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Experimental characterisation in sheet forming processes by using Vickers micro-hardness technique

Ali Mkaddem *, Riadh Bahloul, Philippe Dal Santo, Alain Potiron

LPMI-ERT-ENSAM/CER, 2 Boulevard du Ronceray, BP3525-49035 Angers, France

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Abstract

In this paper, an experimental micro-hardness procedure is proposed to evaluate the evolution of HSLA steel behaviour during each sequence of sheet forming process. As micro-hardness technique offers a reliable inspection, it was retained here to follow the mechanical characteristic changes, which may happen during manufacturing progress. This contribution consists in characterisation of sheet material at different steps: virgin sheet, unreeled sheet, straightened sheet and bent sheet. Measurement performed on virgin HSLA steel showed that material is highly heterogeneous within the sheet thickness. The micro-hardness profiles examined after the bobbing-off step showed a high sensitivity of sheet behaviour to straightening operation that is widely adopted in steel working in order to make sheet sufficiently flat for forming. A level of hardening ratio between virgin material and straightened material has been clearly observed. Moreover, micro-hardness is investigated on bent parts at the fold zone for displaying the mechanical properties modifications under a large gradient deformation. In this way, hardening phenomenon and damage phenomenon, which are generally activated simultaneously for elastoplastic steel, are quantified accurately. Results compared into them gave a good idea about the interaction of process–material during manufacturing.

Keywords: Micro-hardness; Sheet metal; Bobbing; Straightening; Bending; Damage

1. Introduction

Sheet metal forming industry has become one of the major manufacturing centres of the automobile industry. The popularity of sheet metal products is attributable to their light weight and their higher formability.

Sheet working consists in a more complex plane straining process, designed with high ratio of thickness reductions involving a considerable amount of texture evolution as mentioned by Tang and Tai [1].

Diversity of sheet metal manufacturing sequences as bobbing, bobbing-off, straightening and bending, as shown in Fig. 1, leads to a level and progressive change of material characteristics.

At several time, mechanical and environmental conditions of forming are considered among the main causes that induce a decrease in steel strength designed with microstructure changes during forming cycle [2].

In pioneering studies [3–7], the main investigation of material strength, resistance to thinning, damage and ability of material to forming are extensively performed for one material state or for separate steps.

Indentation micro-hardness testing at low loads is a well-accepted tool for assessing various mechanical properties such as flow stress, fracture stress, Young's modulus and fracture toughness of rolled material [8]. Thus, a proposed method for measuring micro-hardness is used to follow the properties variation with the evolving of manufacturing sequences of 0.09% HSLA sheet metal carbon steel. Curves deduced from the measured values within the sheet thickness are discussed for all considered steps of the forming processes.

2. Rolling process

2.1. Rolling cycle

The rolling process consists of several successive steps as shown in Fig. 2, which govern the final state of matrix material. The level of thickness reduction leads to a high-hardened metal by introducing an important change to the crystallographic texture [9].

* Corresponding author.
E-mail address: ali.mkaddem@angers.ensam.fr (A. Mkaddem).

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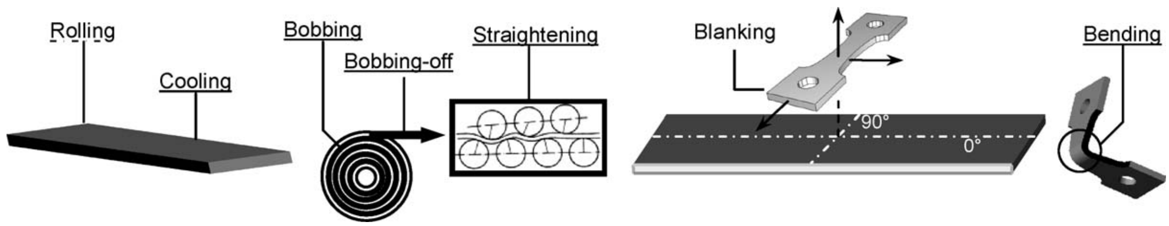

Fig. 1. Main sequences for manufacturing cycle.

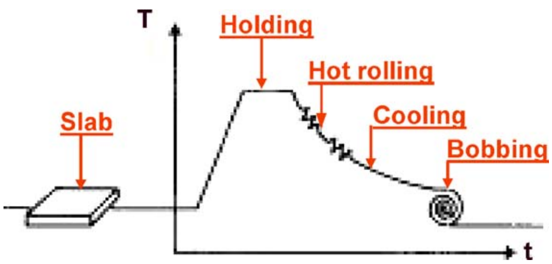

Fig. 2. Main steps for sheet rolling processes.

