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Development of a Procedure for Low-Temperature Testing of Wire Materials and Basic Research into the Behaviour of Materials in the Temperature Range of -50 to -80 °C

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Abstract. New technical applications and the ongoing infrastructural and industrial development of regions with extreme climatic conditions place ever greater demands on the properties of the materials used. On the one hand conventional materials can often meet such demands only to a limited extent whilst, on the other, a lack of experience means that sometimes no solid conclusions can be drawn regarding their suitability under extreme conditions. The examination of the influence of extreme environmental conditions on the behaviour of the material and the development of innovative materials with a tailored profile of properties is therefore one of the main tasks of modern material research as well as the material manufacturing and processing industry.

Introduction

New technical applications and the ongoing infrastructural and industrial development of regions with extreme climatic conditions place ever greater demands on the properties of the materials used. On the one hand conventional materials can often meet such demands only to a limited extent whilst, on the other, a lack of experience means that sometimes no solid conclusions can be drawn regarding their suitability under extreme conditions. The examination of the influence of extreme environmental conditions on the behaviour of the material and the development of innovative materials with a tailored profile of properties is therefore one of the main tasks of modern material research as well as the material manufacturing and processing industry.

One important sector here is the wire industry, the products of which are hugely important in almost all technical areas of application. Such products come under particular stress in low temperatures, whereby materials can be exposed to temperatures as low as -80 °C. This affects technical machinery operated in the world's Polar Regions, equipment used offshore, liquid gas systems or even components of aircraft and extraction technology. Technical applications of this kind represent growing markets that are highly attractive for manufacturers of wire materials and the wire processing industry. Here though, it is still widely unknown what influence temperatures below -50 °C have on the behaviour of wire materials. In addition, there are currently no suitable testing procedures to cover the temperature bracket between -50 and -80 °C for the examination of the stress behaviour of available wire materials in low temperature applications.

The increasing relevance of applications relating to low temperatures means there is a great need for research into the development of suitable testing procedures and the further development of the material. Based on the high level of complexity, the sophisticated equipment required and the high scientific demands, the predominantly medium-sized individual companies in the wire industry cannot really afford to come up with suitable procedures by themselves. Hence the approach for which the application is being submitted involves close cooperation between companies in the wire industry (production and processing), the German Iron and Steel Wire Association (Eisendraht- und Stahldraht-Vereinigung) and the company TA Instruments as a manufacturer of testing equipment together with the Freiberg University of Mining and Technology as a leading research institute in the area of material technology.

Deposits and low temperatures

When it comes to tapping existing sources of raw materials, regions of the earth with extreme climatic conditions are increasingly being exploited. In offshore areas and in the Polar Regions in particular, there are thought to be huge reserves of raw materials (see Fig. 1 and 2), which are attracting a great deal of interest as a result of the global scarcity of materials.

Figure 1: Raw material deposits in the North Polar Region [1]

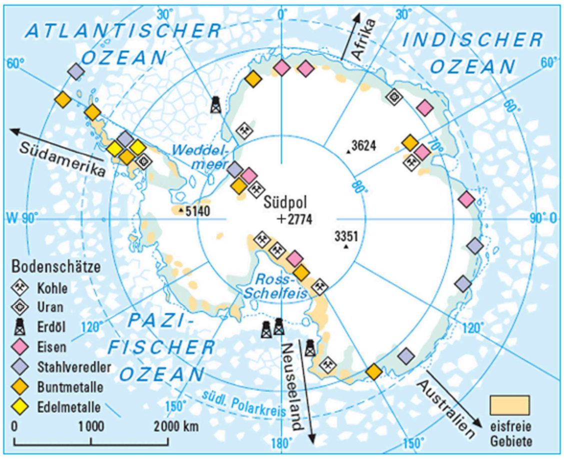

Figure 2: Raw material deposits in the South Polar Region [1]

The utilisation of these raw materials however is not only linked to the availability of suitable mining and processing technology but also the development of the necessary infrastructure and the availability of suitable transportation. Wire materials are hugely important here, particularly in relation to offshore technology, extraction equipment for oil and gas (Arctic or Siberia), road building (suspension bridges, crash barriers) and in high-voltage cables. Here they are exposed not only to low temperatures but also to substantial mechanical stresses that are caused from the build-up of ice.

