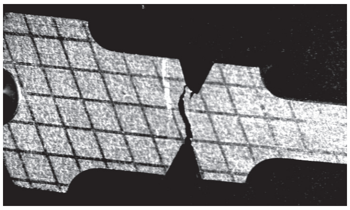


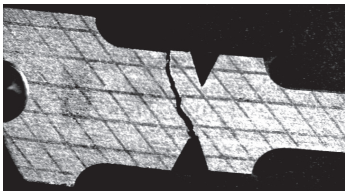
Fig. 4a. Fracture macrophotographs of the specimens under chock at 0% of pre-forming rate conditions



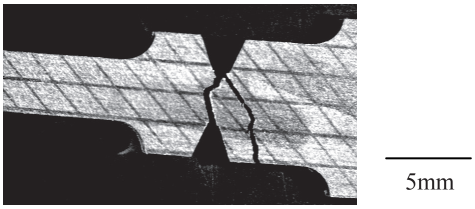
b) Pre-forming rate, ε=27%



c) Pre-forming rate, ε=27%



d) Pre-forming rate, ε=52%




e) Pre-forming rate, ε=52%

Fig. 4b-e. Fracture macrophotographs of the specimens under chock at 27 and 52 % of pre-forming conditions

Ductile-brittle transition curves of fracture mode of the tailored blanks of another grade of IFS, in the case of without pre-forming and pre-forming-shearing- up to 20 %, are given in the Figure 5. On the contrary to base metal testing, specimens including welds have heterogeneous structure because of local modification due to phase transformations during welding.

Fracture competition between these two sections during impact loading is more complex because of different mechanical properties. At this stage, it is convenient to introduce a "matching" parameter α for quantifying the ratio between the load capacities of the two sections during the impact testing.

Failure always occurred in the smooth part at high temperatures with much strain. (the same as for base metal specimens)and in the notch at low temperatures with little energy and no macroscopic deformation i.e. it is lower than for base metal specimens. The failure generally happens in the weld zone.

When the notch is located in the HAZ, the failure is naturally in the HAZ (Figure 6). In our cases, the transition temperatures are found for each forming rate: -130°C (0%), -120°C (ε=20%).

Here, an increase in DBTT due to forming rate is determined about 10°C. In the case of pre-formed TBs, the crack deviation is weak, the fracture follows weakly the direction of forming (in the shearing direction). But, pre-forming of the TBs leads also to an embrittlement corresponding to the preferential –forming- direction under chock.

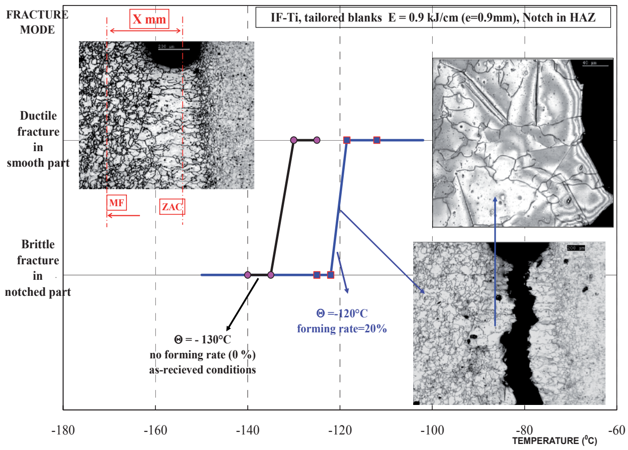
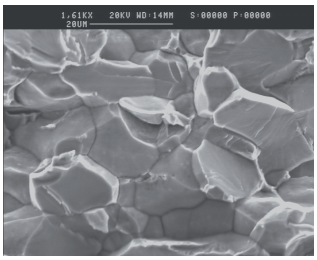
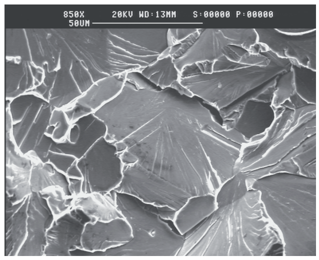


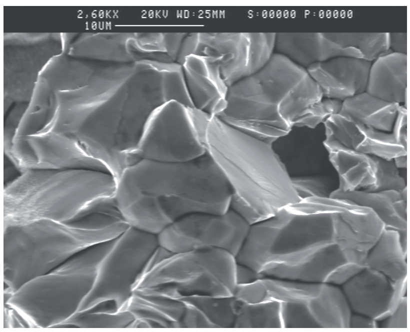

Fig. 5. Ductile-brittle transition (DBTT) curves of fracture mode obtained by simulated crash test of the tailored blanks



ε=0% (test= -140°C)



ε=20% (test= -140°C)



. ε=0% (test= -130°C)

Fig. 6. SEM microphotographs of the non-preformed and pre-formed tailored blanks under the chock, IF-Ti

## 4. Conclusions

This study contains partially the results of global crash test project which is going on. Here only some major trends can be underlined:

The results of the simulated crash test applications designate that this test is well adapted for the characterisation of thin sheets, in particular of the tailored blanks, for ranking the materials or the fabrication conditions with respect to their resistance to fracture in the presence of a defect. It can be used very successfully to understand the role of welding parameters, forming rate and microstructures, and to study easily the "matching" problems in the welded joints.

