Smart Transportation Alliance

Recondition & Reuse of crash barriers after impact: features & risks

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Summary

Steel material presents excellent mechanical characteristics. As well as strength it possesses high deformation capacity, which not only makes it suitable for cold (notably by roll forming and stamping) or hot forming, but also allows it to be able to deform and absorb energy, notably in case of impact.

For this reason steel is one of the materials whose use is most indicated for the manufacture of crash barriers. In fact it can not only resist high loads without breaking but, in addition, absorb energy, which greatly increases survival chances for the vehicle occupants.

It can be tempting to want to reuse an old road barrier or a device damaged after a vehicle impact because, in theory, the mechanical characteristics of the steel permit it to be easily roll-formed again. However, without monitoring this practice can present danger for road system users.

This note thus provides an update on the potential consequences of crash barrier rails reconditioning to restore the original profile.

1. Elementary reminders on the mechanical characterisation of a steel

1.1. Stress-deformation curve

The mechanical properties of steel are identified by three basic concepts: elasticity, plasticity and impact resistance (or toughness).

- **Elasticity** is the ability of a metal to undergo a temporary deformation. When the load that caused this deformation is removed, the piece of metal returns to its original form. The maximum load that steel can withstand without causing permanent deformations is called the "elastic limit".
- **Plasticity** or ductility is the ability to undergo a permanent deformation without breaking. This property is used in forming metals to form and permanently modify the shape of a component. Plasticity also permits continuous absorption of energy by the steel structure, which is of particular interest for passive safety applications such as crash barriers. The maximum load that steel can endure without breaking is often called its "failure load" but several other names are also used.
  It will be noted that a material capable of significant deformation (5 to 20%) is said to be "ductile". Steel is a very good example of a ductile material. Conversely a material that has little or no deformation capacity is said to be "brittle" (for example glass or concrete).
- **Impact strength** represents the ability of the steel to absorb energy under the effect of an impact.

Each of these properties can be evaluated by very specific mechanical tests. Elasticity and plasticity can be defined from the results of tensile tests. The impact strength is determined by an impact test on a standard specimen (Charpy test). The present document focuses on the tensile test.

1.2. Tensile test – ISO 6892 characterisation

1.2.1. Introduction

The tensile test is one of the most classic tests: the purpose is to evaluate the behaviour of a material when it is subjected to a mechanical load.

This test consists of submitting a sample of metal to an axial tensile load, which is very slowly progressively increased to permit equilibrium to be continuously established between the applied load and the stress induced in the sample. The test machines continuously record the distance between the reference marks as a function of the applied load, which allows plotting of a stress-deformation curve representing the variation of the deformation with stress (load per unit area).

Figure 1 gives an example of the type of diagram obtained and illustrates the deformation of the sample during the test.

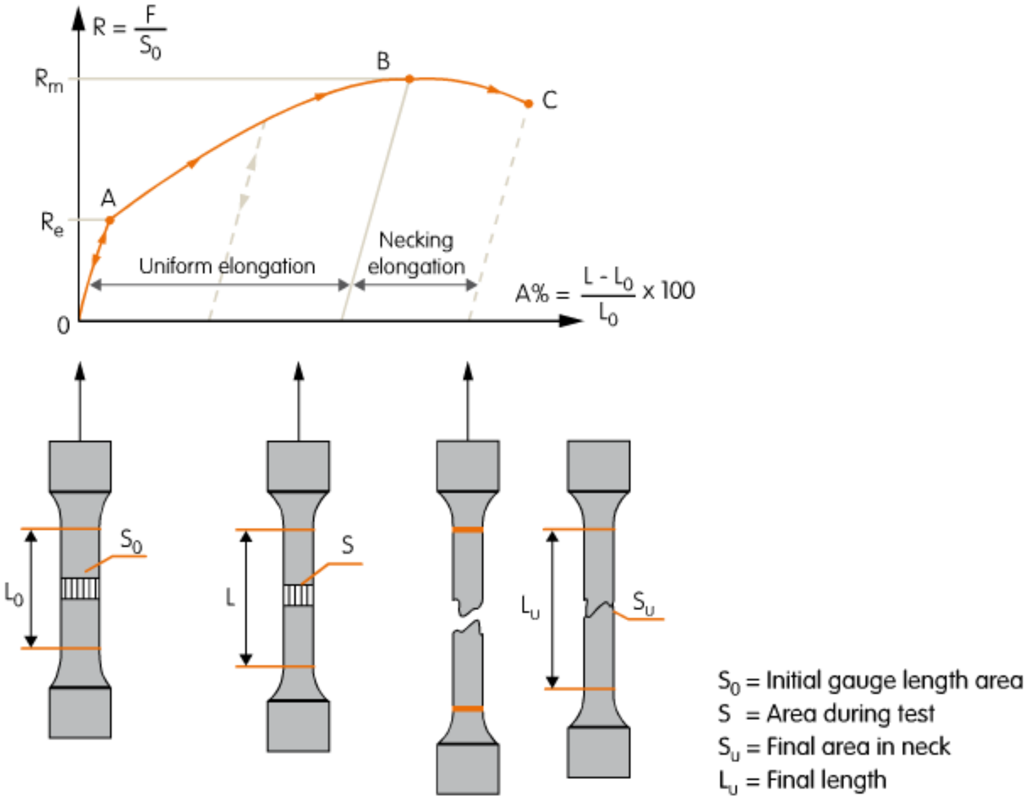


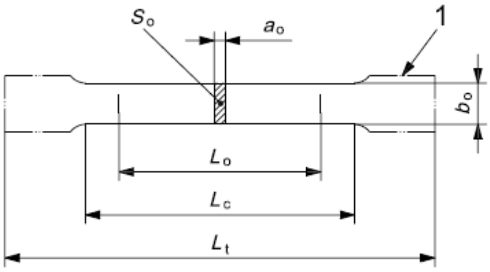
Figure 1: Test specimen deformation and Stress-Elongation Curve

1.2.2. Standard ISO 6892

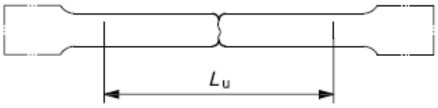
One of the standards currently most used for the mechanical tensile test is standard ISO 6892:2009.

During the tensile test two equal and opposite forces are progressively exerted on a standard specimen that is thus progressively deformed to rupture.

The specimen includes two reference marks, initially spaced by a distance L0 (length between the reference marks). When a force is applied to the sample, the deformation involves an increase in the distance between the reference marks up to a value L.



a) Avant essai



b) Après essai

Figure 2: Definition of length of machined specimens (ISO 6892 -1 :2009)

Legend (cf. ISO 6892 -1 :2009):

a_0 = initial thickness of a flat specimen or wall thickness of a tube
b_0 = initial width of the calibrated length of a flat specimen
L_c = calibrated width
L_0 = initial length between reference marks
L_t = total length of specimen
L_u = ultimate length between reference marks after rupture
S_0 = initial area of cross section of the calibrated length
1 = grip ends

The specimen geometry can vary as a function of:

- Type of material to be tested;
- Production process for the material to be tested;
- Type of component from which the specimen has been cut.

The specimen cross section can be circular, square or rectangular. For thin sheets typical geometries are shown in figure 3.