Details of steel wire material testing

The authors are not aware of any studies relating specifically to wire materials at low temperatures, so solid statements on the stress behaviour of such materials at low temperatures are not currently possible. In DIN EN 12385-3 “Steel Wire Ropes – Safety”, there is at least reference to the fact that the functionality of steel wire can be reduced at low temperatures, even though its strength is not affected in operating temperatures down to -40 °C. Nevertheless, the standard does not make any further statements on material behaviour at temperatures below -40 °C. Due to the fact that material properties are dependent on the relevant manufacturing process, results from studies of other forms of materials can only be applied to a limited extent and can only offer pointers [2, 3, 4, 5].

In order to be able to draw firm conclusions on the practical material behaviour of steel wire materials at low temperatures, a suitable testing procedure has to reproduce the stress situation arising from the application as realistically as possible. This relates not only to the corresponding thermal conditions, but also the mechanical stresses that are typical for the application situation.

The testing and supply conditions for patented cold-drawn wires are set out in standards DIN 10270-1 and DIN EN 10264-2 “Cold drawn non alloy steel wire for ropes for general applications” and take into account only the properties at room temperature. These are determined primarily by means of tensile testing in accordance with EN ISO 6892-1:2009. Currently there is no consideration of low-temperature properties here.

At the Institute of Metal Forming, measures were taken within the scope of an AiF project that focus on the development of new testing procedures for wire materials. The task was defined as follows:

- It should be possible to carry out the testing in a temperature range from -80 to 200 °C
- The samples should retain their untreated surface from the manufacturing process
- The process should allow for the programming of various states of tension and expansion as required
- The permissible torque and forces of the system should be sufficient for strengths of up to 2600 MPa
- The sample materials used should be high-strength and ultra-high-strength rope and spring wire
- The deformation should take place within a defined range so that the flow curve can be calculated

The required tools, the cooling system and the controlling system were developed at the Institute of Metal Forming in cooperation with the steel wire industry, as well as with the company TA Instruments.

Measuring system developed

The existing multi-directional deformation simulator (figure 3) was used as a basis system for the development of the testing procedure. The possible cooling works by means of a specially adapted mechanism and the cooling is interlinked with the heating within a PID-controlled system. The cooling and heating power are dependent on one another. The temperature is measured using a thermocouple (type K) and is used to control the system so that the temperature fluctuation at the measuring point is no greater than 1 K within a stable testing time frame. Cooling takes place by means of a gas (helium), which is cooled within a heat exchanger to the temperature of the liquid nitrogen.

In order to be able to clamp the high-strength wire, a clamping mechanism has been developed, which can transfer the momentum and the force to the hard sample material. Here, the gripping pincers (ER25 according to DIN standard) of CNC milling machines are used, which are commercially available. Another advantage of the removable gripping pincers of the clamping system is the possibility of clamping wires with different diameters. As shown in Fig. 3, the sample is clamped between two gripping pincers at a distance of 70 mm. The deformation that takes place within the test length is defined through a rise in temperature at this point.

Figure 3: From left: Basic MDS 830 machine with a cooling system, test chamber, clamped sample wire in the ER25 gripping pincers and the heating coil

Since the cooling takes place with helium and must be concentrated on the sample, a plastic sheathing was selected that can still accommodate deformations with these low temperatures. As Fig. 4 shows, after clamping the sample is equipped with a plastic tube into which the cooling medium is injected. Three zones form and the temperature is measured within each. The temperature at thermocouple 1 (TC 1) corresponds to the test temperature and remains consistent. The temperatures TC 2 and TC 3 correspond to the edge temperatures, which should be significantly lower than the test temperature, since there is no heating through induction in these areas (figure 4). Thanks to this temperature field setting, a sharp temperature transition between the zones can be achieved. The consistent temperature field represents the test length, which amounts to 40 mm. As a result of the local undercooling, both the edges and clamping zones have a much higher yield stress. As a result, the forming is concentrated in the area of the test length.

