

NIL-STRENGTH TEMPERATURE AND HOT TENSILE TESTS ON S960QL HIGH-STRENGTH LOW-ALLOY STEEL

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Abstract

The physical simulation is an ultimate innovative way to develop the welding processes. The paper introduces the connection between weldability and physical simulation, hot-cracking sensibility, the Gleeble 3500 thermo-mechanical physical simulator, respectively, and early experiments on the S960QL high-strength low-alloy (HSLA) steel. Identification of the Nil-Strength Temperature (NST), furthermore the results of the hot tensile tests (on heating and on cooling parts of the welding simulation curve are also investigated) are being introduced. The future approaches of the research are also exposed.

Keywords: *physical simulation, weldability, Nil-Strength Temperature (NST), hot tensile test, high-strength low-alloy (HSLA) steel*

1. Introduction

It is a complex task to determine weldability either on an overall or a specific level. A high number of semi-empirical and empirical approaches, technological investigations and tests, as well as the computer simulation facilitate to find the answer to the complex questions. The scope of such facilities has been widened through the possibilities offered by physical simulation. The paper aims, on one hand, describing the connection between weldability and physical simulation as well as the issue of hot crack sensitivity, furthermore, the first tests and their results are being introduced.

2. Weldability and physical simulation

The technological investigations and tests regarding weldability date back to the development of different welding technologies. Not only the diverse qualities of materials, but the different welding processes as well as the high variety of these processes have resulted in the elaboration of further tests [1]. They are specified by their variety, applicability within limits, as well as their limited comparability. Considering the complex issue of weldability (such as material quality, technology, structure, etc.) [2, 3], there is not

one single test which would allow evaluating the problem, it is not and would not be sensible either, consequently weldability cannot be determined with a single characteristic. The underlying reasons are to be examined separately under specific conditions, which then will enable us to rank the different materials based on the given results. The order of ranking depends on the requirements, i.e. it is not considered constant. The complex correlations between the factors do not allow defining other properties (e. g. mechanical properties) through characteristics. Besides the investigations and tests, semi-empirical and empirical investigations are given an ever increasing emphasis in order to avoid limitations [4]. A large number of experiments have been conducted [5, 6] to make algorithms with the aim of ensuring easier comparability.

There is at least double contradiction in the investigations and tests. On one hand, the actual processes can only be performed on small parts and in small volumes, which means that there are only small-size specimens available to define the data belonging to the materials and/or technologies [7]. This fact, due to the aspect of size effect, will decrease the reliability of the results. On the other hand, the technological investigations are reflected within limits as regards the real processes and physical simulations.

The mathematical (computational) simulation may contribute to cancelling the limitations of investigations and tests, as well as those of the different approaches [5], which are not to be considered in the current study. However, the other consideration is physical simulation. Physical simulation applied in metallurgy dates back to the mid-20th century. The basic purpose of the first physical simulators was to provide reproducibility for the welding heat-affected zone (HAZ) [8]. The first commercial physical simulation system (in the late 1950s) was produced in the USA and was given the name Gleeble 501. The equipment installed with a pneumatic loading system was designed for the simulation of welding HAZs. Two decades later (1979) Dynamic Systems Inc. (DSI) launched the second-generation Gleeble 1500 system, which was equipped with modern electronics and hydraulic units supplied with a resistance heating device. This scheme allowed further applications of physical simulations. According to the increasing demand, newly developed systems have continuously emerged. These developments resulted in the development of Gleeble 3500 and later Gleeble 3800 systems [9]. Gleeble 3500 simulator installing at the Department of Mechanical Technology at the University of Miskolc is shown in Figure 1.



Figure 1. *Gleeble 3500 thermo-mechanic physical simulator installing at the Department of Mechanical Technology at the University of Miskolc*

The object of the simulation is the base material of an industrial process, which – as a volume element of the industrial process – is exposed to effects similar to the industrial process. It is a widely known fact that the mechanical, thermal, and environmental stresses and effects during the industrial processes do not tend to occur separately but in a complex way, nevertheless, not necessarily simultaneously. Considering all these facts, a possible definition of physical simulation is as follows: physical simulation is the performance of real and possible industrial processes – in our case material technologies –, in real time scale and in geometrical (volume) scale relevantly approaching reality.