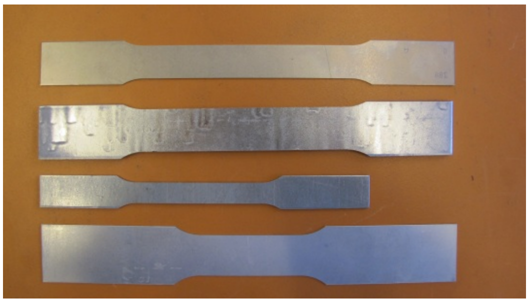


Figure 3: Tensile test specimens

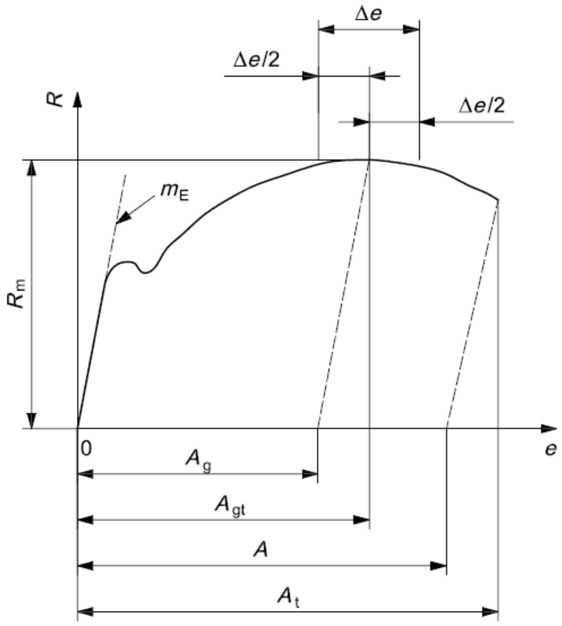


Figure 4: Definition of extensions (ISO 6892 -1 :2009)

Generally tensile test results are presented in a stress/deformation graph of which a typical example is shown in figure 4.

Legend (cf. ISO 6892 -1 :2009):

A = Elongation after rupture

A_g = Plastic extension at maximum force

A_{gt} = Total extension at maximum force

A_t = Total extension at maximum fracture

e = Extension

m_E = Slope of the elastic part of the unit force/extension curve

R = Stress

R_m = Tensile strength

Δe = Plateau extent

For a large number of metals and alloys the curves obtained show a zone called the elastic domain, illustrated in the graph as a straight line (segment OP1). For all the points on this straight line the deformation, or elongation, is proportional to the stress, or to the force exerted, and the material (the specimen) is perfectly elastic (behaves as a perfect spring).

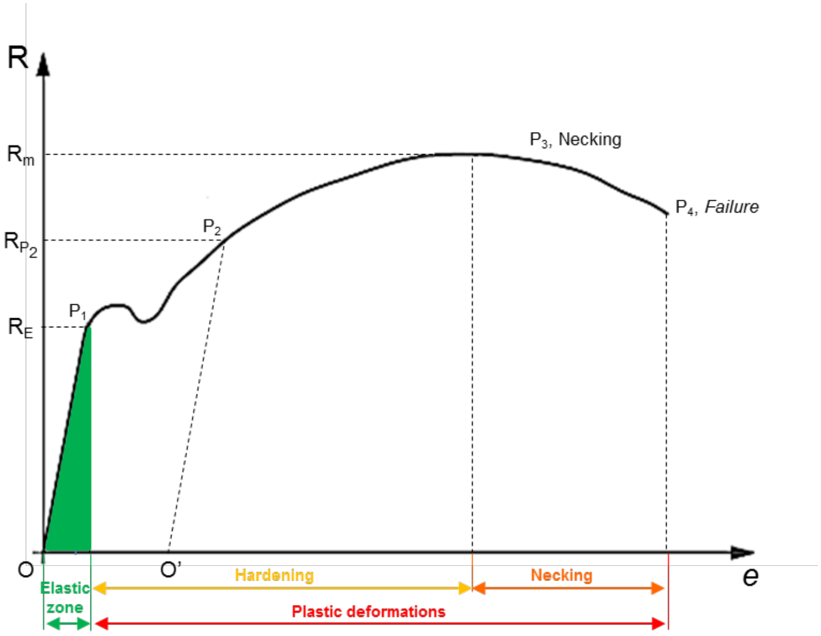


Figure 5

- *Longitudinal modulus of elasticity, E (N/mm²)*: this characterises the slope of the above proportionality straight line and the elasticity of the tested material. The greater E, the more rigid the material and conversely.
  E = tan (Ψ)
  E_{steels} = 210,000 N/mm^2, this value is constant for all carbon steels.
- *Hooke's Law (σ = E*A)*: this law, or equation for the straight line OP1, translates the previous proportionality (σ in N/mm², E in N/mm² and A dimensionless).
- *Elastic limit, RE (N/mm²)*: this marks the end of the elastic region (point P1). For greater values the material no longer deforms elastically, but plastically: the sample does not return to its initial dimensions after unloading, a permanent elongation remains.
- *Poisson's Modulus (ν)*: characterises the contraction of the material perpendicular to the applied force.
- *Ductility*: this is the ability of a material to deform plastically without breaking. It is characterised by the percentage elongation A%: the higher A%, the more ductile the material.
- *Modulus of resilience*: represents the elastic energy that is absorbed by the material. Graphically, this corresponds to the area in green (fig. 5).

The results of a tensile test are influenced by numerous parameters, which must thus be controlled during the test:

- *Load rate and strain rate*: influences the max resistance value and the elastic limit. The speed values must conform to the requirements specified in standard ISO 6892:2009.
- *Co-axiality of jaws & Rigidity of the test machine*: influences the upper and lower yield limit value.
- *Specimen manufacture*: influences the ductility of the material.
- *Temperature*: global influence on all the results.

1.3. Tensile test – ISO 6892 characterisation

The following images show an example of a tensile test, performed according to standard ISO 6892:2009.

The 9 specimens (ISO 20/80 geometry) have been cut from a steel sheet 2.5mm thick.

The tensile test was done with a hydraulic machine:

- Testing rate in the creep range: 2.5 10-^{3}/s;
- Testing rate: 8.0 10-^{3}/s.

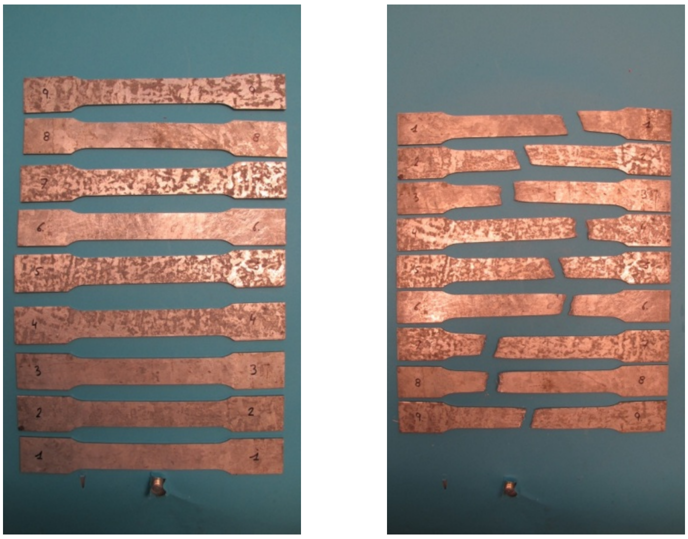


Figure 6: Specimens: before test (left) / after test (right)

The results obtained for these 9 tensile tests are summarised in figure 7 in terms of Stress-Elongation curves. Each curve corresponds to a test: the offset between the curves allows better display of the appearance of each of the curves.

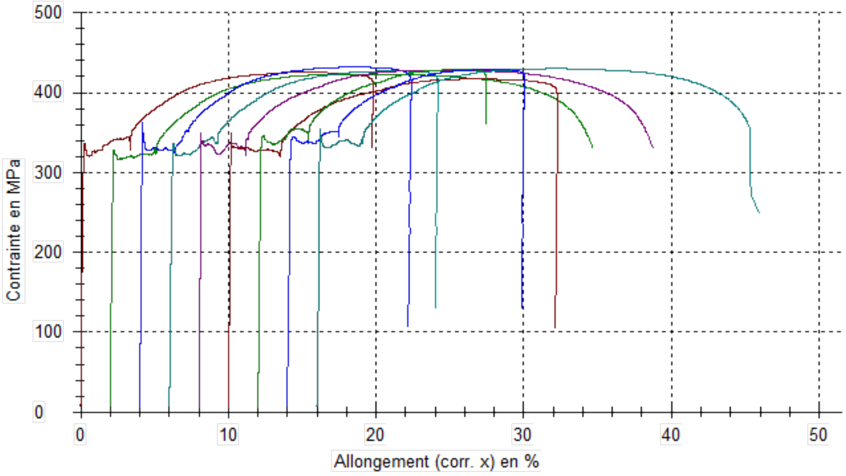


Figure 7: Stress-Elongation Curves

1.4. Elastic deformations vs. Plastic deformations

To properly understand the concept of elastic deformation and plastic deformation, the atomic structure of the materials must be examined.