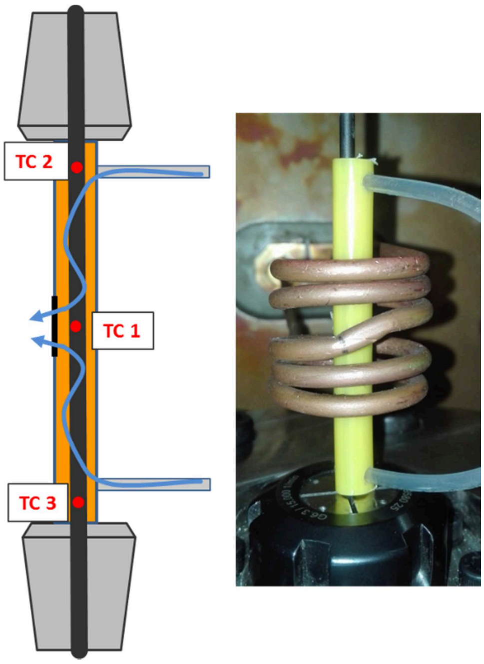

Figure 4: Schematic preparation with coolant flow and the positions of the thermocouples (left) and integrated cooling system on the sample (right)

In order to the practical use of measurements, a commercially produced wire made of steel C80 after the patenting at 1900 MPa was used. The samples were cut to lengths of 130 mm. The experiments took place with two different strain rates and in temperature range between -80°C up to 20°C with pace of 10K. The samples were also torqued without longitudinal force and at longitudinal loading of 500 MPa and 1000 MPa. For the sake of comparison, the maximum effective strain degree (φ_{max}), effective initial stress of the material flow (σ_0) and the maximum effective stress (σ_{max}) were used. The calculation of those values follows Mises solution [6].

Test of the system

After start-up of the device, the functionality of the test system was tested. The temperature distribution was compared with the calculated assumptions. As can be seen in Fig. 5, temperatures TC2 and TC3 are much lower than TC1. TC1 follow programmed temperature TProg after 30 seconds because of heat energy in the system before test start. The differences can amount to up to 50 K and ensure the forming location in the measuring area. The test sequence is subdivided into four parts. In the first part, the entire measuring system is cooled to a temperature of -120° C. The heat of the clamping device is then dissipated by the cooling to prevent potential heat flow from the drive shaft to the measuring area. The third stage of the test consists of constant cooling of the system. At the same time the measuring length of wire is heated by induction. At this point, the temperature differences between the edge and measuring length undergo controlled adjustment. The final stage of the process is the actual deformation, which, depending on requirements, corresponds to a realistic application load. Axial forces can be applied of up to 100 kN and torques of up to 25 Nm.

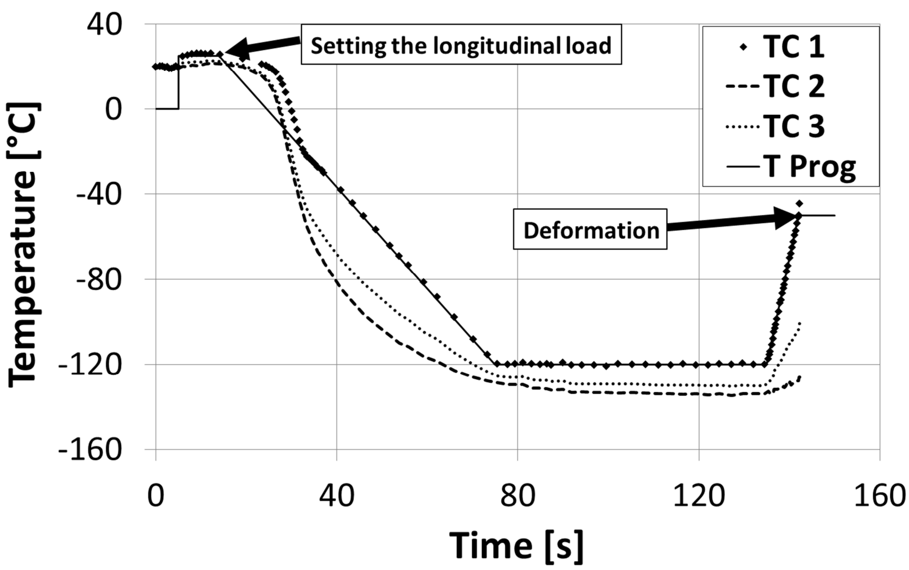

Figure 5: Temperature sequence for the low temperature test

The position or axial force can be kept constant during the deformation so that the loads, as shown in Fig. 6, generate a complex stress condition that can also undergo controlled adjustment via the deformation progress.