In the general manufacturing practice, the holding temperature of the slab must be enough high to make once again the precipitations, formed at the end of coiling, in the austenitic solution. It must be controlled accurately in order to lead to good material properties.

At the end of hot rolling step, the temperature would also be adapted precisely to make certain the successful precipitation of as small a grain size as possible. During this sequence, it must be assured that the used temperature cannot conduce to a heterogeneous microstructure.

After rolling, the sheet is cooled by soaking, and then bobbed. The grain size of material microstructure depends strongly on the adopted cooling speed. The grain size is as small as the cooling speed is high.

The bobbing step has a specific influence on the final mechanical and microstructure characteristics of rolled steels. The bobbing temperature consists in an own thermal treatment of reheating the sheet. It has a particular effect on grain size and precipitates that can be developed during process progression [10,11]. The distribution of matrix material contents is firstly a function of present elements quantities in the HSLA steel and secondly it is a function of the rolling conditions, which play great actions in microstructure evolution during each step of the rolling cycle.

2.2. Reference material

Generally, rolled materials are delivered in bobbin form. Before bobbing, the matrix material is considered “virgin”. This state of sheet would be considered the reference metal. It was kept from the inner extremity of the bobbin that is sufficiently flat as can be seen in Fig. 3a. Reference sheet allows for quantifying the microstructure hardening for the following state of straightening and bending.

The thermo-mechanical rolling control process leads to a small grain size that provides high mechanical characteristics associated with a high formability. Fig. 3b shows the microstructure of the 0.09% C sheet steel. Ferrite grains for the considered material are generally smaller than 10 μm and preferred orientation caused by rolling are clearly marked. The previous elaboration steps, essentially, govern these final properties of microstructure.

3. Behaviour characterisation

3.1. Virgin sheet

3.1.1. Micro-hardness test

During the rolling step, when the final temperature is reached, the precipitates density increases rapidly and firstly close to the sheet surfaces where cooling rate is the highest. Consequently, grain development stops and a sufficiently small grain size would be obtained. Moreover, the microstructure characteristics are not homogeneous within the sheet thickness on HSLA steel.

The difference of microstructure specificities induces obligatory changes in the subsequent mechanical behaviour through the thickness as a consequence of granular gradient. Micro-hardness that is performed from inner surface to outer surface of the considered steel with 200 g load, offers

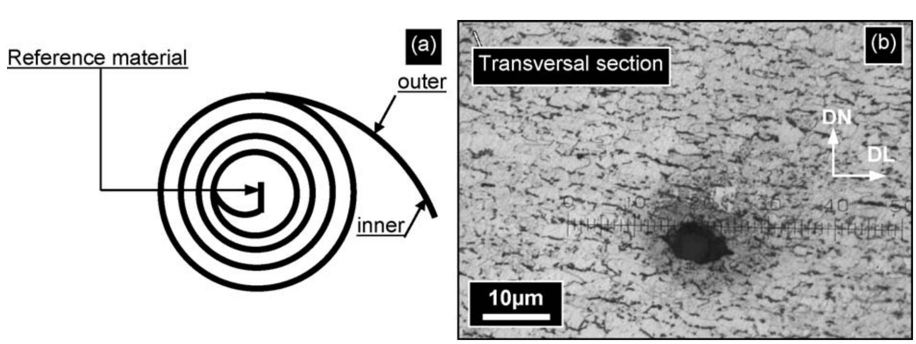

Fig. 3. (a) Reference sheet and (b) based matrix material for HSLA rolled steel.

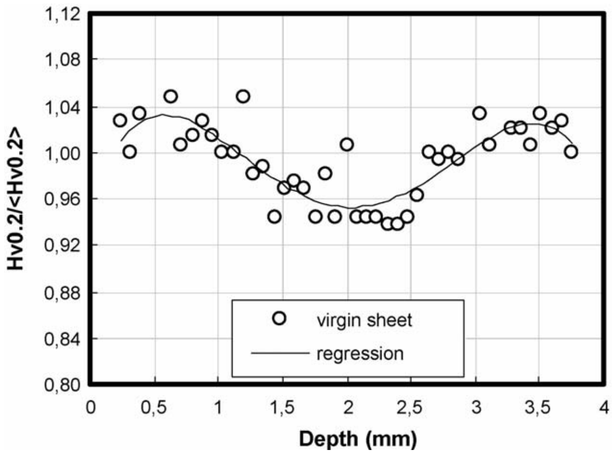

Fig. 4. Micro-hardness evolution within the virgin sheet thickness.

