Testing of high strength steel S960 at elevated temperatures

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Abstract

Since steel is nowadays one of the most used materials for structural engineering, it is important to check how it behaves in fire conditions. From the point of fire safety engineering, the strength of steel at elevated temperatures is of the biggest interest.

In this Master's thesis, the behaviour of S960 high strength steel at elevated temperatures is investigated. In order to see what happens with the steel strength, fire conditions are simulated. Five different temperatures (20 °C, 400 °C, 550 °C, 700 °C and 900 °C) with two different strain rates (0,2 %/min and 1,0 %/min) are tested.

Reduction factors for Effective yield strength, Proportional limit and Young's modulus are obtained. Results are compared with EC3 recommendations for structural steel design at fire. It is concluded that EC3 underestimates reduction factors for Effective yield strength. Effects of two different strain rates used are also observed. Possible relationship with microstructure of high strength steel is discussed, according to the latest research done in this field.

Abstract (Serbian)

Budući da je čelik jedan od najkorisćenijih materijala u izgradnji, veoma je važno znati kako se ponaša u uslovima požara. Sa stanovništa protivpožarne zaštite, čvrstoca čelika na povišenim temperaturama je od velikog značaja.

U ovom Master radu, ispitano je ponašanje S960 visokovrednog čelika pri povišenim temperaturama. Kako bi se uočilo šta se dešava sa čvrstoćom čelika, uslovi požara moraju biti simulirani. Pet različitih temperatura (20 °C, 400 °C, 550 °C, 700 °C i 900 °C) pri dve različite stope razvlačenja (0,2 %/min i 1,0 %/min) su testirane.

Faktori redukcije za Efektivnu čvrstoću, Granicu elastičnosti kao i za Modul elastičnosti su izračunati. Oni su upoređeni sa EC3 preporukama za gradnju čelikom u uslovima požara. Uočeno je da EC3 podcenjuje faktore redukcije za Efektivnu čvrstoću. Efekti dve različite stope razvlačenja su takođe posmatrani. Moguća veza mikrostrukture visokovrednog čelika je prodiskutovana, u skladu sa poslednjim ispitivanjima obavljenim u ovoj oblasti.

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List of acronyms and symbols

θ	Temperature
σ	Stress
ϵ	Strain
ε	Strain rate
S	Name of the specimen (1 - 28)
F	Force
A	Area
k_y	Reduction of the effective yield strength
k_p	Reduction of the proportional limit
k_E	Reduction of the slope of the linear elastic range
f_y	Effective yield strength
$f_{y,\theta}$	Effective yield strength at elevated temperature
$f_{y,a}$	Effective yield strength at ambient temperature
f_p	Proportional limit
$f_{p,\theta}$	Proportional limit at elevated temperature
$f_{p,a}$	Proportional limit at ambient temperature
E	Young's modulus (Modulus of elasticity)
E_θ	Young's modulus at elevated temperature
E_a	Young's modulus at ambient temperature

1 Introduction

When talking about materials used in structural engineering, fire engineers are mostly interested in how the specific material behaves in a fire and how long a building made out of that material will remain stable. Critical conditions that are present in fires are important to investigate, but it is also important to figure out how the material will react in such conditions. Although a lot of materials are non - combustible and will not burn in contact with fire, problem of loss of the strength remains. Steel tends to lose its strength above 300 °C and this produces great danger to the overall stability of steel structures [1].

After the conditions required for flashover are reached, the safety of fire service personnel entering the building is the primary one [2], as well as prevention of economic loss due to the structural collapse. Even the building is caught on fire, goal is to protect its stability and avoid complete loss of it.

Steel is very important material used in the structural engineering nowadays. Continuous research on steel is crucial in making it safer and easier to implement in buildings. Even steel is non - combustible material, the main problem it that it loses strength in a fire [3]. With advancement in steel manufacturing, it is possible to produce stronger steel in order to develop more slender and aesthetically accepted constructions. On the other side, fire safety is of primary importance. According to Eurocode 3: Design of steel structures which is the official document used for designing steel structures by many countries in the EU, high strength steel is considered as any structural steel above nominal yielding strength of 460 N/mm^2 [4]. This grade and grades above this one are not widely used, except for particular parts of bridge constructions. However, usage of these steel grades is becoming more common and they are expected to be used in next 20 years.

The goal of this Master's thesis is to investigate the behaviour of high strength steel S960 at elevated temperatures and using tensile tests. Effective yielding strength, proportional limit as well as the Young's modulus are important characteristics of steel to investigate at fire. Reduction of these parameters will show what happens with the mechanical properties of steel at high temperatures. S960 is high strength steel with nominal yield strength of 960 N/mm^2, and not so much used in structural engineering nowadays, but as time passes by, it will see more and more application in the field. It is important to see how this material would behave in a fire, so this condition has to be simulated.

The steady - state approach is used to do the testing of steel. Five different temperatures (20 °C, 400 °C, 550 °C, 700 °C and 900 °C) as well as the ambient temperature (20 °C) are analyzed. Two strain rates are used to perform the testing: 0,2 %/min and 1,0 %/min. In total, 28 specimens of grade S690 and 3 "dummy" specimens of grade S690 are used in the experiment.

Since the steel as structural material losses its strength due to high temperatures, the main benefit of this Master's thesis is to obtain the reduction factors at different temperatures and different strain rates. These results are useful in further research on high strength steel and its safety during fires.

Eurocode 3: Design of steel structures suggests the reduction factors at different elevated temperatures, but the main application of these codes are only for mild steel grades. By comparison between experimental results for high strength steel and Eurocode values, it would be interesting to see how safe is it to use the proposed codes for designing structures. These results should also act as a proposal for making designing steel structures safer in fire conditions.