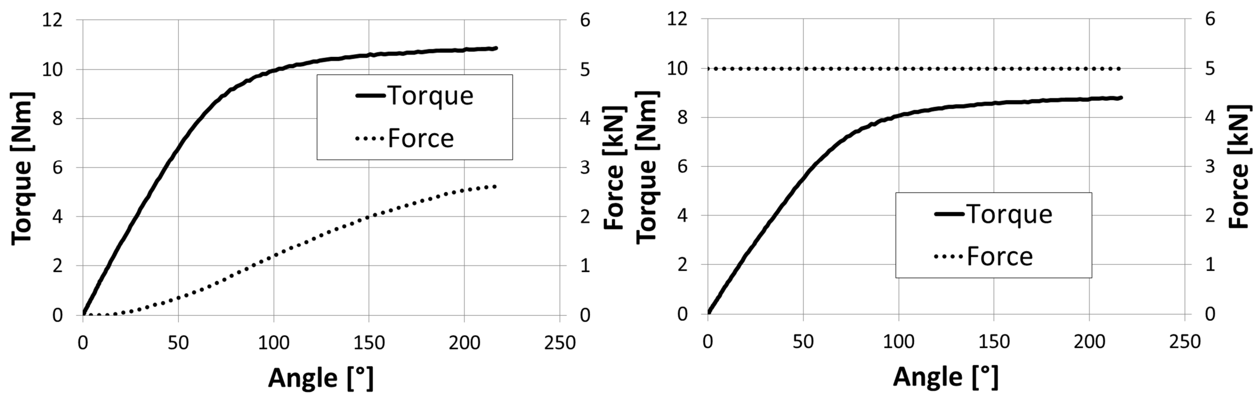

Figure 6: Torque and force sequence given differing system adjustment (left: constant length, right: constant force)

By the torsion test of commercial material without longitudinal loading was carried out in falling temperatures, both effective stresses rise on the one hand and on the other, the maximum of strain falls slightly (see Fig. 7).

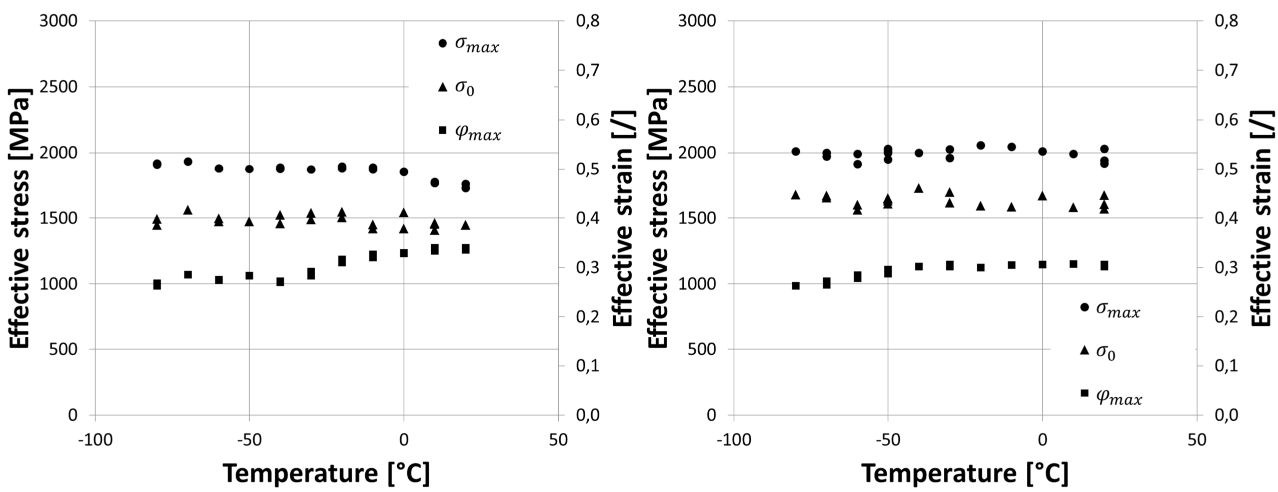

Figure 7: Influence of temperature on maximum effective strain ($\boldsymbol{\varphi_{max}}$), effective stresses of flow begin ($\boldsymbol{\sigma_0}$) and maximal effective stress ($\boldsymbol{\sigma_{max}}$) for strain rates left 0.01 s^{-1} and right 0.1 s^{-1} without axial stresses