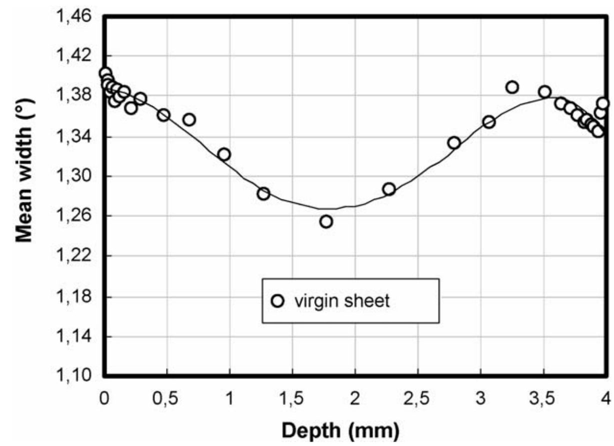

Fig. 5. Mean width X-ray diffraction evolution within the virgin sheet thickness.

precisions to understand the material behaviour of the virgin microstructure.

A specimen has been taken from the reference zone (Fig. 3) where material is considered with less deformation. Then, it was coated and polished to improve accuracy of measurement. Later, several indentation tests were carried in the cutting plan where the surface is polished.

Fig. 4 shows that the relative micro-hardness (values attributed to the mean value $\langle H_v \rangle$) is not uniform within the sheet thickness. In particular, highest values are located close to surfaces where grain is smaller. Hardening ratio seems to be low in the neutral zone where precipitates are generally developed belatedly compared to near surface zones. The micro-hardness evolution confirms the great importance of an accurate adjustment of temperature for holding step, rolling step and cooling step.

The difference between the relative values in neutral zone and surfaces reaches 8%, whereas there is no clear variation between the two surfaces of the sheet. Micro-hardness measurement performed on virgin microstructure would be considered as the reference behaviour of the sheet before any large deformation. In a practical way, micro-hardness characterisation must serve to identify the material behaviour progress with the subsequent manufacturing sequences.

3.1.2. Mean width X-ray test

Typical analysis has been carried out on the virgin sheet by mean X-ray diffraction technique.

The measured values of the mean width X-ray peaks which design the variation in terms of plastic strain in the matrix material are plotted within the thickness from inside surface to the outside surface of the sheet as given in Fig. 5.

It is worth noting that mean width distribution is inhomogeneous which confirms once again the results obtained by micro-hardness measurement. This typical evolution indicates that the different steps of elaboration process have a direct effect on the following material behaviour and induce a marked deviation between surfaces and neutral zone designed by the hardening ratio variation within the thickness.

High values of mean width, as has been noted by the micro-hardness investigation, are located at the surfaces of the sheet. The curve shows minima for an angle of 1.27°. There is no representative difference between the states of the two surfaces.

3.1.3. Correlation results

The typical distribution of micro-hardness and mean width investigated in the sheet thickness lets us to think of an evident based-experimental relation that can lead proportionally to predict micro-hardness values from the mean width X-ray peaks measurement for a fixed indention loads. In this way, a simple combination between Figs. 4 and 5 indicates that a linear relation can be found for the considered steel.

As expected in Fig. 6, there is a marked fitness of the measured values to the linear law that is, essentially, based on the fact that Vickers number and X-ray measured values have a relatively high fluctuation.

3.2. Straightened sheet

After rolling, the sheet metal is bobbed. During this operation, the microstructure undergoes some mechanical modifications

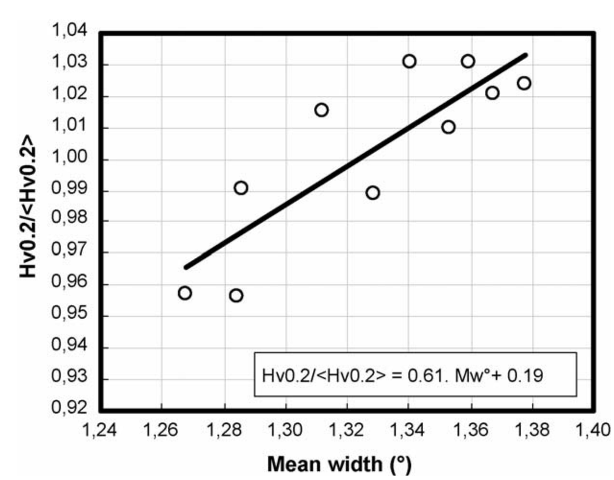

Fig. 6. Variation in relative Vickers micro-hardness with the mean width X-ray.