The elasticity of metals is due to interatomic forces that act to move atoms, displaced by the application of the tensile load, towards their equilibrium position.

It should be noted that in crystals, there are directions in which the density of atoms is greater, and consequently, the forces are greater. The Young's modulus is greatest in the directions in which the concentration of atoms is highest. The structure of materials comprises an aggregate of grains each differently oriented: the Young's modulus is thus the mean the moduli of the grains.

In the first part of a tensile test that goes from a zero load to the elastic limit, the macroscopic elastic deformation appears as small variations of the interatomic distance and their stretching.

Beyond the elastic limit the material experiences an elongation under load that is equal to the sum of the elastic deformation and the plastic deformation: Hooke's Law is no longer observed.

During elongation part of the work of the force is absorbed in the form of elastic energy (which has a reversible character, so no heat is produced) and part is dissipated in the form of heat, which causes irreversible plastic deformation.

Once the load is removed, the specimen thus experiences on the one hand an elastic return and on the other hand it also retains a permanent plastic deformation. The plastic deformation corresponds to the rupture of the bonds between neighbouring atoms, their displacement and the creation of new bonds.

2. The work hardening phenomenon

2.1. Modification of mechanical properties

To give the road barrier the desired geometry, different forming methods can be used:

- Bending;
- Stamping;
- Roll forming.

Each of these methods involves plastic, hence permanent, deformations of the material.

Figure 8 shows an example of roll forming of a rail for a road restraint system: the steel coil, after having been cut, is sent to the roll former where it is deformed to obtain the final profile.

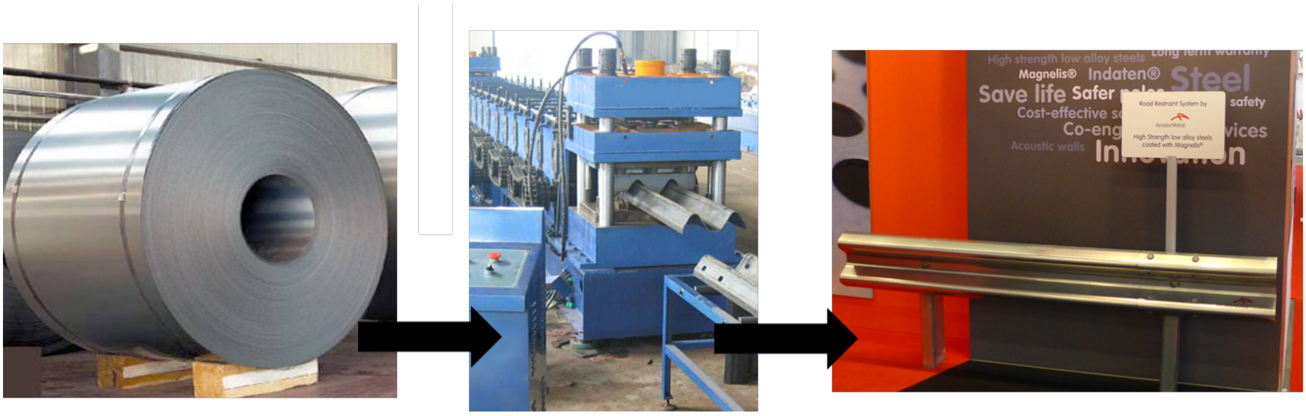


Figure 8: Example of roll forming of rail for crash barrier

One of the consequences of the above-mentioned manufacturing techniques is work hardening.

Work hardening consists of the hardening of the metal material following plastic deformations.

If we consider steel loaded into the work hardening zone and then unloaded (fig. 9), the behaviour on unloading is elastic (straight line P2 O').

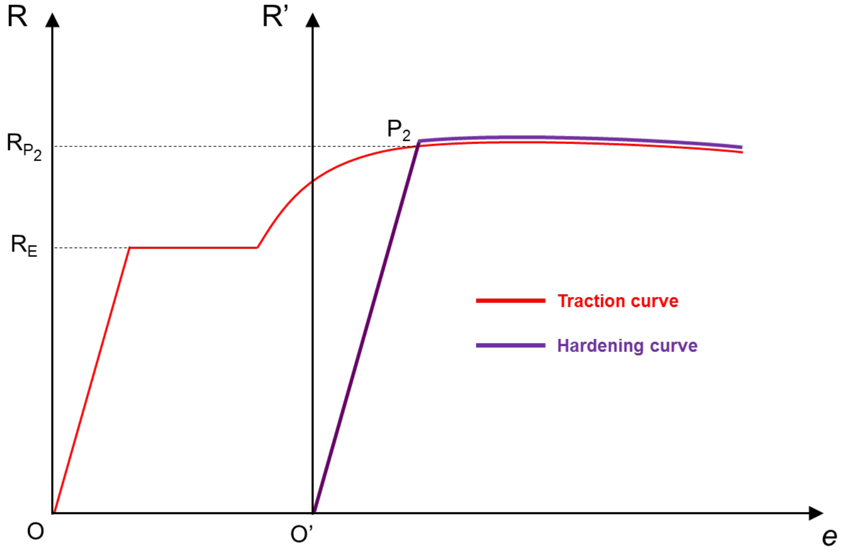


Figure 9: Work hardening

If the specimen is loaded again it rises following the straight line O'P2 (purple curve).

The result of work hardening is thus a steel that has a higher apparent elastic limit, compared to the same steel without work hardening, but that is also less ductile: the available deformations before rupture are reduced, which thus leads to a reduction in ductility.

2.2. Loss of ductility

Work hardening affects the physical, chemical and mechanical properties of the metals.

Effects on mechanical properties:

- Increase in the elastic limit and the hardness;
- Reduction in ductility and toughness.

Effects on physical and chemical properties:

- Increase in the thermal expansion coefficient and compressibility;
- Reduction in electrical conductivity and magnetic permeability.

For a structure like road barriers for which the performance depends on the ability of each component to deform during an impact with a vehicle, work hardening can thus lead to a deformation capacity less than that provided without work hardening.

3. The work hardening phenomenon

Following the impact with a vehicle, the components of the road barrier can experience large deformations without being broken.

Figure 10: Damage to a crash barrier after impact

It can thus happen that "slightly" damaged components are roll formed again and reused on the road.

To do this, after having been taken from the damaged system, components are first flattened and then roll formed. This process leads to a modification of the mechanical properties of the steel, with notably a reduction in the elastic limit value. This loss of elasticity is above all linked to the nature of the alternating type loads to which the material is subjected.

Following the degradation of the steel's mechanical properties, the structure performance can thus no longer be ensured, which could have extremely dangerous consequences for road users.

3.1. Bauschinger Effect and modification of mechanical properties of the steel

Because of its microstructure (crystal type and grain size) and the distribution of dislocations present (Orowan model), the elastic limit of a metal that has already been permanently deformed following the application of a load in one direction, if loaded again by a load in the opposite direction (reversal loading), is reduced. This phenomenon is known under the name of Bauschinger Effect.

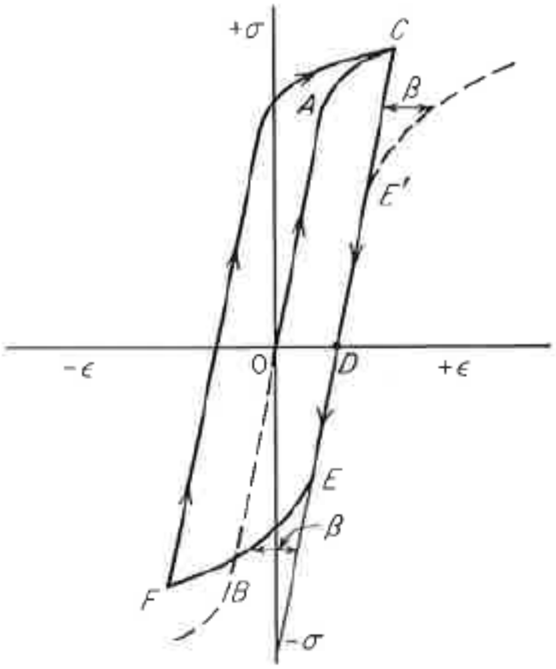


Figure 11: Bauschinger Effect and hysteresis

In order to evaluate the variation of elastic limit due to the Bauschinger Effect, a test campaign was performed on samples of S460MC steel (EN 10149-2 :2013), 3.0 mm thick.