2 Methodology

2.1 Equipment

The experiment was conducted with equipment in the laboratory of the Institute for Structural Engineering, Swiss Federal Institute of Technology (Institut für Baustatik und Konstruktion, ETH Zürich). A tensile machine used is Zwick 1424 as showed in Figure 1. This universal testing machine has capacity of ± 200 kN. The electric furnace (Figure 2) is able to develop a maximum of 1000 °C with heating rate of 900 °C per hour. A nominal voltage is 230 V with a nominal electric current of 30 A. The maximum power of this furnace is 75 kW [5].

One personal computer is connected via COM ports to the tensile machine and the furnace as well. In this way, all commands can be sent directly from the computer and the results are visible on the monitor (Figure 3). The program used to control both tensile machine and furnace is called TestXpert and it is supplied by the manufacturer Zwick. All results after the testing is done are exported into files that can be used to develop the graphs.

2.2 Test material

2.2.1 Samples

In total, 31 specimens were analyzed in the experiment, 28 specimens were of grade S960 (Figure 4) and 3 specimens were of grade S690. First 28 specimens were used to obtain results and to present them in this Master's thesis, and 3 specimens were called "dummy" ones. The exact dimensions of the specimen are presented in Figure 5.

The "dummy" specimens were used to check if the setup of tensile machine was done properly and to obtain proper settings for furnace at each of the elevated temperatures. All specimens were cut from the steel plate with thickness of 12 mm. However, specimens had a thickness of 6 mm.

S960 is the material with nominal yield strength of 960 N/mm^2 and S stands for structural steel. The exact composition of this material is presented in Table 1 [6].

Figure 1: Tensile machine used to execute experiments.

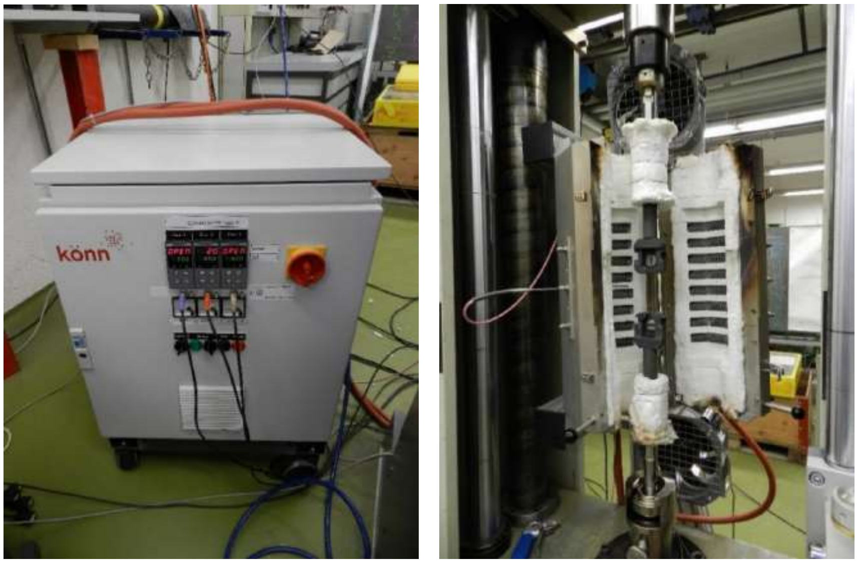

Figure 2: The furnace and oven used along with the tensile machine.

Figure 3: The computer which is connected with software to both furnace and tensile machine.

Figure 4: Test specimen made out of S960 high strength steel.

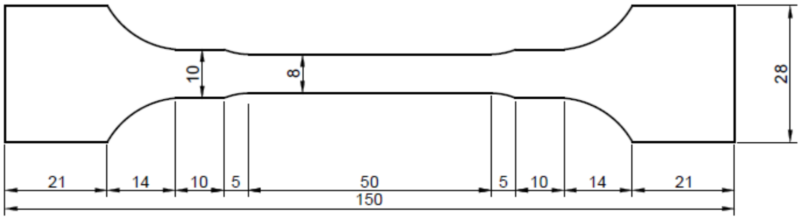

Figure 5: Dimensions of the specimen in mm.

Table 1: Chemical composition of the tested steel in % (information for DILLIMAX 965).

C	Si	Mn	P	S	Cr	Ni	Mo	V+Nb	B
0,2	0,5	1,4	0,02	0,01	0,9	2,0	0,7	0,1	0,004

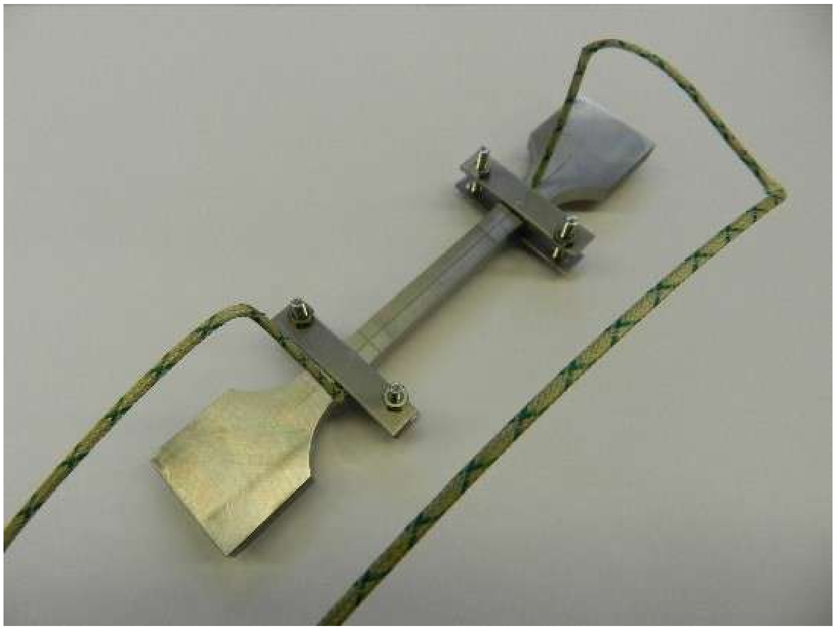

Figure 6: Prepared test specimen.