The specifications of the physical simulation and simulators can be summarised as follows:

- a physical simulator is not considered as „reduced” production system;
- a physical simulator is not a target equipment;
- the physical simulation is always a real time process;
- the effects on the specimens being applied in a physical simulator are determined by the specification of the concerned industrial process;
- specimens treated in a physical simulator must be suitable for further tests as well;
- the physical simulation is definitely closer to an industrial process considering mathematical (numerical and computational) and physical simulations;
- physical and mathematical simulations create an inseparable unit [10-12].

3. Hot-cracking sensitivity

Hot cracks occur at high temperatures during a welding process. The hot cracks formed in the weld metal are the solidification cracks, while the hot cracks occurring beside the seam, on the transition between the seam and the base material, on the fusion line or in the base material, are the liquation cracks [2, 3]. The deformation theory of the occurrence of hot cracks can be described as follows in Figure 2 [13].

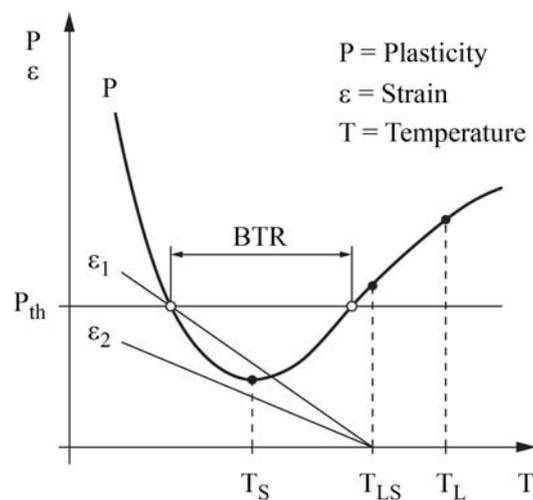


Figure 2. A sketch to the theory of hot crack occurrence concerning to the strain [13]

Plasticity of a metal alloy (P) varies between the liquidus (T_L) and solidus (T_S) temperatures according to the curve, while the deformation capability required for avoiding hot cracks is P_{th} . In BTR (Brittleness Temperature Range) where plasticity will not reach the required (threshold) deformation capability, hot cracks may be formed. During the crystallisation process tensile strains – due to unequal heating and cooling as well as to restrained shrinkage – exert effect on the weld metal, which will cause deformation. If the deformation of the weld metal exceeds the deformation capability, cracks will occur (ε_1), while in the case of more minor deformation (ε_2), cracks will not be formed. The report [14] expressed the reserve deformation (ε_z) with strain caused by thermal cycle (ε_s) and shrinkage strain (ε_k), between the real strain (ε_1') and the deformation limit (ε_1) (Figure 3).

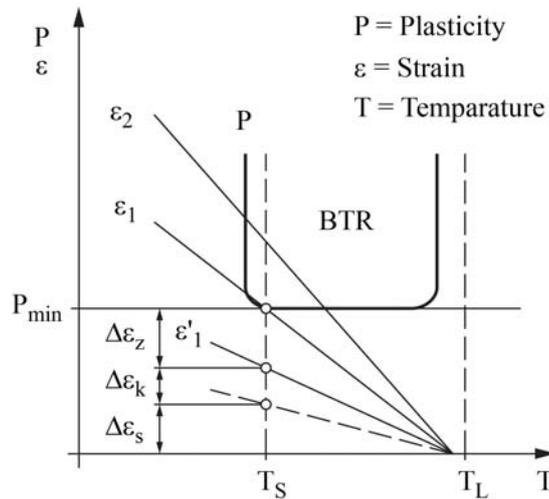


Figure 3. Deformations in the theory of hot crack occurrence [14]

Measuring based on the physical simulation of hot cracking sensitivity and the comparison of the sensitivity of different materials (more exactly that of welded joints made by means of different welding technologies) various measures are used, depending partly on the material quality as well. These are presented in Figure 4 [1, 15, 16] based on tests performed on heating and on cooling which are aiming at defining hot-tensile and nil-strength temperatures.