Increase in DBTT due to pre-forming is very weak for the BM and the TBs. This work showed that the pre-forming of the parts lead to an embrittlement in the forming direction under the crash test.

Additionally, very useful results were also determined in point of view of fracture mechanism to take apart the responsibility of the steel makers (microstructural evolution and formability capacity of the materials) and also designer (welding parameters, etc.) on the damage mechanism of the base metals and welded joints under crash test simulation.

In our experimental conditions, overmatching of HAZ / BM and WM is found always favourable for toughness values of tailored welded blanks.

However, complementary studies are needed to well correlate the results derived here with more complex and global crash tests on the welded structures.

## Acknowledgements

This project is supported by ARCELOR CED Auto Applications. In the name of LISMMA-Paris, E. Bayraktar is indebted to the research managers of ARCELOR Auto for their valuable help for this project which is going on.

## References

[1] M. Grumbach, G. Sanz, Ductile-Brittle Tests by Impact Tensile Test (ITT), Journal of Metallurgy, 2 (1972) 145–164.

[2] E. Bayraktar, J.P. Moiron, D. Kaplan, "Effect of welding conditions on the formability characteristics of thin sheet steels; mechanical and metallurgical effects", Journal of Materials Processing Technology, 175, 1-3 (2006) 20-26.

[3] Welding-Resistance spot and projection welds-Destructive tests of welds - Specimen dimensions and procedures for impact shear test and cross tension testing'. Document ISO/DIS 14323, IIW/III-949-88, 2001.

[4] E. Bayraktar, D. Kaplan, C. Buirette M. Grumbach, Application of Impact tensile testing to the welded Thin Sheets, Journal of Materials Processing Technology, 145 (2004) 27-39.

[5] H. Zhao, G. Gary, Behaviour characterisation of polymeric foams over a large range of strain rates. Int. J. Vehicle Design, 30 (2002) 135-145.

[6] H. Huh, W.J. Kang, Crash-worthiness assessment of thin walled structures with high strength steel sheet, Int. J. Vehicle Design, 30 (2002) 1-21.

[7] E. Bayraktar, D. Kaplan, D. Hugele, J.P. Jansen, Evaluation of Pipe Line LASER Girth Weld Properties by Charpy and Impact Tensile Tests, Journal of Materials Processing Technology, 147 (2004) 155-162.

[8] E. Bayraktar, D. Kaplan, M. Grumbach, Application of impact tensile testing to the spot welded Sheets, Journal of materials processing technology, 153 (2004) 80-86.

[9] ISO 14273, Specimen dimensions and procedure for shear testing resistance spot, seam and embossed projection welds, 2000.

[10] H. Zhao, G. Gary, The testing and behaviour modelling of sheet metal at strain rates from $10^{-4}$ to $10^{+4}$ $s^{-1}$, Materials Science and engineering, 207 (1995) 46-50.

[11] D. Zeng, S. Liu, V. Makam, F. Zweng, Specifying steel properties and incorporating forming effects in full vehicle impact simulation, SAE technical paper series 2002-01-0639 SAE World Congress Detroit, 2002.

[12] M.M. Haque, M.S.J. Hashmi, Investigation on microstructure of medium carbon steel deformed at strain rates of up to $10^5$ per second at −30°C to 235°C, Journal of Materials Processing Technology, 56 (1996) 119-125 .

[13] H. Vegter, H. Pijlman, J. Huetink, Advanced mechanical testing of aluminum alloys and low carbon steels for sheet forming, Proceedings of Numisheet, 99 (1999) 3-8.

[14] A.G. Odeshi, S. Al-Ameeri, M.N. Bassim, Effect of high strain rate on plastic deformation of a low alloy steel subjected to ballistic impact, Journal of Materials Processing Technology, 162-163 (2005) 385-391.

[15] B.S. Yilbas, M. Sami, J. Nickel, A. Coban, S.A.M. Said Introduction into the electron beam welding of austenitic 321-type stainless steel, Journal of Materials Processing Technology, 82 (1998) 13-20.

[16] J.A. Goldak, D.S. Nguyen, A fundamental difficulty in Charpy V notch testing narrow zones in welds, Weld. Res. Sup., 2 (1977) 12–19.

[17] M. Brunet, F. Morestin, H. Walter-Leberre, Failure analysis of anisotropic sheet-metals using a non-local plastic damage model, Journal of Materials Processing Technology, 170 (2005) 457-470.

[18] B.Y. Ghoo, Y.T. Keum, Y.S. Kim, Evaluation of the mechanical properties of welded metal in tailored steel sheet welded by $CO_2$ LASER, Journal of Materials Processing Technology, 113 (2001) 692-698.