2.2.2 Preparation of the samples

Each specimen had to be prepared in order to proceed with the tensile test at elevated temperature (Figure 6). Width and thickness in the middle part of the specimen were measured three times with measuring tool and averaged. This is important since the tensile machine uses this information to calculate the area of the specimen and moreover the stress it undergoes. The length was also measured in order to have a clear picture about the final elongation at each one of the elevated temperature. The specimen was also marked with two lines, each 22,5 mm away from the middle, so extensometer was able to be positioned properly. Thermocouples were fixed not too tight with steel plates on the specimen.

2.2.3 Test programme

Specimens were tested at different temperatures and using different strain rates. Five different temperatures were implemented: 20 °C (ambient temperature), 400 °C, 550 °C, 700 °C and 900 °C. Two strain rates were used to perform the testing: 0,2 %/min and 1,0 %/min.

Three specimens were tested at the same temperature and the same strain rate, in order to gather accurate results and to see if the tests were able to repeat with the same results. Additionally, three specimens of grade S690 were also tested, but as "dummy" specimens before testing specimens of grade S960. In Table 2, programme of testing is shown. The only exception was the last specimen S28, which was tested as fourth specimen at 550 °C and with strain rate of 1,0 %/min.

Reason for this additional test was to gather more accurate data, since the second test for this temperature and strain rate differed from others. In order to make the testing more efficient, it was decided to do two tests per day. Strategy was to do test at lower temperature in the morning, cool down the machine and after that do the next test at higher temperature. Using this principle, the machine has time to cool down during the night and it is ready for the next test tomorrow. For example, test at 400 °C was done in the morning and test at 700 °C was done in afternoon.

Table 2: The temperatures and strain rates used to test the specimens.

θ [°C]	20	400		550		700		900	
ε [%/min]	0,2	0,2	1,0	0,2	1,0	0,2	1,0	0,2	1,0
	0,2	0,2	1,0	0,2	1,0	0,2	1,0	0,2	1,0
	0,2	0,2	1,0	0,2	1,0	0,2	1,0	0,2	1,0

2.3 Procedure

2.3.1 Approach

The principle used to conduct the experiment was steady - state test. In this approach, specimen was heated to desired temperature, and after that the load was applied. Hence, temperature was constant during the tensile test. After checking the Modulus of Elasticity, the heating phase began. With heating rate of 900 °C/h the desired elevated temperature was reached. Another 30 minutes were required for temperature to stabilize in conditioning phase. If the temperature differed significantly, the settings of the furnace were changed. The common problem was overshooting or undershooting the goal temperature, and in this case the values had to be adjusted manually. Although the better correlation to reality (real fire conditions) gives the transient - state approach since the temperature rise takes place, the steady - state approach was selected. Reason for this was that this approach took shorter time to conduct but the results did not vary too much. There was an experiment with S460 steel both with steady - state and transient - state principle. Results for two different approaches [7] are not that different, and assumption is that it will not differ too much for S960 as well.

2.3.2 Testing of Young's modulus

In order to be sure that the specimen was properly put in the tensile machine and everything was ready to begin with the experiment, it was important to check the Young's modulus or Modulus of Elasticity in the beginning of each test. For steel, value of Modulus of Elasticity is 210000 MPa. If the specimen was properly positioned and fixed in the tensile machine, at ambient conditions, it was expected to get the values of Young's modulus in range from 205000 MPa to 215000 MPa (± 5000 MPa). It is important to keep the tensile machine always clean and to put the specimen in a complete vertical position. Failing to do so will produce the bending of a machine in fixers and the value of Young's modulus will be wrong.

At higher temperatures (above 700 °C) the specimen tends to melt. Parts of the specimen in direct contact with the tensile machine could melt due to high temperature and fixation applied. Remains of the material could be found on fixers (Figure 7) and pincers of the tensile machine after testing.

These remains of the melted steel have to be cleaned. Otherwise, the next specimen for testing will not be positioned properly due to the little remains of steel. In Figures 8 and 9 show cleaned parts of the tensile machine that are in direct contact with specimens.

After the machine was cleaned, the specimen was vertically positioned. Its position was checked with different pre - force values (1000 N, 2000 N, 4000 N, 8000 N and 12000 N). If the specimens were still vertical and correctly aligned, the fixers were attached. In this way, specimen was secured and ready for testing of Young's modulus (Figure 10).

Figure 7: Fixers of the tensile machine.

Figure 8: Pincers of the upper fixer.

Figure 9: Pincers of the lower fixer.

Figure 10: Properly positioned and fixed specimen.

Figure 11: Sticks of the extensometer on the specimen.

After the specimen was fixed, extensometer was put on it. Extensometer was used to accurately measure the elongation of the specimen during the test. It was important to position the extensometer correctly since it is very sensitive. Distance between two sticks of the extensometer was checked with equipment supplied from manufacturer.

In Figure 11 the extensometer that is positioned on the specimen is shown. Specimen of grade S960 was tested at strain rate between 4000 N and 23000 N, but the range used to calculate the Young's modulus is between 7000 N and 22500 N. Additionally, five tests were made, but only four were used to average the values and get the final value of the Young's modulus.

2.3.3 Tensile test at elevated temperatures

If the Young's modulus which was measured stayed in the limits defined before, next steep was to proceed with the tensile test at elevated temperatures. The furnace was closed and well insulated, in order not to have heat losses and differences in temperature during the test.