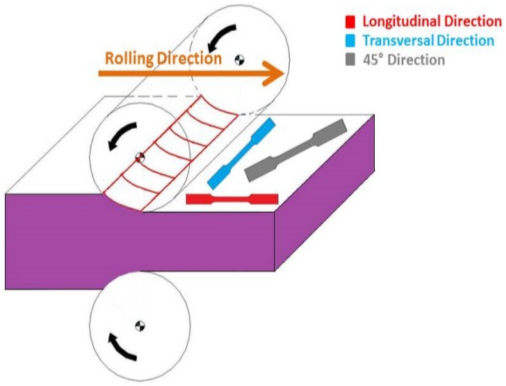


Figure 12: Direction of manufacture of specimens

A lot of thirty specimens were machined: 15 specimens in longitudinal direction (parallel to the rolling direction) and 15 specimens in the transverse direction.

The test procedure consists of the following steps:

1. Tensile test on specimens to standard ISO20/80;
2. Bending of specimens to achieve a permanent residual deformation;
   Two internal bending angles and two internal bending radii were chosen:
   i. Angle: 135° and 155°;
   ii. Radius: 3 mm and 20 mm.
3. Unbending of specimens and verification of flatness;
4. Tensile tests on flattened samples.

The table below shows a general summary of the tested specimens:

Specimen type	ISO 20/80			
	Longitudinal direction		**Transverse direction**	
Number of specimens	3		3	
Specimen type	ISO 20/80			
	Bend angle: 135°			
	Internal radius: 3.0 mm		**Internal radius: 20.0mm**	
	Longitudinal direction	**Transverse direction**	**Longitudinal direction**	**Transverse direction**
Number of specimens	3	3	3	3
Specimen type	ISO 20/80			
	Bend angle: 155°			
	Internal radius: 3.0 mm		**Internal radius: 20.0mm**	
	Longitudinal direction	**Transverse direction**	**Longitudinal direction**	**Transverse direction**
Number of specimens	3	3	3	3

Table 1: Specimens details

3.1.1. Results of tensile tests on standard ISO 20/80 specimens

The tensile tests were performed according to standard ISO 6892:2009, with a hydraulic machine. Six specimens were analysed.

Figure 13: ISO 20/80 specimens and detail of the tensile test machine

The main results of these tests are summarised in table 2:

	Steel	DIR	Width	Thick.	Rp 0.2	Rm	Rp/Rm	Ag	A
Code			mm	mm	MPa	MPa	%	%	%
1	S460MC	T	20.064	3.049	541	596	90.8	9.8	17.6
2	S460MC	T	20.135	3.051	540	594	90.8	10.1	18.4
3	S460MC	T	20.109	3.061	536	596	90.0	10.0	18.4
4	S460MC	L	20.085	3.065	480	579	82.9	11.2	22.1
5	S460MC	L	20.042	3.060	482	580	83.1	11.1	16.3
6	S460MC	L	20.086	3.063	480	579	82.8	11.0	20.9

Table 2: Tensile test results

3.1.2. Modification of mechanical properties

The specimens were bent using 4 configurations that differed from one another in two parameters:

I. Internal bending angle (135° and 155°);

II. The internal bending radius (3mm and 20mm).

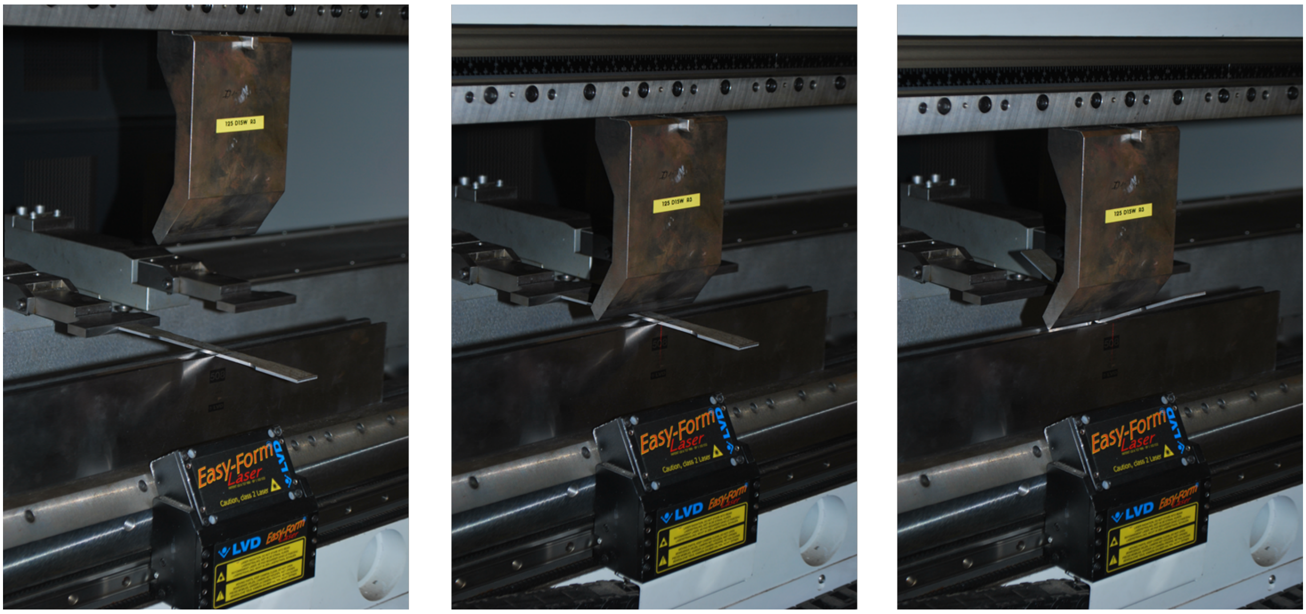


Figure 14: Specimen bending sequence

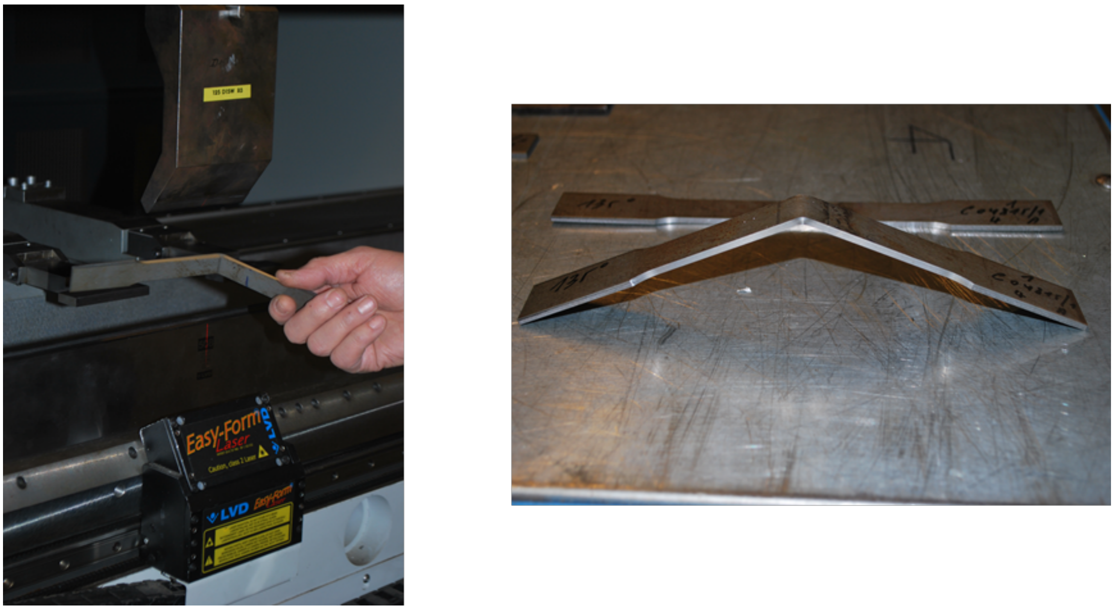


Figure 15: Bent specimen

The internal bending angle values were chosen to develop a permanent residual deformation in the specimen.