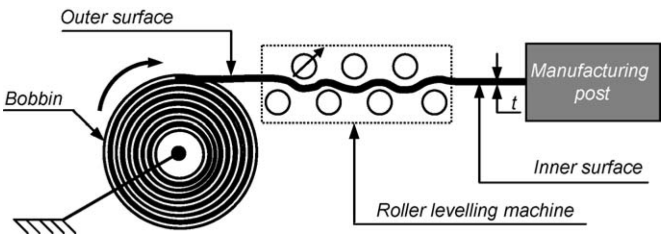

Fig. 7. Principal of roller levelling for straightening process.

such as the introduction of residual stress. To produce high quality parts, the bobbin must be bobbed-off and straightened. Roller levelling is a method widely used in steel working in order to straighten steel plates after rolling, heat treatment or cooling operations.

Roller levelling is carried out by subjecting the plate or bobbin to multiple back and forth bending sequences with decreasing roll penetration as shown in Fig. 7. It is a complex process and few details are known about the plate material behaviour modifications during this process. The sheet is exposed to reversed bending effect during straightening and the strains in the sheet are controlled by the device geometry of the levelling machine. This means that the sheet is subjected to reversed strain controlled cyclic loading.

This operation consists in applying a variable pressure to the sheet by acting different rollers in the machine. It is essential for steel manufacturing that, after straightening [12], the sheet would be sufficiently flat with required roughness and low residual stresses level which can increase the forming success of parts by using any subsequent processing step. Compulsorily, material undergoes plastic deformation during the straightening sequence which causes an amount of hardening ratio within the sheet designed by a micro-hardness level observed specially at surfaces.

Several micro-hardness tests have been performed on straightened sheets with different combinations of roller penetration. From the three pre-existing rollers, only the position of the first one will be changed. The positions of the second and third rollers are kept constant.

In the industrial practice, the highest penetration is necessarily performed on the first roller which is placed behind the bobbin, whereas the less penetration is performed on the roller following the second one or the third one. The considered material is of 4 mm thickness. The roller position will be designed by the triple combination [t, t, t] when there is no penetration. For different penetrations a, b and c, respectively, for the first, the second and the third rollers, the roller position will be designed by the combination [$t-a$, $t-b$, $t-c$]. The three investigated combinations are reported in Table 1.