With all settings implemented, the heating phase started and after it, the tensile test began. Two fans positioned in back of upper and lower parts of the tensile machine helped machine hot to heat up and elongate. In order not to harm the extensometer, it had to be taken away since there was

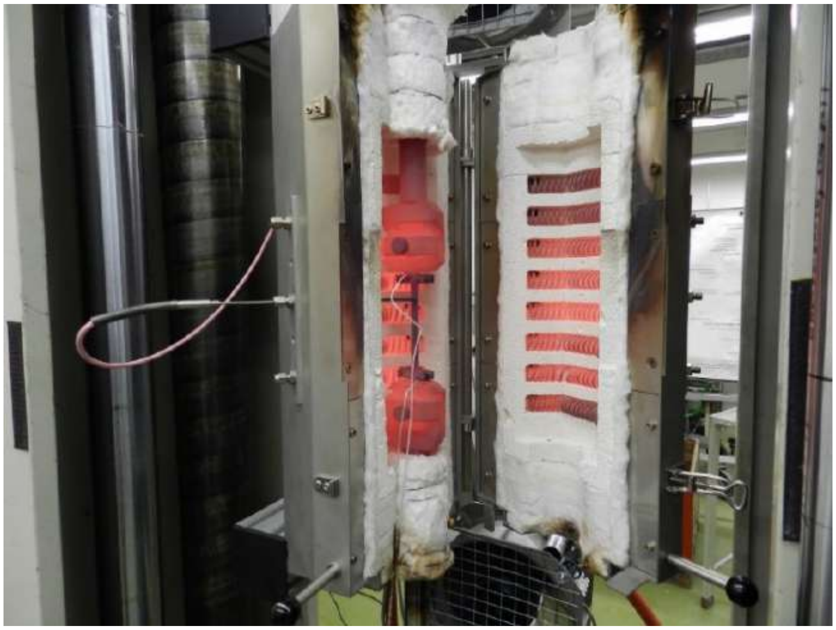

Figure 12: Opened oven and specimen in it, at 900 °C.

a possibility of specimen to break down. Breakage of specimen at higher tensile force can be dangerous for extensometer. After the specimen was broken, the furnace was opened as shown in Figure 12 and the cooling phase took place. Sometimes, if the specimen did not break during the phase e.g. the tensile machine reached "soft" ends, the specimen was left to cool down with machine. At some point of time, due to shrinking, specimen broke down.

The end of each curve on the stress - strain graphs marks the point when the extensometar is removed. This is done due to safety reasons. At this point, it is estimated that there is a possibility to specimen to broke at higher tensile stress and damage the extensometar. It has been removed and the tensile machine continued to take measurements onwards. Problem with this way of measuring is that it is not very accurate. Tensile machine has many different moving and fixed parts, which could also stretch. The elongation is measured for the whole machine, and not only for the specimen.

3 Results

3.1 Stress - strain curves

The stress - strain curves for the specimens tested using 0,2 %/min and 1,0 %/min are shown on Figures 13 and 14. In both cases, great reduction happens already at 400 °C. As said before, literature suggests that steel loses strength after 300 °C. This correlates good with the experimental results and the results obtained in another studies found in research papers [8] and [9].

At 20 °C (ambient temperature), since S960 is quite strong material, it has steady plateau for a long time.

Curves representing specimens at 700 °C and 900 °C became very ductile because of the applied high temperature. The test lasted very long (sometimes up to 6 h) and the strain was near 25 %. At the end, they did not break during the test.

In Figure 15, stress - strain curves at 1,0 %/min for specimens S13, S14, S15 and S28 are shown. S14 is the specimen which differed too much from others so S28 was tested additionally.