The values considered in Figure 4 are as follows:

- Nil-Strength Temperature (NST);
- Nil-Ductility Temperature (NDT);
- Ductility Recovery Temperature (DRT);
- Brittleness Temperature Range (BTR);
- Nil-Ductility Range (NDR);
- Ductility Recovery Rate (DRR);
- Ratio of Ductility Recovery (RDR).

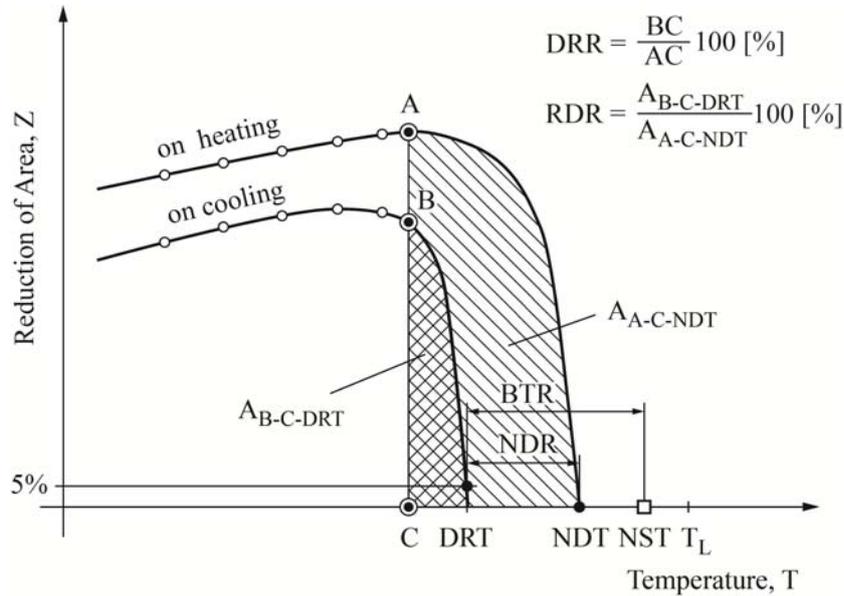


Figure 4. Possibilities for expressing hot cracking sensitivity characteristics by physical simulation (based on [15])

4. Experiments on S960QL high-strength low-alloy steel

In order to define the temperature regarding nil strength as well as for hot tensile tests, S960QL (WELDOX 960) high-strength low-alloy steel (produced by SSAB Swedish Steel AB in 15 mm thickness) was used. The chemical composition and the mechanical properties of the steel are as follows: C = 0,16 %, Si = 0.22 %, Mn = 1.24 %, P = 0.09 %, S = 0.01 %, Cr = 0.19 %, Ni = 0.05 %, Mo = 0.81 %, V = 0.041 %, Ti = 0.004 %, Cu = 0.01 %, Al = 0.056 %, Nb = 0.016 %, B = 0.001 %, N = 0.03 %; $R_{p0.2} = 1007$ MPa, $R_m = 1045$ MPa, $A_5 = 16.0$ %.

Nil-strength temperature (NST) is the temperature which causes the specimen under the effect of even some minor load to tearing. Most of the materials testing equipment are not suitable for precisely defining the NST of steel. There are double reasons for this fact: firstly, the specimen has to be heated in a well-controlled way up to a temperature which is close to the melting point of steel, at a low heating rate close to the testing temperature (1-2 K/s); on the other hand, the device is to provide the minimum pre-strained state, the maintenance of which, due to thermal expansion, causes serious problems in control techniques. These tests are mostly carried out in shielding gas atmosphere or most frequently in vacuum.

Gleeble 3500 is an equipment developed to simulate extremely fast metal processes. During the tests the high performance hydraulic system creates mechanical stress in the given specimen. However, a specific pneumatic system was installed in the whole system so that NST could be defined. This system allows keeping the permanent value of the minimum load required to define NST.

The diameter of the cylindrical specimens applied in the tests was 6 mm, with a length of 80 mm, and the testing length was 25 mm. Several factors must be taken into consideration when the pre-load is selected to the purpose. The load must be as low as possible; however, too low pre-load will decrease the reproducibility of the test and increase uncertainty in defining NST. Considering all this as well as the geometry of the specimen, 80 N pre-load was applied in the tests.