The experiments showed that the temperature impact on deformability and the flow stress of the commercial steel wire investigated appears at a longitudinal loading of more than 500 MPa. Under longitudinal loading, the temperature effect becomes stronger and it is quite evident that a transition temperature cracking is developing. For an axial load of 500 MPa, the transition of the maximum strain can be recognised even at temperatures starting at -60°C. With a further increase of the load, this transition temperature can even increase up to 0°C. Here, small differences are noticeable in the stresses. Both of the stresses fall as a result of applying higher axial stress.

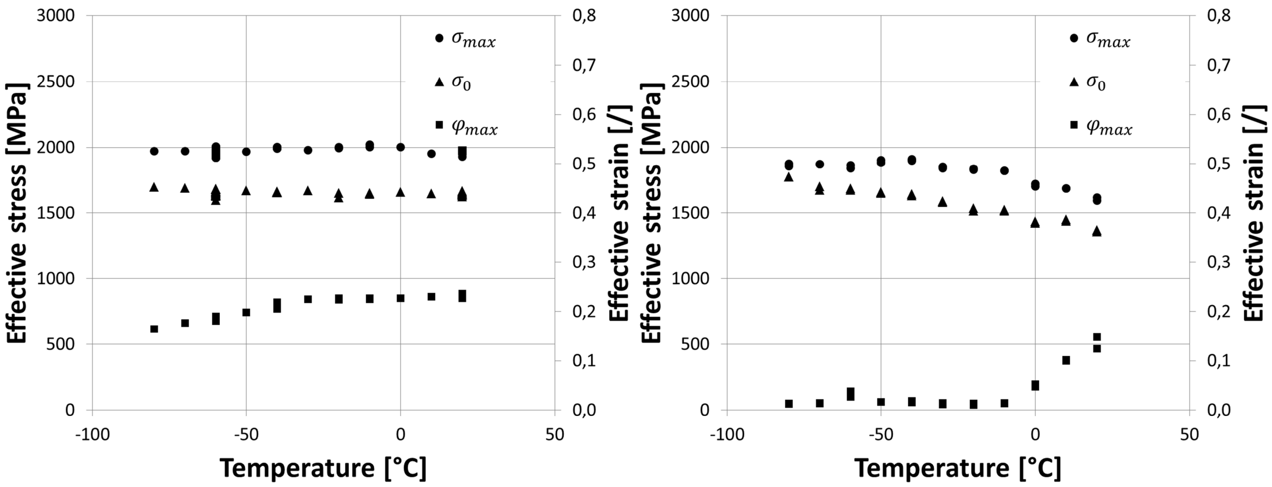

Figure 8: Influence of temperature on maximum effective strain ($\boldsymbol{\varphi_{max}}$), effective stresses of flow begin ($\boldsymbol{\sigma_0}$) and maximal effective stress ($\boldsymbol{\sigma_{max}}$) for strain rate 0.1 s^{-1} with axial stresses left 500 MPa and right 1000 MPa

Summary

In this publication, the scale of the problems when using high tensile and ultra-high tensile materials in climatic zones with extremely low winter temperatures was presented. The necessity of low-temperature material testing in the event of dynamic loads was deduced in this regard. The MDS830 system present in the Institute of Metal Forming was specified in order to be able to carry out this test. The control system and test sequence were specially adjusted for this temperature level. The first experiments provided an initial insight into the process, test cycle and test options. It is possible to generate complex stress conditions in the case of different form changes, which can affect the deformability and flow stress.
The experiments carried out demonstrate that the stress state in low temperatures has an enormous impact on the deformability and finally on the safety of the wire elements. The complex stress state can even heavily impair the fracturing formability at a temperature of 0°C and would lead quickly to a malfunction in the component.

Thanks

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