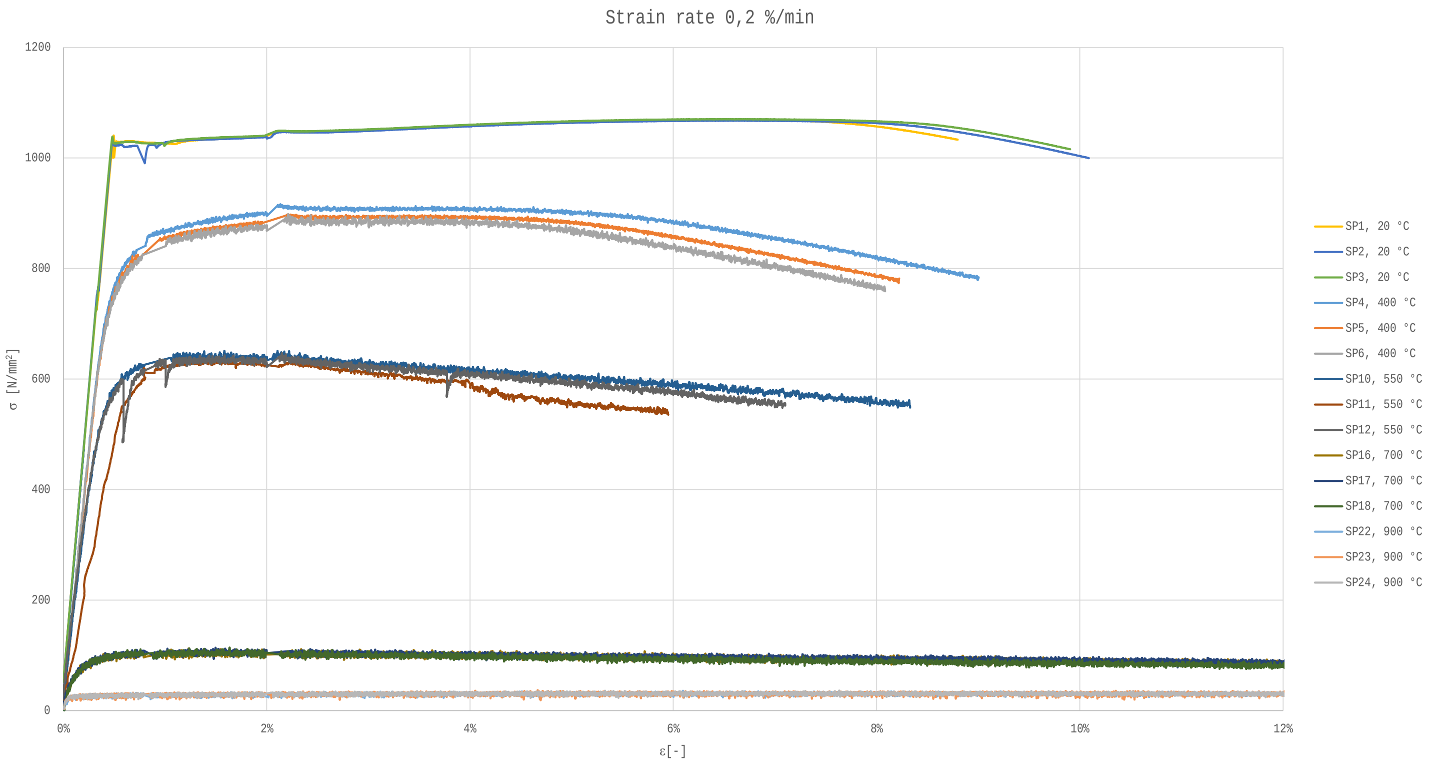

Figure 13: Stress - strain curves at 0,2 %/min.

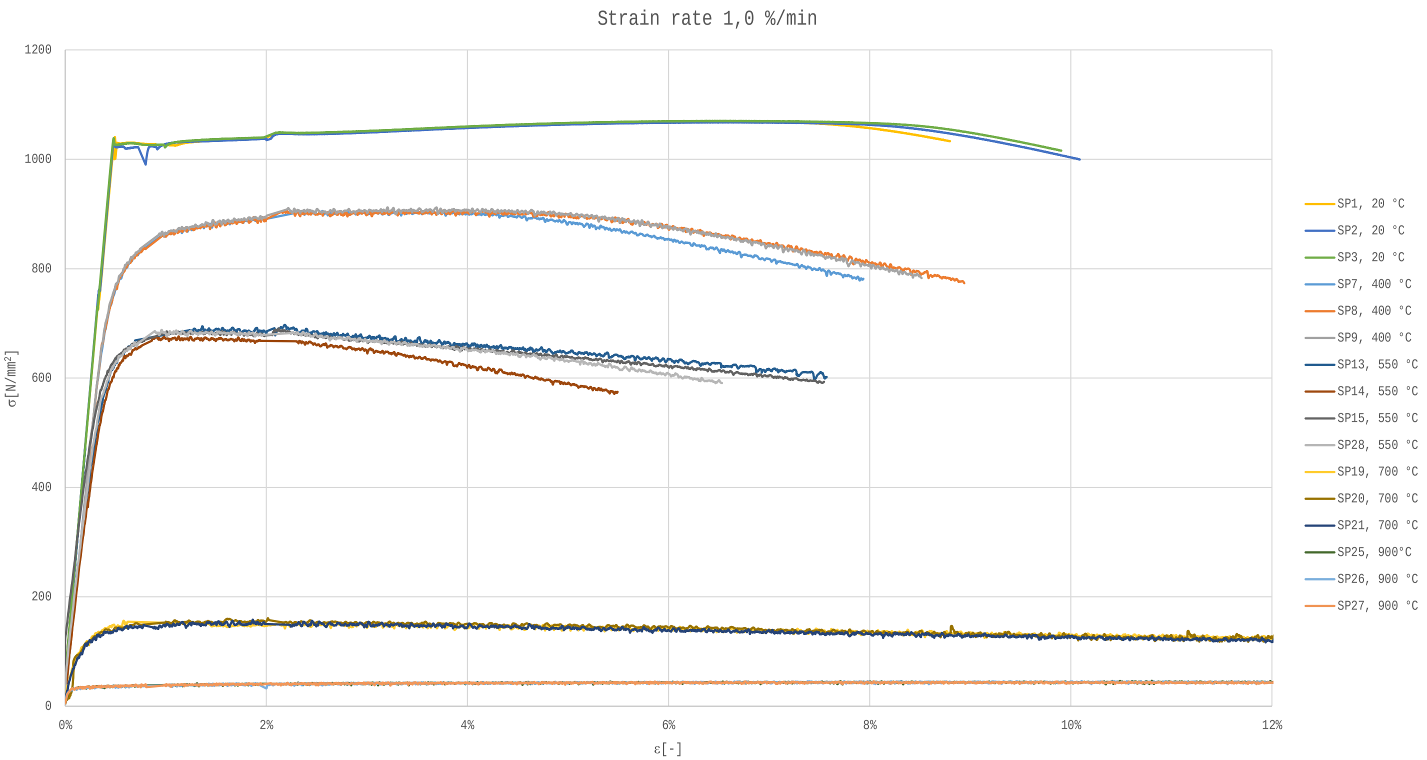

Figure 14: Stress - strain curves at 1,0 %/min.