The specimens thus machined were than bent and flattened to be able to be tested in tension. To guarantee that the tests took place in standard conditions, according to standard ISO 6892:2009, the flatness of the specimens was verified using a 3D machine.

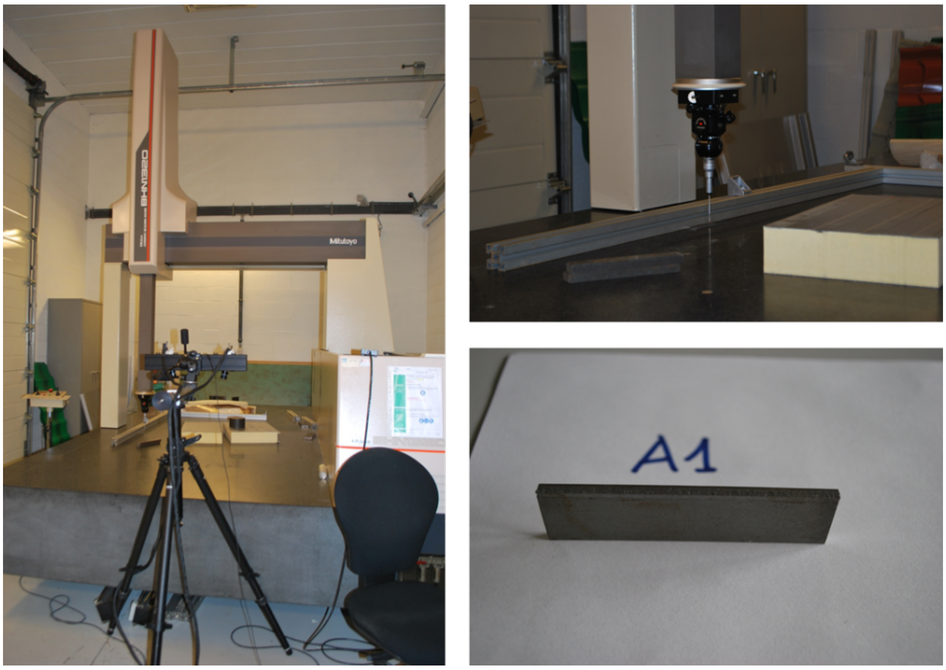


Figure 16: 3D Machine

The main results of the tensile tests are summarised in table 3 (specimens in transverse direction) and table 4 (specimens in longitudinal direction):

	Steel	DIR	Width	Thick.	Rp 0.2	Rm	Rp/Rm	Ag	A
Code			mm	mm	MPa	MPa	%	%	%
7	S460MC	T	20.069	3.048	417	591	70.5	10.4	16.2
8	S460MC	T	20.005	3.050	422	598	70.6	10.0	17.2
9	S460MC	T	20.061	3.057	425	596	71.4	10.3	17.2
13	S460MC	T	20.051	3.046	411	596	69.0	9.7	16.8
14	S460MC	T	20.102	3.051	414	593	69.7	9.9	17.6
15	S460MC	T	20.040	3.042	418	595	70.2	9.8	17.8
19	S460MC	T	20.004	3.056	432	597	72.3	10.3	17.7
20	S460MC	T	20.081	3.054	421	596	70.6	10.2	16.9
21	S460MC	T	20.050	3.041	419	596	70.3	9.7	16.9
25	S460MC	T	20.102	3.061	396	589	67.3	9.5	15.6
26	S460MC	T	20.032	3.052	414	597	69.3	10.2	17.5
27	S460MC	T	20.090	3.050	406	591	68.7	10.2	18.8

Table 3: Results of tensile tests on bent and unbent specimens, transverse direction

	Steel	**DIR**	**Width**	**Thick.**	**Rp 0.2**	**Rm**	**Rp/Rm**	**Ag**	**A**
Code			**mm**	**mm**	**MPa**	**MPa**	**%**	**%**	**%**
10	S460MC	L	20.033	3.063	378	581	65.1	10.8	14.1
11	S460MC	L	20.106	3.052	377	577	65.4	11.0	18.5
12	S460MC	L	20.118	3.057	380	579	65.5	10.8	17.2
16	S460MC	L	20.071	3.050	368	578	63.6	11.0	16.2
17	S460MC	L	20.123	3.052	339	579	58.5	10.1	12.5
18	S460MC	L	20.062	3.055	364	581	62.7	10.6	14.1
22	S460MC	L	20.038	3.043	366	579	63.1	11.0	16.2
23	S460MC	L	20.093	3.038	380	581	65.5	11.0	19.6
24	S460MC	L	20.154	3.060	369	577	63.9	10.6	14.1
28	S460MC	L	20.103	3.060	366	577	63.3	11.0	16.5
29	S460MC	L	20.064	3.057	366	575	63.6	10.5	19.2
30	S460MC	L	20.119	3.050	360	575	62.6	10.5	17.7

Table 4: Results of tensile tests on bent and unbent specimens, longitudinal direction

3.1.3. Microstructure analysis

The dependence of kinematic work hardening on the microstructure of the steel has been demonstrated by several studies: the size of the grains and the nature of the microstructure play an important role in the formation and movement of dislocations.

The microstructure of an S460MC sample was analysed using an optical microscope (Zeiss Axio Imager).

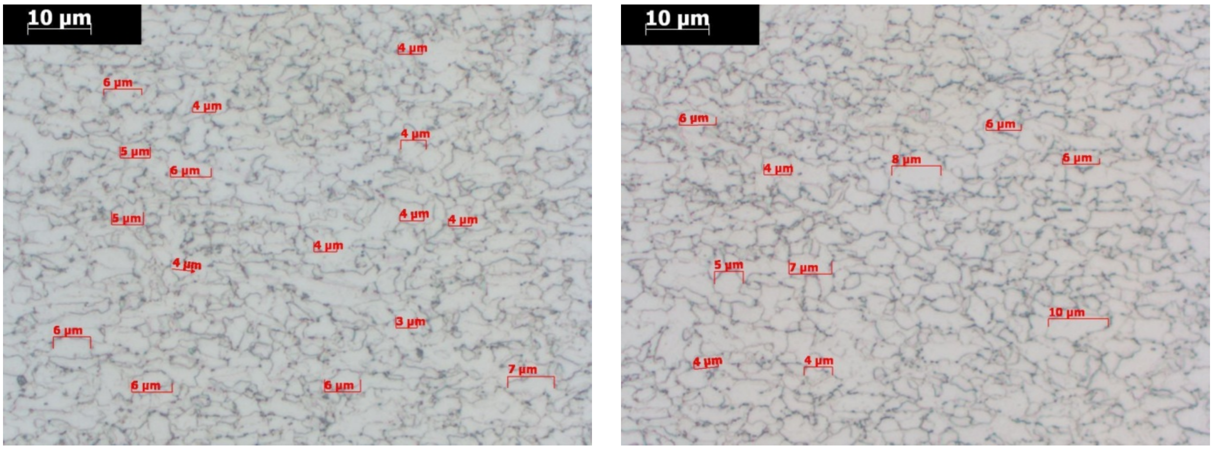


Figure 17: Optical microscope analysis

This steel shows a very fine grain size: the dimension varies between 4µm and 8µm.

3.1.4. Discussion of results obtained

By comparing all the results obtained during this tensile test campaign (Figure 18), the difference in terms of elastic limit between specimens 1 to 6 and specimens 7 to 30, subject to reversal loading is obvious.