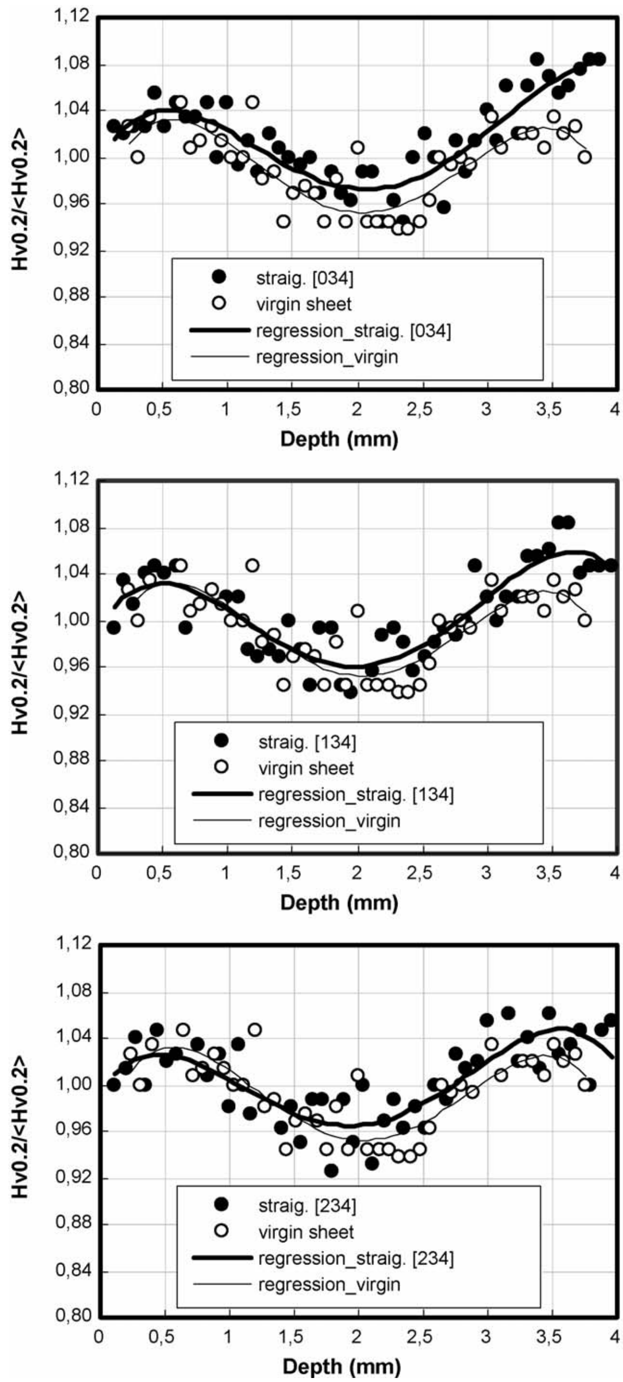

Fig. 8. Relative micro-hardness results obtained for straightened sheet.

Table 1
Different straightening adjustment for characterisation

	Roller 1 (mm)	Roller 2 (mm)	Roller 3 (mm)	Combination
First adjustment	0	3	4	[034]
Second adjustment	1	3	4	[134]
Third adjustment	2	3	4	[234]

Table 2
Bending parameters used for the investigated part

Punch radius (mm)	Die radius (mm)	Blank-holder radius (mm)	Stroke (mm)	Clearance (mm)	Thickness (mm)	Bending angle (°)
4	4	4	29	0	4	90

The measurement results are designed by the curves illustrated in Fig. 8, with virgin micro-hardness profile for each investigated case.

With comparison between virgin state and straightened state of sheet, variation of mechanical properties of the considered steel, resulting from the straightening sequence, can be clearly identified.

Referring to Fig. 8, it can be noted in all cases that straightened material becomes more hardened than the reference one. In addition, the behaviour seems to keep a similar non-linear evolution within the sheet thickness as it has been observed for micro-hardness evolution performed on virgin sheet.

In the three cases, microstructure modifications seem to be more localised near the surface than in middle zone of thickness when the measured relative values are less. In particular, the highest hardening ratio has been measured at the outer surface, which undergoes a positive stress field at bobbing sequence. The difference of micro-hardness level between the two sides of the sheet can be attributed to the superposition of plastic deformations in the external zones of the bobbin during bobbing and straightening operations.

In an aforementioned work [13], it has been laid down that the bobbin's outer side is more sensitive to micro-hardness quantification than the inner zone, that residual stress field is not similar within the sheet thickness and that it depends greatly on the previous manufacturing steps.

At this stage, the sheet is subjected to a low plastic deformation but it is sufficient to identify the only hardening level induced during straightening sequence. As can be seen in Fig. 8, the hardening level especially at the outer zone of the sheet is not similar for the three investigated cases. Referring to the micro-hardness profile, which is carried out in the reference material, it can be noted that the degree of hardening designed by the variation of Vickers micro-hardness values is as marked as roller penetration is high. This observation is associated with the effect of the plastic strain quantity that is induced in the matrix material and which depends directly on the roller penetration. When material flow occurs, a local shearing process is activated which leads to a fast amount of dislocation number. A high level of crystallographic texture density designs this phenomenon, which is followed by a local hardening process into grains and leads to a highly strengthened matrix material. The high crystallographic texture density of matrix material causes a relative local motion of shearing plans to which the variation of micro-hardness values in the middle thickness zone is attributed.

In detail, 1% hardening level has been computed for 0.5 mm depth, whereas the hardening level reaches 4.5% for 4.5 mm depth, respectively, for inner side and outer side of the sheet in the more severe straightening case of [034] roller combination. The variation between inner side and the middle thickness zone remains relatively constant referring to the virgin state of sheet.

Straightening conditions would have a direct effect on the mechanical behaviour during the following forming step. Strengthening caused by the roller levelling increases the properties gap between the middle thickness zone and closed surface zones of the sheet. The straightening process would lead to a homogeneous distribution of residual stress but the introduced hardening level would modify the material formability for the subsequent sheet processing sequences.

3.3. Bent sheet

During bending, material undergoes an important straining ratio, especially in the fold zone, which is characterised by the hardening phenomenon [14].

Depending on the process parameters, plastic strain in the enclave of fold zone can take a severe gradient leading to a high level of hardening ratio and damage that is designed by generation and development of micro-defects [15].

In an aforementioned investigation, Kurt [16] has deduced that micro-hardness is higher in the outer zone than in the inner zone of part's fold.

In this investigation, HSLA sheet steel parts have been bent by means of wiping die-bending process. Vickers number is investigated particularly in the fold zone of parts from the compression zone to the tensile zone. Tests are performed in such a way that the inner sheet surface corresponds to the inner fold zone where compressive hydrostatic stress state is applied. In this case, the outer sheet surface would correspond to the tension fibres zone. The main bending parameters used for the investigated specimens are reported in Table 2.