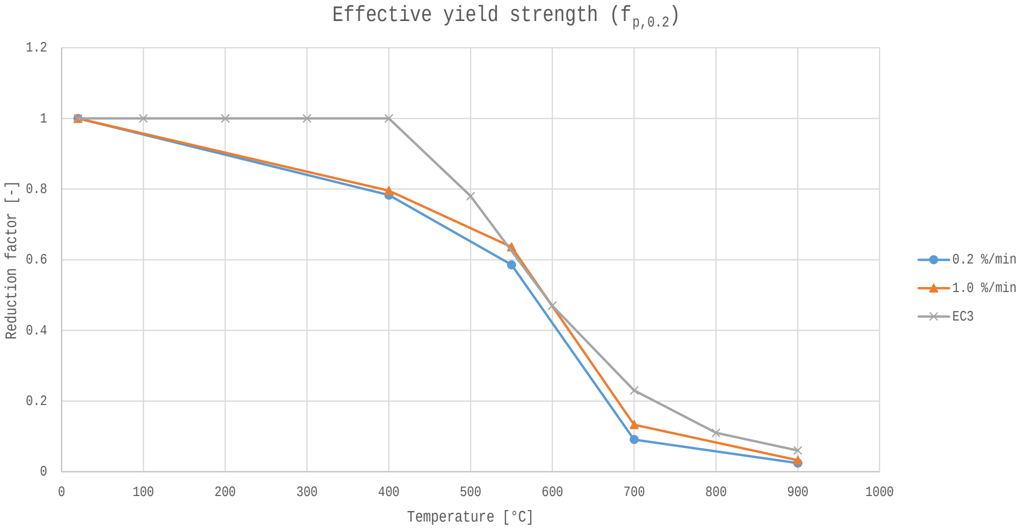

Figure 15: Reduction of effective yield strength.

3.2 Effective yield strength

Since it is hard to determine by looking on shape the yield point of high strength steel, offset yield point is checked [10]. It is set to 0,2 % by EC3 and uses the slope of the first loading in experiment. In this case this point is denoted as $f_{p,0.2}$. Reduction is obtained by diving the Effective yield strength at elevated and ambient temperature (Figure 15).

$$k_y = \frac{f_{y,\theta}}{f_{y,a}} \tag{1}$$

There is a great difference between experimental results and EC3. According to EC3, the reduction starts at 400 °C, and not before. The reduction is in general underestimated, which shows that high strength steel behaves differently, in comparison to mild steel. Good correlation is obtained at 550 °C and 900 °C.

Table 3: Effective yield strength and reduction for steel S960 at 0,2 %/min.

Specimen	θ [°C]	f_y [N/mm^2]	k_y [-]
SP1	20	1028	1
SP2	20	1021	
SP3	20	1028	
SP4	400	815	0.7829
SP5	400	799	
SP6	400	795	
SP10	550	602	0.5856
SP11	550	601	
SP12	550	599	
SP16	700	97	0.091
SP17	700	93	
SP18	700	90	
SP22	900	26	0.0244
SP23	900	25	
SP24	900	24	

Table 4: Effective yield strength and reduction for steel S960 at 1,0 %/min.

Specimen	θ [°C]	f_y [N/mm^2]	k_y [-]
SP1	20	1028	1
SP2	20	1021	
SP3	20	1028	
SP7	400	813	0.7956
SP8	400	815	
SP9	400	820	
SP13	550	656	0.6363
SP14	550	642	
SP15	550	660	
SP19	700	137	0.1333
SP20	700	143	
SP21	700	130	
SP25	900	34	0.0325
SP26	900	33	
SP27	900	33	

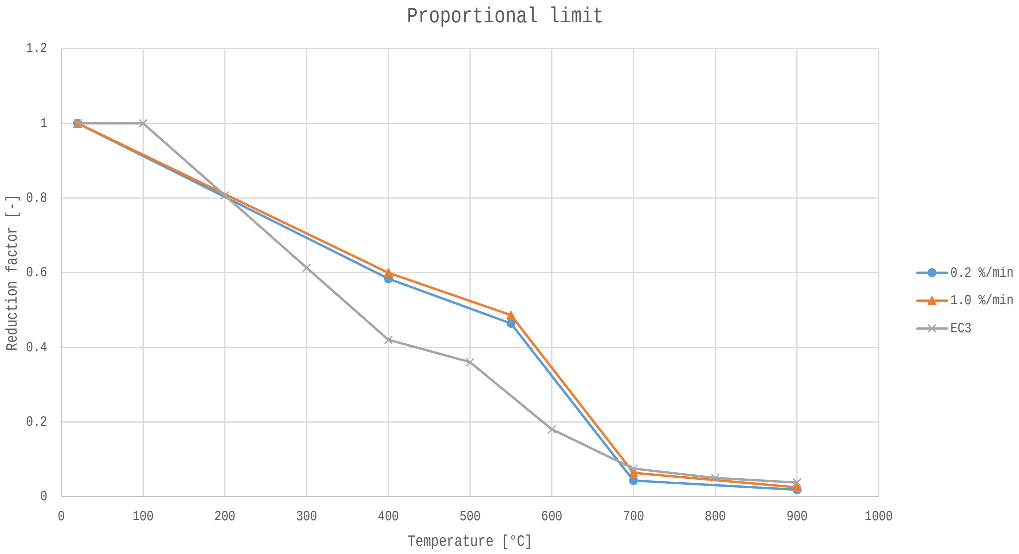

Figure 16: Reduction of the proportional limit.

3.3 Proportional limit

Proportional limit is the point until steel behaves according to Hook's law. Amount of stress is proportional to strain, so the stress - strain graph is a straight line. After reaching Proportional limit, Hook's law is not applicable anymore.

In order to compare the results of S960, values of the proportional limit for 0,2 %/min and 1,0 %/min are taken on the different temperatures and the values of EC3 recommendations are compared as well (Figure 16).

$$k_p = \frac{f_{p,\theta}}{f_{p,a}} \tag{2}$$

There is great reduction in strength at 400 °C and at 900 °C material has only small part of strength comparing to ambient temperature. EC3 curve is overestimating the reduction in proportional limit until 700 °C but shows good correlation with experimental results at 900 °C. Additionally, reduction factors are also showed. They are calculated by averaging three specimens at the same temperature and strain rate and dividing them by the values at ambient temperature. Since the overall strength of the steel is higher for higher strain rate, greater reduction is applied for strain rate of 0,2 %/min.