NST is a value close to the solidus temperature (TS) of the tested material. In order to define it precisely, the heating rate prior to the solid temperature must be as low as possible. Two different heating rates are to be applied during the test. In the starting phase of the test, i.e. from room temperature up to below the solidus temperature, approximately 100-150 °C (in our case up to 1200 °C), the heating rate may be relatively high (20 °C/s), while in the phase afterwards this rate must be decreased (1-2 °C/s). Figure 5 represents the diagram of the control and the real temperatures measured on the specimen.

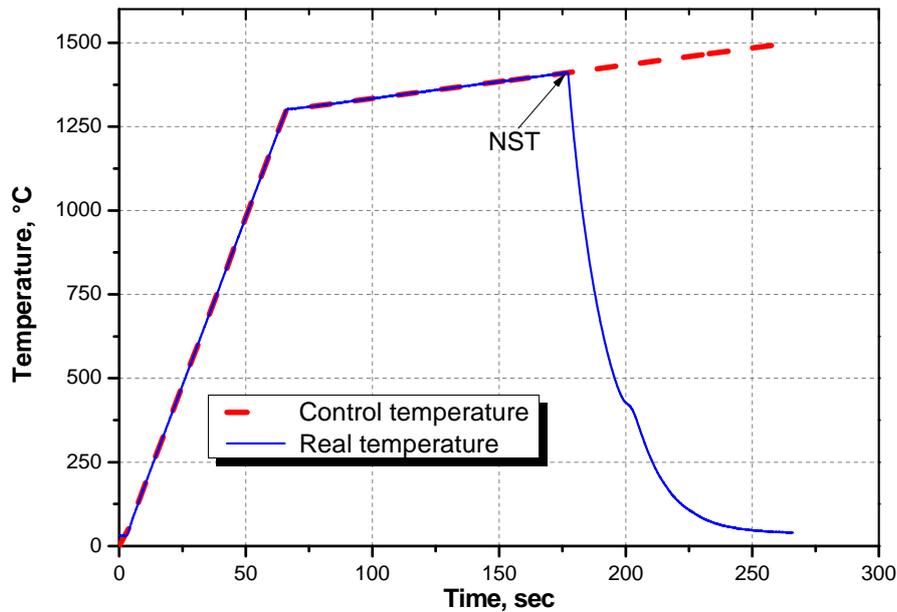


Figure 5. Control and real temperatures measured on the specimen (NST-No.1)

On the diagram the broken line shows the control input while the solid line stands for the temperature defined from the data provided by the thermoelements mounted on the specimen. It is easy to observe that the two curves run parallel due to the equipment control. When the two curves are separated, it shows the tearing of the specimen with NST.

Figure 6 demonstrates the four specimens after the tests have been performed.



Figure 6. Specimens after the NST tests have been performed

NST values deriving from the tests and the statistical parameters of the sample composed of four elements are summarised in Table 1. Despite the fact that the result on the specimen NST-No.2 significantly differs from the others, the coefficient of variation is considered satisfactory.

Table 1. NST values determined from the tests and statistical parameters of the sample

Specimen ID	NST, °C	Statistical parameter	Value
NST-No.1	1434.0	Average	1403.8 °C
NST-No.2	1358.3	Extension	75.7 °C
NST-No.3	1412.5	Standard deviation	32.2 °C
NST-No.4	1410.4	Coefficient of variation	2.29 %

The crack line is without contraction, its surface is silvery, and the crack occurred cross the grain boundaries. The image of the specimen NST-No.1 is shown in Figure 7.

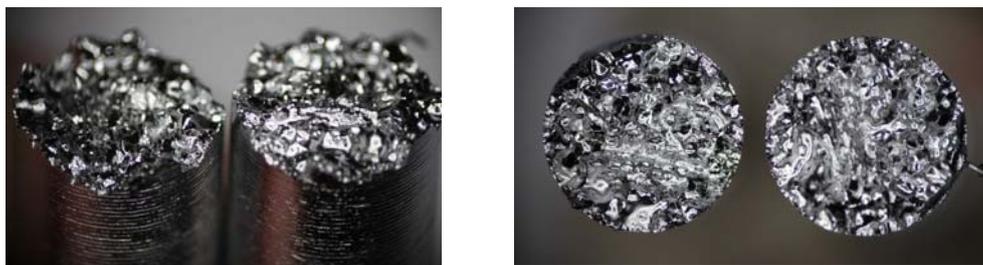


Figure 7. The specimen NST-No.1 applied for defining NST, after the fracture

Hot tensile tests were carried out using on heating and on cooling specimens. The smooth, cylindrical specimens applied in the tests have a diameter of 10 mm, a length of 116.5 mm, and a testing length of 80 mm.