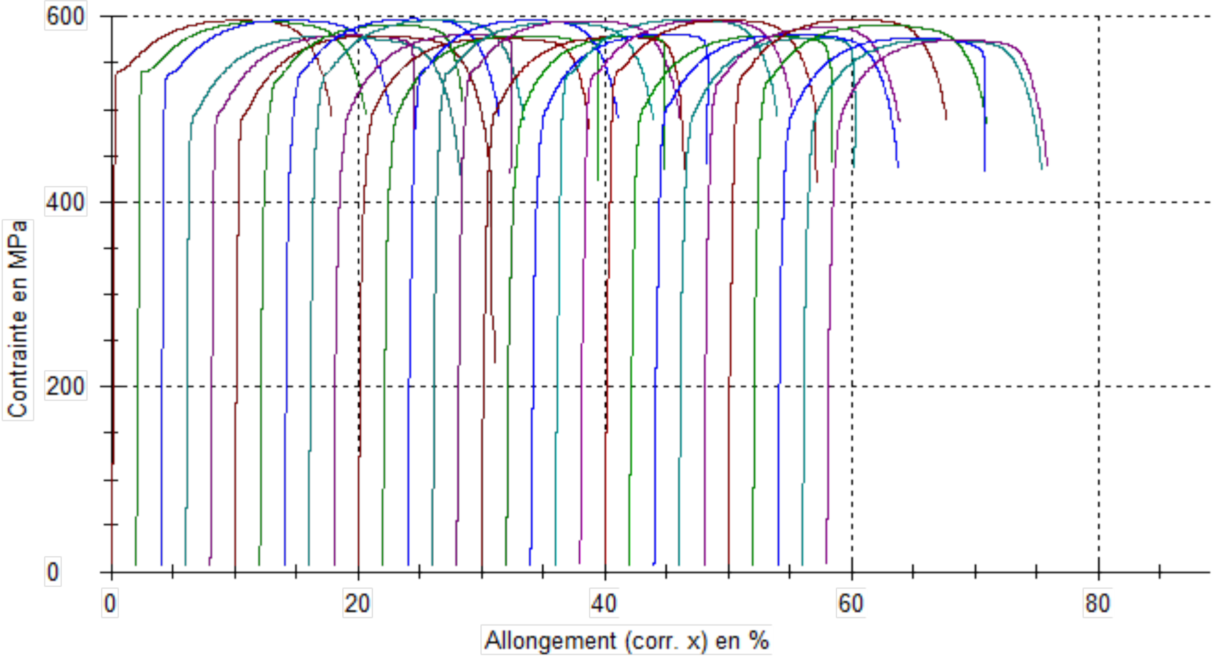


Figure 18: Summary of tensile tests

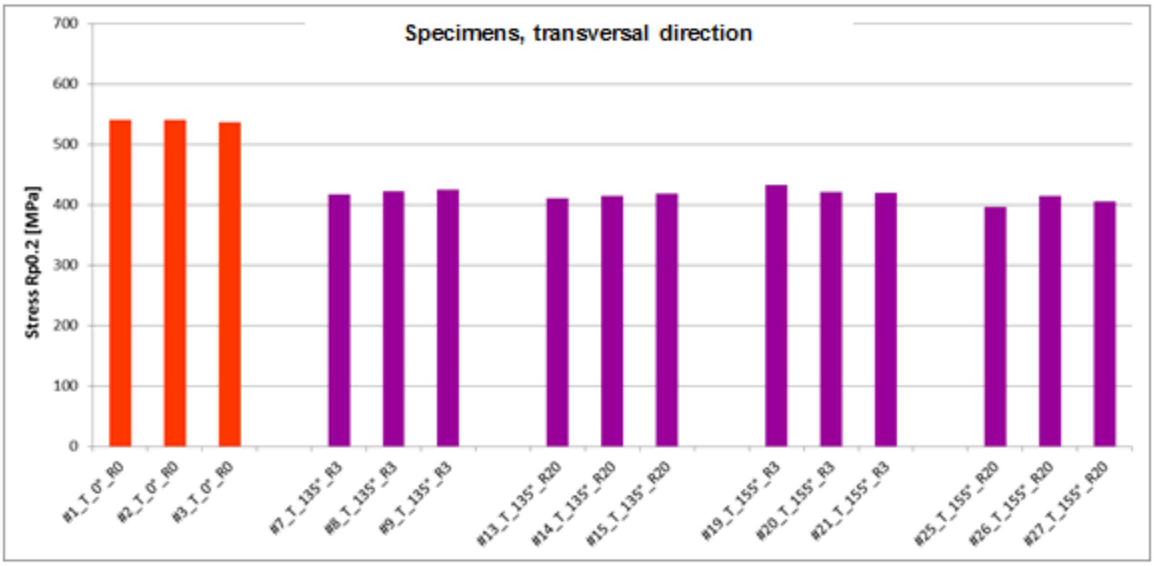


Figure 19: Results (Rp0.2), for transverse specimens

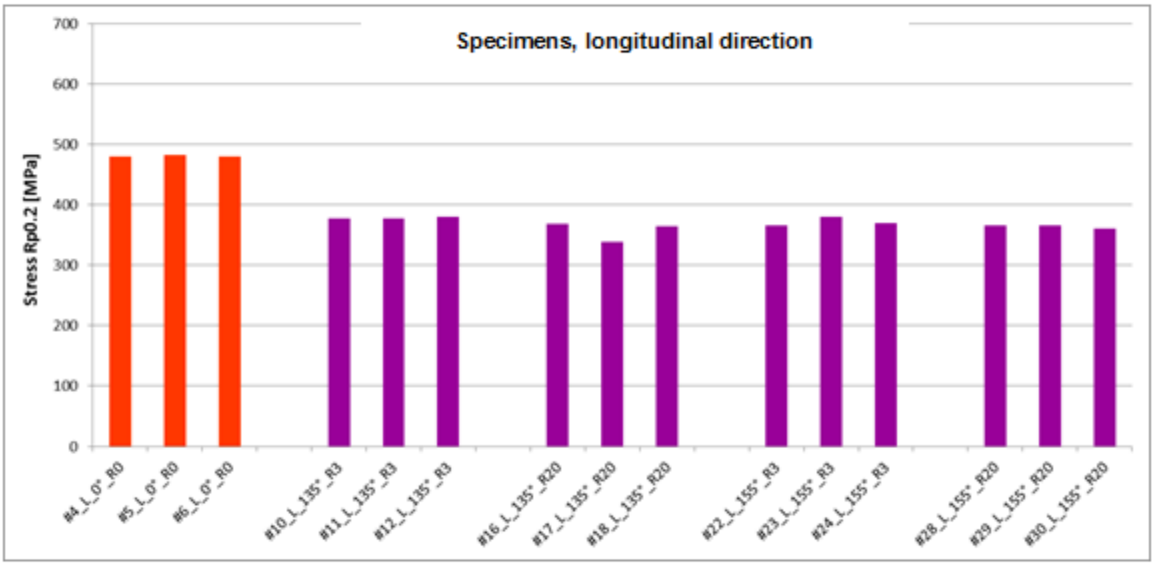


Figure 20: Results (Rp0.2), for longitudinal specimens

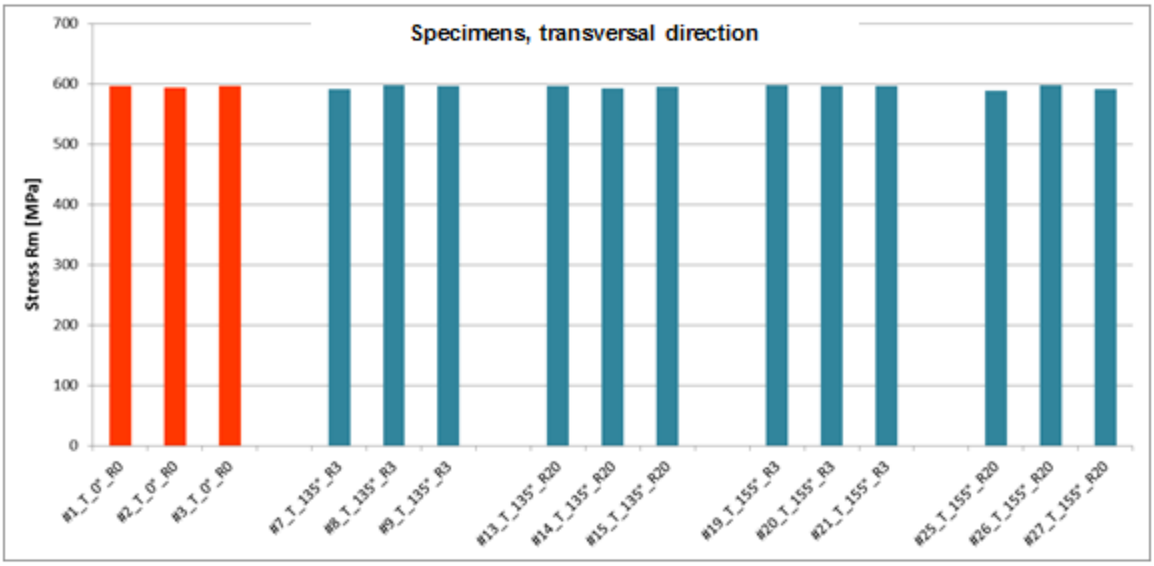


Figure 21: Results (Rm), for transverse specimens

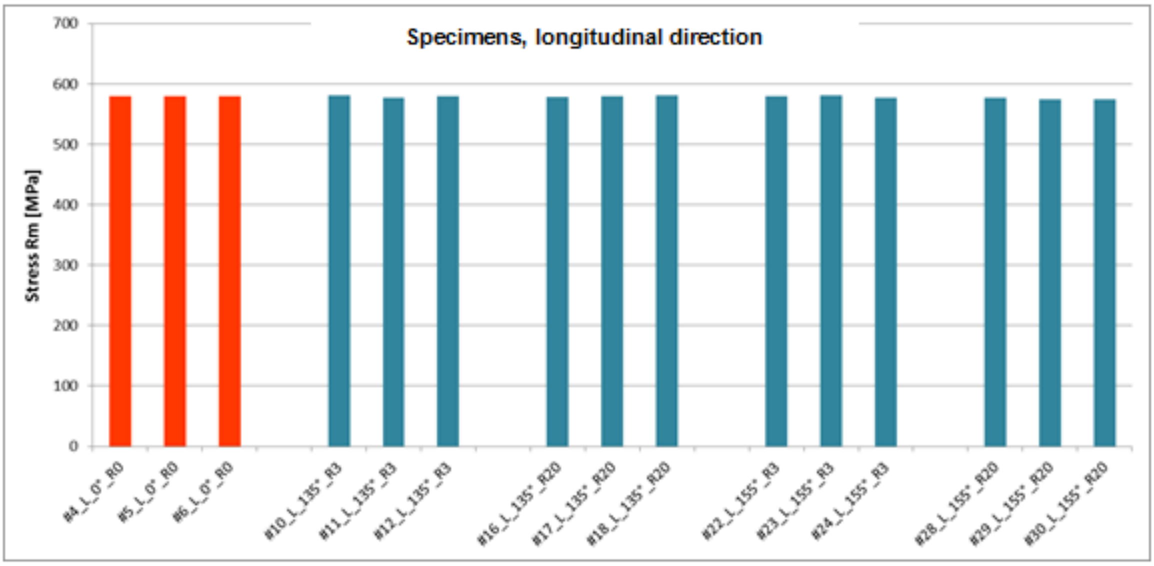


Figure 22: Results (Rm), for longitudinal specimens

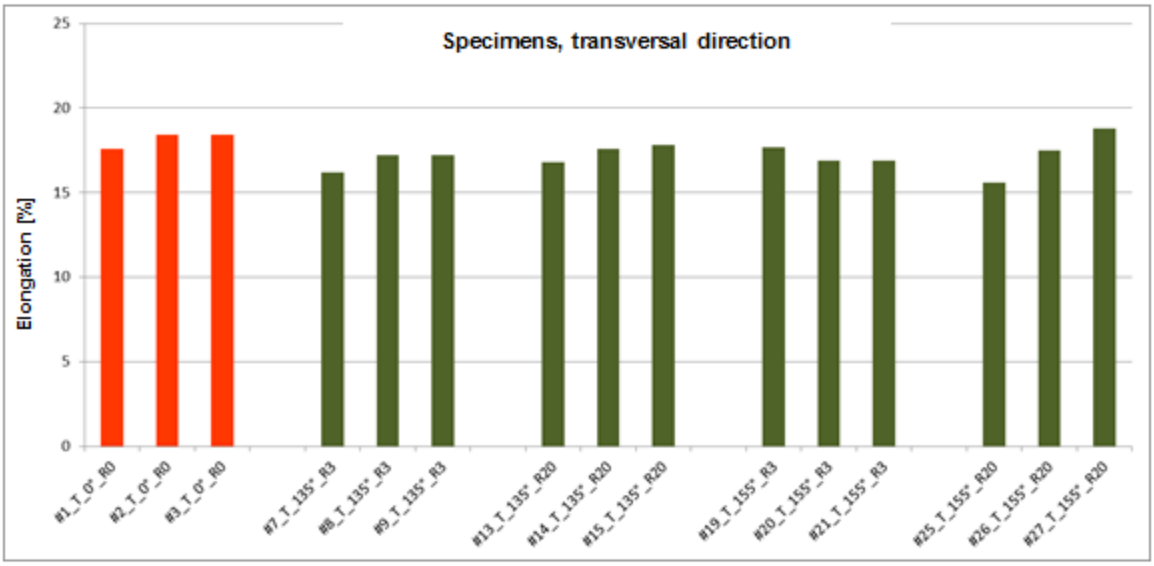


Figure 23: Results (A), for transverse specimens

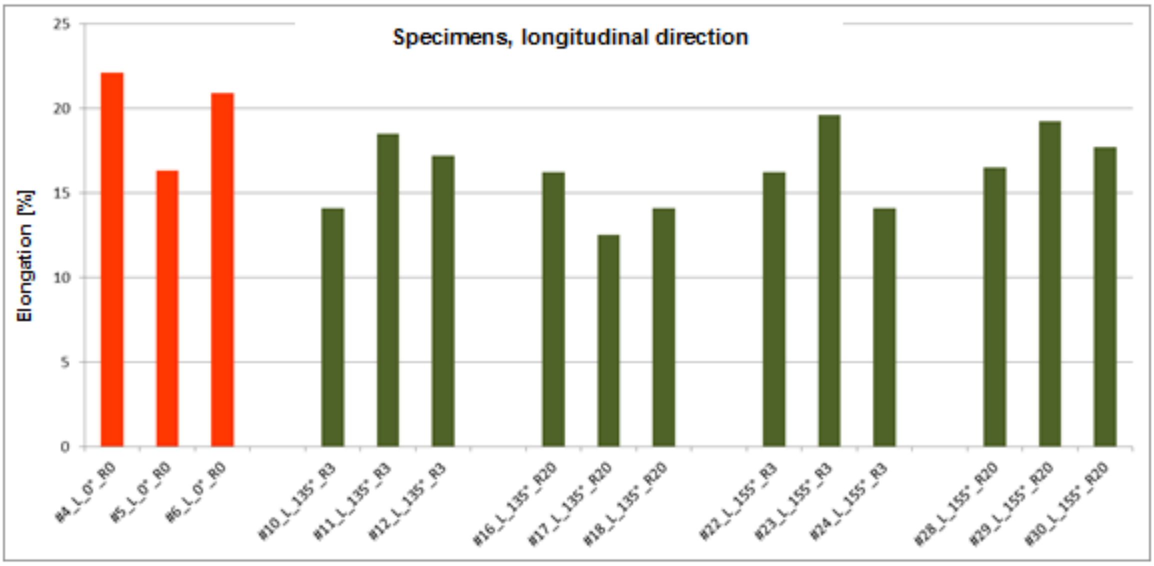


Figure 24: Results (A), for longitudinal specimens

As figures 19 to 24 show, the variation of the elastic limit (Rp0.2) and the variation of the elongation (A) can become very large. If the deviation from the reference test values is estimated in terms of mean values (Table 5), the variation of the elastic limit can be up to about -25% for longitudinal and transverse specimens. It is the same for the value of elongation at rupture, which, in the case of longitudinal specimens, is reduced by 28%. In contrast the value of the tensile strength (Rm) remains rather constant.