The influence of the bending operation has been analyzed through the micro-hardness testing profiles measured by using 200 g-indention load.

The treatment of measurement data leads to micro-hardness profiles of virgin, straightened and bent sheets plotted in Fig. 9.

It is found from the plotted data that the micro-hardness law is also non-linear for the bent specimen. The deviation of values

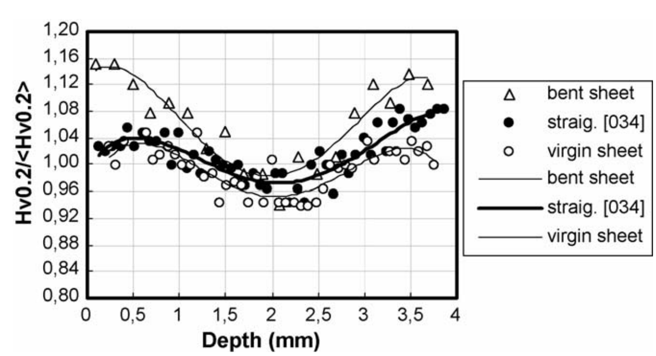

Fig. 9. Relative micro-hardness profiles for virgin, straightened and bent sheets.

between the neutral zone and the closed surface zones becomes more marked with bending. Certainly, during this operation the induced plastic deformation is higher than the one developed by the roller levelling machine during straightening step. The microstructure seems to be more sensitive to the bending operation than to the straightening one.

In particular it can be expected that the relative Vickers number is now more important in the inner zone than in the outer zone of the bent specimen. This observation is based on the fact that material undergoes compression hydrostatic stress in the inner fibres, which leads to stopping of the generation and development of micro-defects. In fact, the hardening level increases in the inner fold zone.

Referring to the virgin sheet, the relative micro-hardness has an increase of about 10% and 10.5%, respectively, in the tension fold zone and in the compression fold zone. On the other hand, it can be noted that microstructure changes designed by the micro-hardness value are negligibly small in the neutral zone.

Micro-hardness testing technique shows that it is sufficiently reliable to follow the material behaviour with the progress of manufacturing sequences. If the hardening ratio is directly designed by the micro-hardness amount within the sheet, the damage development that is directly affected by plastic strain evolution might be investigated only intuitively.

In order to go into more detail, a new approach for damage investigation is proposed in this paper.

4. Damage characterisation

4.1. Theoretical formulation

It was experimentally shown and theoretically found in several previous contributions [15–18] that the micro-hardness H_v for steel metal evolves linearly with the flow stress σ_{eq} in such a manner that:

$$H_v = k\sigma_{eq} \quad (1)$$

where k is a material dependent constant. The equivalent stress can be written as:

$$\sigma_{eq} = \sigma_y + R(\varepsilon^{Pl}) \quad (2)$$

where σ_y is the yield stress and $R=f(\varepsilon^{Pl})$ is the hardening law of considered steel. In the case of damaged material, Eq. (1) would be written as:

$$\frac{H_v}{1-D} = k\frac{\sigma_{eq}}{1-D} \quad (3)$$

where D designs a scalar damage variable. In fact, Eq. (3) can be rewritten in the following way:

$$H_v^* = k\tilde{\sigma}_{eq} \quad (4)$$

$H_v^*(\varepsilon^{Pl})$ defines the measured micro-hardness for the virgin material and $\tilde{\sigma}_{eq}$ is the effective equivalent stress. $H_v^*(\varepsilon^{Pl})$ is an extrapolation law of micro-hardness that represents the undamaged material behaviour.

For a power law, the hardening evolution would be written as:

$$R = Q_R(\varepsilon^{Pl})^{n_R} \quad (5)$$

Allowing that the micro-hardness is linearly proportional to the hardening law, the following relation can be deduced:

$$H_v^* = Q_H(\varepsilon^{Pl})^{n_H} \quad (6)$$

where Q_R and Q_H are, respectively, the hardening and the micro-hardness modulus. n_R and n_H are, respectively, the hardening and the micro-hardness components that must be equal if the linearity between H_v^* and R is admitted. For the subsequent development, it would be retained that $n_R = n_H = n$.