In a given material the definition of NST is always prior to the definition of strength on heating and on cooling since the maximum temperature of the tests is to be below NST at least by 20-30 °C. In the case of the tested material NST was below the average 1403.8 °C, this was the reason why 1380 °C was chosen as peak temperature. The temperature-time diagram with its further parameters (heating rate, heating time at the peak temperature, and cooling rate) as well as the actual testing temperature is represented in Figure 8, with reference to research can be found in the literature [17-21].

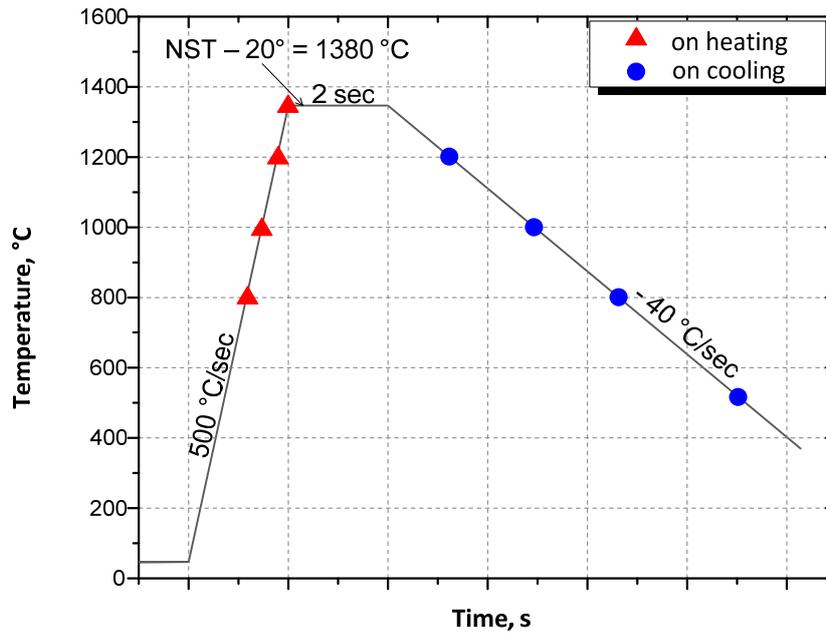


Figure 8. Temperature-time diagram applied in hot tensile tests and the actual testing parameters

Figure 9 shows a specimen after the test. In this chart the contraction on the spot of tear is well observed close to the clamping of the specimen.



Figure 9. Clamping of a hot tensile specimen and the specimen after the test

Figure 10 shows eight specimens after the executed tests.



Figure 10. *The specimens after the hot tensile tests*

The actual testing temperatures in accordance with Figure 8 and the values of the determined tensile strength (R_m) and reduction of area (Z) are shown in Table 2. Rounded data of the reduction of area values were summarized in the table, which also show minor differences between the results.

Table 2. *Actual temperatures and results of hot tensile tests*

Thermal cycle	T_{testing} , °C	R_m , MPa	Z , %
on heating	800	292.8	93.05
	1000	146.0	99.82
	1200	84.4	99.99
	1380	52.8	100.0
on cooling	1200	82.5	99.93
	1000	160.5	96.43
	800	252.0	92.73
	500	446.7	83.98

Tensile strength results related to the testing temperatures are shown in Figure 11, while Figure 12 represents the reduction of area values. In both charts on heating and on cooling data are distinct.