Table 5: Proportional limit and reduction for steel S960 at 0,2 %/min.

Specimen	θ [°C]	f_p [N/mm^2]	k_p [-]
SP1	20	1029	1
SP2	20	1030	
SP3	20	1038	
SP4	400	606	0.5836
SP5	400	607	
SP6	400	605	
SP10	550	492	0.4639
SP11	550	494	
SP12	550	460	
SP16	700	43	0.0428
SP17	700	47	
SP18	700	44	
SP22	900	21	0.0183
SP23	900	18	
SP24	900	18	

Table 6: Proportional limit and reduction for steel S960 at 1,0 %/min.

Specimen	θ [°C]	f_p [N/mm^2]	k_p [-]
SP1	20	1029	1
SP2	20	1030	
SP3	20	1038	
SP7	400	630	0.5997
SP8	400	625	
SP9	400	612	
SP13	550	505	0.4862
SP14	550	504	
SP15	550	505	
SP19	700	66	0.0633
SP20	700	63	
SP21	700	68	
SP25	900	26	0.0247
SP26	900	25	
SP27	900	26	

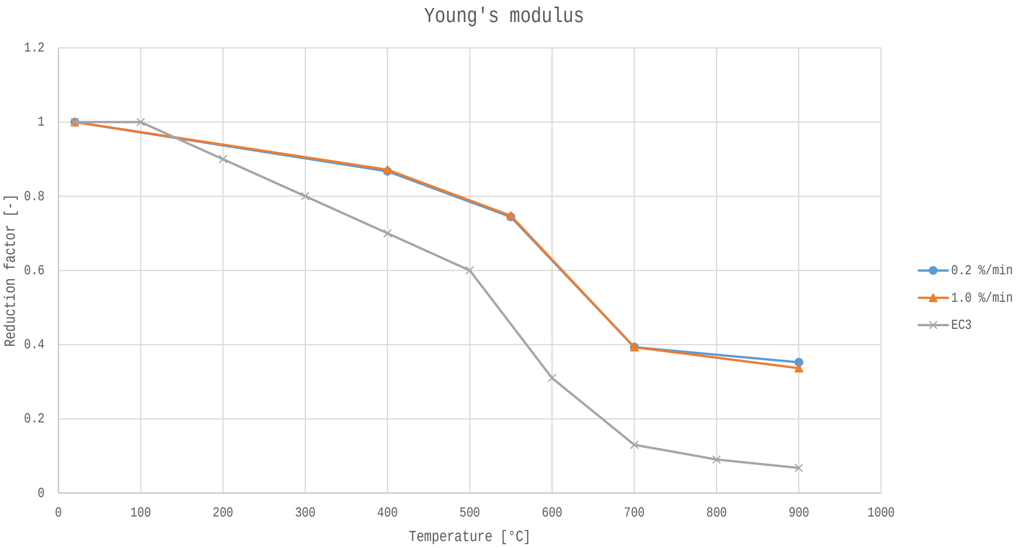

Figure 17: Reduction of the Young's modulus or Slope of the linear elastic range.

3.4 Young's modulus

Young's modulus of Modulus of elasticity is the value that measures material's resistance to deform plastically. It is actually the slope in the elastic deformation region. Hence, in EC3 it is defined as Slope of linear elastic range. Reduction of Young's modulus is calculated by dividing the average values of Young's modulus for three specimens at elevated and ambient temperature (Figure 17).

$$k_E = \frac{E_\theta}{E_a} \tag{3}$$

The reduction is almost the same for both strain rates but EC3 tends to overestimate it after 200 °C.

Table 7: Young's modulus and reduction for steel S960 at 0,2 %/min.

Specimen	θ [°C]	E [MPa]	k_E [-]
SP1	20	205344	1
SP2	20	198545	
SP3	20	203787	
SP4	400	178584	0.8671
SP5	400	176453	
SP6	400	171860	
SP10	550	150713	0.7444
SP11	550	153243	
SP12	550	148412	
SP16	700	78201	0.27932
SP17	700	79267	
SP18	700	81471	
SP22	900	61230	0.27523
SP23	900	80516	
SP24	900	72325	

Table 8: Young's modulus and reduction for steel S960 at 1,0 %/min.

Specimen	θ [°C]	E [MPa]	k_E [-]
SP1	20	205344	1
SP2	20	198545	
SP3	20	203787	
SP7	400	175675	0.8713
SP8	400	176623	
SP9	400	177184	
SP13	550	153974	0.7457
SP14	550	152737	
SP15	550	147533	
SP19	700	66521	0.27931
SP20	700	87611	
SP21	700	84736	
SP25	900	64445	0.27365
SP26	900	68335	
SP27	900	71677	

3.5 Effect of different strain rates

In Figure 18 are presented averaged curves for each temperature but on different strain rates used to perform the experiment. For example, three specimens at 400 °C were averaged (in order to get one representative curve) at 0,2 %/min and the same is done for 1,0 %/min. In this way, one can see that values of stress are not the same. They are different for different strain rate, so that stresses are higher for higher strain rates. The difference gets larger with higher temperatures. At 400 °C this difference is small, but at 700 °C there is high difference. From this, conclusion can be made, that strain rates affect the values of stress, especially at higher temperatures.