Tensile test conduces easily to identify n and Q_R. Micro-hardness tests lead to finding the H_v-law for damaged material. In addition, admitting that for a so small plastic strain ε_0^{Pl}, damage and hardening are so negligible that the following relation can be verified:

$$Q_H(\varepsilon_0^{Pl})^n = a \cdot Q_R(\varepsilon_0^{Pl})^n \quad (7)$$

and then,

$$Q_H = a \cdot Q_R \quad (8)$$

where a is a dependent material constant deduced from measured values, so that the micro-hardness law for undamaged material designed by H_v^* is found. The difference between H_v^* and the measured value H_v is then a measure of the damage D.

4.2. Identification of micro-hardness law

Knowledge of material behaviour is necessary for our experimental strategy. The micro-hardness law for virgin material

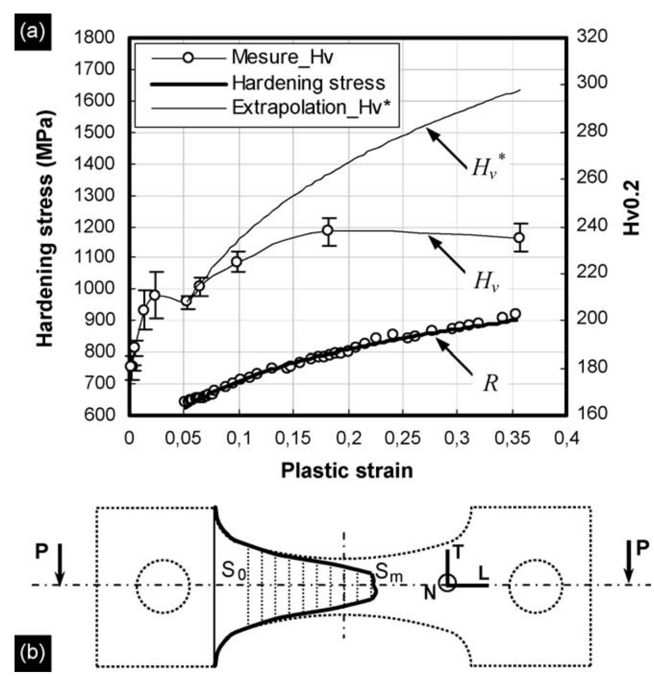

Fig. 10. (a). Micro-hardness law of damaged and virgin sheets and (b) specimen shapes before and after failure by tensile test.

cannot be found without the identification of the hardening parameters Q_R and n_R. For this reason, uniaxial tensile test has been performed on the considered material.

Before carrying out tensile tests, references have been drawn at the surfaces of specimens among the standard tensile length. The cross-sections have been measured at references before and after failure. The variation of thickness reduction consists in a measure of plastic strain in each position among the standard tensile length at the end of tensile test.

Micro-hardness tests have been conduced, by using Vickers indenter, according to the tensile direction, on transverse surface designed by (N, L) as shown in Fig. 10b. Measurements have to start at the less plastic strain region S_0 and finish at failure zone S_m where plastic strain is maximal. The field indentation data (H_v) deduced from tests have been plotted in Fig. 10a. Then, the extrapolation micro-hardness law (H_v^*), representing the virgin behaviour of material, was found thanks to hardening parameters identified previously by tensile test.

4.3. Identification of damage law

This approach has been retained in this investigation to characterise the damage law parameters for the considered HSLA steel. The measurements are carried out on specimen of the virgin material previously subjected to tensile test. Following the work of Mkaddem et al. [13], the damage values are deduced from the based micro-hardness approach and they are computed as follows:

$$D_H = 1 - \frac{H_v}{H_v^*} \tag{9}$$

The damage values calculated by means of Eq. (9) are plotted against plastic strain in Fig. 11a. A linear regression method is retained to investigate the based experiment damage results. As can be clearly observed, damage starts at 0.05 plastic strain value that designs the threshold point ε_D and then increases linearly with the plastic strain. The critical damage value D_R is identified at 0.21 for an associated plastic strain value of 0.36 at which failure of specimen occurs.

In order to confirm the reliability of the micro-hardness testing approach to characterise the constants damage law, several consecutive loading–unloading tensile tests are performed for the considered steel. The used tests specimen has been equipped by strain gauges adapted for large deformation. Three consecutive gauges have been bonded in each surface of specimen allowing reaching total failure. The measured load by using load cell leads to computation of the suitable stress value for each measure of plastic strain.