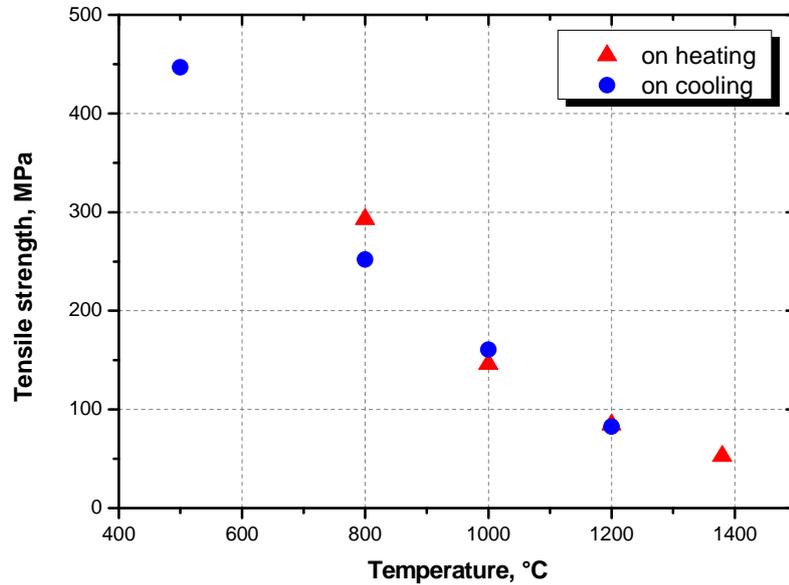


Figure 11. Results of the hot tensile tests: values of tensile strength at different temperatures

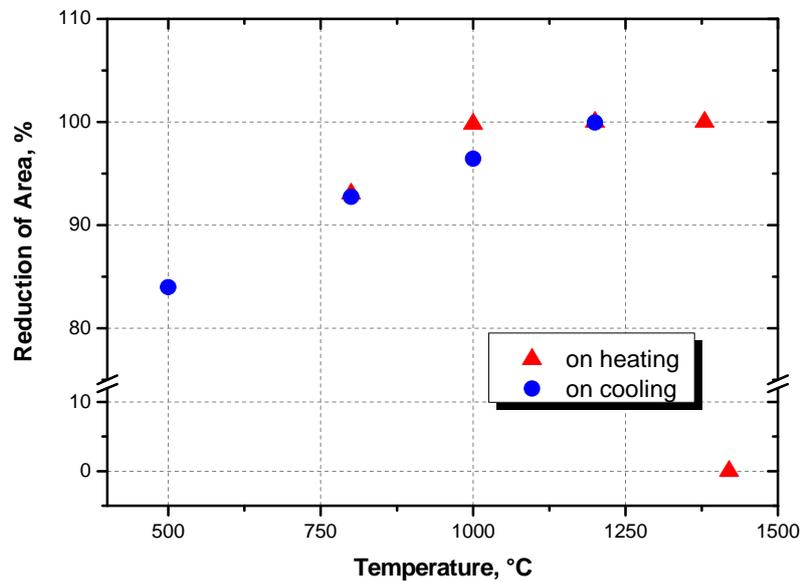


Figure 12. Results of the hot tensile tests: reduction of area values at different temperatures

The characteristics and the concrete values shown in Figure 11 and Figure 12 are in compliance with the data can be found in the literature [14, 17, 18].

5. Conclusions

On the basis of the above described facts, the following conclusions can be drawn.

- Physical simulation (particularly in Hungary) is an innovative and effective way to be applied in understanding and developing the details of welding processes.
- Nevertheless, physical simulation is not and cannot be considered the only way in this field. The possibilities offered by physical simulation and the results to be achieved by its means may fully be explored through the common application of technological investigations and tests, semi-empirical and empirical experience as well as numerical simulations.
- The reliability of the tests made on S960QL high-strength low-alloy steel – that were the first tests executed on the new equipment – is regarded satisfactory.
- NST, the temperature defined to nil strength on the tested material, can be expressed with the average value of the four tests (1403.8 °C).
- The results of hot tensile tests carried out on heating and on cooling specimens are satisfactory, considering their tendencies as well. Further investigations are required in two or even three directions to define further data (see Figure 4) and to draw further conclusions. It seems essential to reduce the difference between the actual temperatures (one direction), as well as to change the heating and cooling rates of the heating period (another direction). After we have had the results of the further tests, we may decide whether it is necessary to increase the number of specimens when performing tests with one parameter respectively (third direction).

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