This large fall in Rp0.2 lowers the value of the elastic limit below the minimum value required by standard EN 10149 :2013: the steel can no longer be classified as S460MC.

Specimen type	**DIR**	**Bend angle**	**Internal radius**	**Rp0.2 (mean)**	**Δ Rp0.2**	**Rm (mean)**	**Δ Rm**	**A (mean)**	**Δ A**
		°	**mm**	**MPa**	**[%]**	**MPa**	**[%]**	**%**	**[%]**
ISO 20/80	*T*	*0*	*0*	*539*	*Ref.*	*595*	*Ref.*	*18,13*	*Ref.*
ISO 20/80	T	135	3	421	-22	595	0	16,87	-7
ISO 20/80	T	135	20	414	-23	595	0	17,40	-4
ISO 20/80	T	155	3	424	-21	596	0	17,17	-5
ISO 20/80	T	155	20	405	-25	592	-1	17,30	-5
ISO 20/80	*L*	*0*	*0*	*481*	*Ref.*	*579*	*Ref.*	*19,77*	*Ref.*
ISO 20/80	L	135	3	378	-21	579	0	16,60	-16
ISO 20/80	L	135	20	357	-26	579	0	14,27	-28
ISO 20/80	L	155	3	372	-23	579	0	16,63	-16
ISO 20/80	L	155	20	364	-24	576	-1	17,80	-10

Table 5: Tensile test results: mean values per specimen type

The optical microscope analysis showed a very fine grain microstructure with mean dimension 6μm typical for the steel grade analysed.

Generally it can be concluded from this that an evident modification of the mechanical properties of the steel is being measured that translates into a loss of ductility. By virtue of the reasons explained in paragraph 3.1, these variations become more or less important depending on the type of steel considered.

3.2. Risks related to restoring a crash barrier

3.2.1. Reduction of the elastic limit

Crash barrier performance depends on the energy absorbing capacity of each component. If this capacity is reduced due to an impact with a vehicle, a road restraint system that originally had certain performance in terms of containment level and severity index can see its functionality reduced if its components are reconditioned to restore the original profile.

- Containment level problems: due to the reduction of the plastic deformation capacity of the material, the vehicle could no longer be retained during the impact and it could pass through the system.
- Severity Index: the reduction in ability to absorb the shock can have negative effects on the Acceleration Severity Index (ASI), due to a more violent impact.

For a better understanding of this phenomenon consider on the same graph (Figure 25), for example, the two tensile curves measured during the tests:

- #4_L_0°_R0: standard ISO 20/80 specimen;
- #29_L_155°_R20: bent and flattened standard ISO 20/80 specimen.

The area under each σ,ε curve represents the energy that is absorbed for each of the specimens (toughness). If we zoom between 0% deformation and 2%, it is obvious that following roll reforming a reduction of the elastic limit and area under the σ,ε curve is measured: there is thus a loss of the energy absorbing capacity. The difference between the two curves is the dotted area.

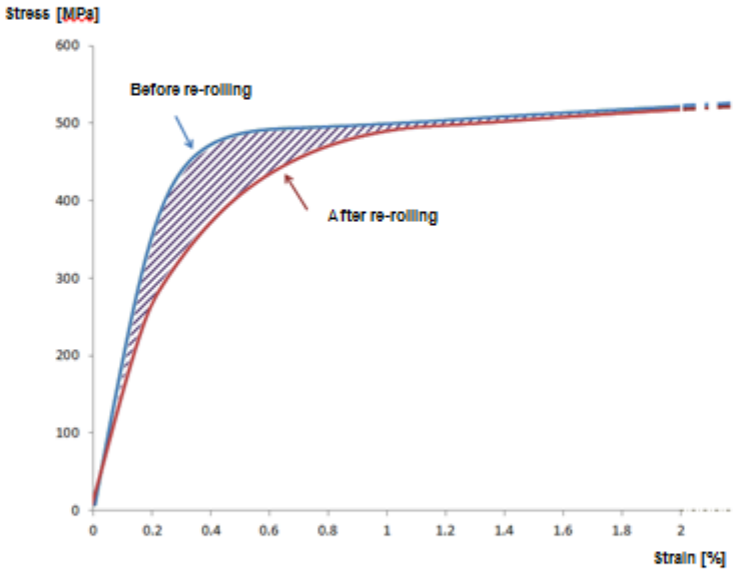


Figure 25: Reduction of the elastic limit

The crash test for vehicle restraint systems certification (EN1317:2010) takes account of the work hardening of system components due to roll forming of these components: the structure performance is already evaluated taking locally work hardened material into account. In contrast this test cannot give any information on the barrier performance in the case of reconditioning of its components through a new roll forming process: which could therefore have uncontrolled rupture of the system as its consequence.

3.2.2. Surface coating damage

As well as the change of mechanical properties of the steel, another parameter that must be considered during the reconditioning is damage to the coating.

Surface coatings have the function of protecting the system components from different corrosion agents. After the impact the surface of the crash barrier components in contact with the vehicle is damaged, even if the shock does not produce large deformations in the parts. The coating damage can be worsened due to reconditioning process to restore the original profile.

Before proceeding to reconditioning the damaged parts it is indispensable to treat the parts, for example by stripping or polishing, to prepare them for a new immersion in a galvanising bath.

3.2.3. Profile reconditioning in the context of standards

Although profile reconditioning and the risks related to this practice have been known for a long time by the European Road Authorities, the number of Countries that have made legislative provisions is unfortunately still very small.

One of the first Countries to approve a national standard that forbids reconditioning of road crash barrier components was Belgium. As can be clearly read in chapter 2.2 "Exigences de performances / Restatie-Eisen" (Performance requirements) of the Prescriptions Techniques / Technische Voorschriften (PTV) 869 (Technical Specifications) for road retaining systems: "Le re-profilage d'éléments précédemment utilisés n'est pas autorisé / Het herprofileren van reeds eerder gebruikte onderdelen is niet toegestaan" ("The recondition of previously used components is not permitted").

PTV 869

PRESCRIPTIONS TECHNIQUES

DISPOSITIFS DE RETENUE
ROUTIERS

Version 3.0 du 2015-04-04
Approuvé par le Conseil Consultatif dispositifs de retenue routiers le 2015-04-03
Entériné par le Conseil d'Administration du 2015-04-24

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PTV 869

TECHNISCHE VOORSCHRIFTEN

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Figure 26: PTV 869 in French and Dutch version

4. Conclusions

The operation of the steel safety rail is based on absorption of the shock energy by deformation and the absence of rupture in the road barriers assemblies. During the crash, the steel is loaded into its work hardening zone. Then, once the vehicle is away from the road barrier, the rail unloads with elastic behaviour. The rail has thus already lost part of its deformation capacity.

During the rail reconditioning process to restore the original profile, the aim is to return it to a suitable form. To do this the rail must be deformed plastically in certain places. This operation makes the steel enter its plastic part again. It thus once again loses part of its deformation capacity. After reversal loading, the mechanical properties of the steel are generally modified.

After damage, then reconditioning, the steel has lost part of its ability to deform: the reduction in the elastic limit can be very large and can go up to about -25%. The value of Rp0.2 falls below the minimum elastic limit value specified by the reference standard. It therefore no longer corresponds to the original system steel that was tested and certified. This can lead to premature rupture of the crash barrier.

The reduction in the elastic limit and the elongation at rupture, even if the tensile strength value remains unchanged, thus lead to the loss of energy absorbing capacity. This can translate, in the case of impact of a vehicle on the road barrier, into a more violent shock with major risks for users: the accelerations measured inside the passenger compartment would become greater and so, in consequence, the ASI would increase.

In addition the problems related to damage to the surface coatings must not be underestimated.

The use of reconditioned rails must thus be considered as a potentially dangerous procedure because it increases the risk of vehicles crossing the barrier by increasing the probability that the reconditioned rail breaks during an accident.

As already done by Belgium in its PTV 869, the practice of reconditioning must be prohibited by Road Authorities through the approval of stricter national standards.

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