The Young's modulus changes designed by the elastic slope for each cycle of loading and unloading consists in the damage measured through the Lemaitre and Chaboche [19] formulation as follows:

$$D_E = 1 - \frac{E}{E_0} \tag{10}$$

where D_E is the scalar damage quantity and E and E_0 are, respectively, the Young's modulus for damaged material and virgin

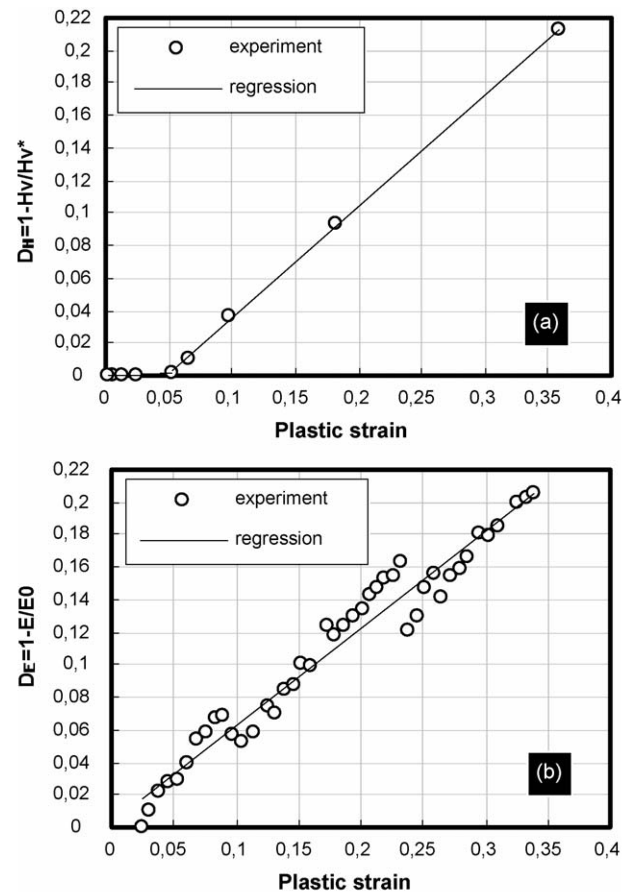

Fig. 11. Damage law deduced by: (a) micro-hardness approach and (b) tensile test procedure.

material. The linear regression of measured values leads to the plot of Fig. 11b. Then, it can be deduced that the threshold point is $\varepsilon_D = 0$; the critical point at which failure occurs is designed by $\varepsilon_R = 0.34$ and $D_R = 0.206$.

It is essential to note that agreement is very good between results obtained by both approaches. In fact, damage evolves linearly and constants are very similar. From a practical point of view, micro-hardness testing procedure seems to be simpler to carry out than loading–unloading tests. Besides, the proposed micro-hardness method is much less costly than the successive tensile tests.

In fact, micro-hardness characterisation showed that this technique is enough reliable to quantify rapidly the microstructure changes with the manufacturing sequences progress and to identify accurately the constants of material.

5. Conclusions and discussion

A comprehensive and accurate characterisation of material behaviour evolution is crucial for the forming of manufacturing parts, which are widely used in automotive and aeronautics industries. The micro-hardness measurement consists in an accurate inspection technique allowing for the characterisation of forming operations. In case of forming small or medium HSLA steel parts, the sheet metal undergoes cooling, bobbing,

Table 3
Hardening level (%) for straightened and bent sheet

Zones/steps	Straightening operation			Bending operation
	[034]	[134]	[234]	[034]
Inner zone (0.5 mm)	0.8	0.0	0.0	10.5
Outer zone (3.5 mm)	3.9	2.6	1.9	10.0

Table 4
Lemaitre damage parameters identified by experiment

Methods/parameters	ε_D	ε_R	D_R	Slopes (H_G)
Loading–unloading tests	0.0	0.34	0.206	0.60
Micro-hardness tests	0.05	0.36	0.212	0.68

bobbing-off, straightening and successive blanking and bending operations. Each of them induces modifications in matrix material, which affect the mechanical behaviour of the final products. In this contribution, it has been shown that micro-hardness measurements are a preferment technique, which can be used for the characterisation of the material hardening in the virgin sheet and for following the hardening progress resulting from the subsequent steps of straightening and bending process.

The experimental tests of micro-hardness carried out in different states of material seem to be so reliable to design the local microstructure changes, as has been found by the measurement within the thickness. In addition, the proposed method seems to be able to quantify accurately these changes even if they are so small. The hardening level introduced during straightening step and bending step is reported in Table 3.

The suitable comprehension and characterisation of material damage that can highly affect the material behaviour during forming and during the working life of a product is essential for the success of each manufacturing operation. The new micro-hardness procedure developed here has successfully led to the characterisation of Lemaitre damage parameters. From Table 4, agreement between damage constants identified by the proposed method and by loading–unloading tests shows the reliability of the micro-hardness procedure.

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