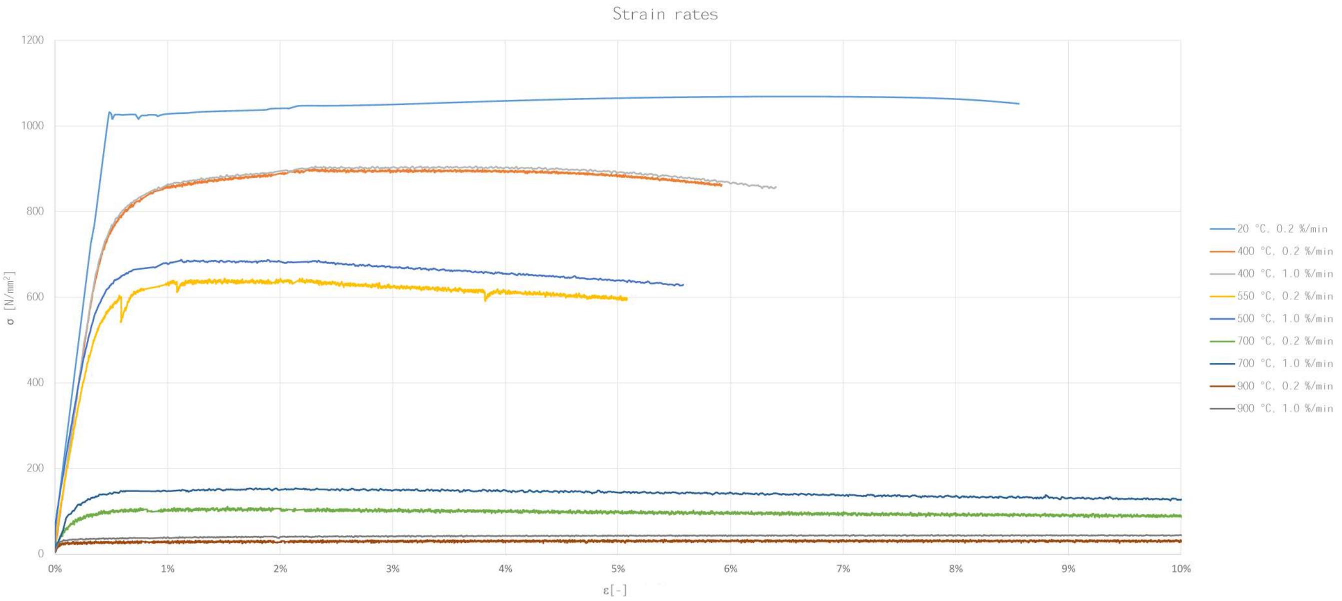

Figure 18: Effect of different strain rates.

3.6 Physical behavior of broken specimens

In Appendix, the photos of the broken specimens are shown. After the test, the specimens were cooled down, taken in two pieces out of the tensile machine and photographed. All of them are put on the same background divided into 5 x 5 mm squares with corresponding name, temperature and strain rate used to test particular specimen. In this way, one can compare different specimens and analyse them.

Specimens tested at 20 °C, 400 °C and 550°C broke during the tensile test. However, specimens at 700 °C and 900 °C did not break in this process, but during the cooling phase. At elevated temperatures, the specimens became very ductile. Before the breakage of these specimens could happen, the tensile machine reached its "soft" edges. This means that maximum movement of the tensile machine was reached. Specimens were left under tension during the cooling phase and eventually, they broke down due to shrinking.

4 Discussion

The main question related to the behavior of high strength steel tested in this Master's thesis is, why it behavies differently to mild steel and thus the EC3 recommendations should not be used when dealing with this type of steel.

Two possible ways to discuss different behavior could be the manufacturing process which this high strength steel undergoes as well as microstructure changes during the experiment at elevated temperatures.

4.1 Influence of making process

When producing steel, the most important content beside iron is carbon, since the amount of carbon highly influences the type of steel that is produced. Although the amount of carbon is low (usually less than 1 %) through changing this element, it is possible to produce different types of steel made for different usage. Very small change in percentage of carbon could produce high differences in final steel which is being produced [11].

Generally, steels with high amount of carbon are stronger (they have higher yield strength) but they do not have such high ductility and toughness [12]. On the other side, steel with lower carbon percentage will have lower yield strength, but higher ductility and toughness. Of course, the properties which the manufacturing process will produce, depends on the usage of material. For example, steel used to produce thin plates which later will be cold formed, will have only 0,04 % of carbon content in it. For another usage, steel with higher carbon content will be suitable, for example for structural engineering (elements of buildings). However, if the carbon content goes above 0,25 %, it will produce problems with welding (weldability will be lower). This material is made for mechanical engineering, for example for bolts or some special parts of machines but not for constructions. According to ration between iron and carbon and temperature, different microstructures which will affect greatly steel properties are formed. Microstructure will be discussed more in the next part, since it is quite related to temperature.

Second most important factor which influences the final steel material is the process of cooling. When the steel is cast, it is very important at which temperatures and how fast it will cool down. According to this, microstructure will form differently and the final material will have another material properties. There is slow and fast cooling process. Using the first process (which is controlled using the furnace or by cooling material in still air, the process called tempering produces normalized steel) the steel will cool down slower and the microstructure will have enough time to form as described in theory, according to iron/carbon phase diagram [13]. However, if the cooling phase is faster (by cooling down the material in water or oil, so called quenching process) the microstructure will form differently, and some parts of it will not integrate as they should.

4.2 Microstructure at elevated temperatures

According to carbon content in steel as well as its correlation with temperature, different microstructures are formed, as presented in Figure 19. In the following part, types of steel microstructures are briefly described.

Ferrite is the structure that consists of most 0,08 % of carbon. Tensile strength is about 250 MPa and elongation can go up to 50 %.

Cementite is form where carbon has its content of 6,67 %. Tensile strength is 750 MPa and elongation about 1 %.

Pearlite is the combination of Ferrite (12 %) and Cementite (88 %). Carbon content is 0,78 % with tensile strength of 500 MPa and elongation of 10 %.

Austenite is the form that appears on higher temperatures (1130 °C) and has carbon content up to 2 %.

For example, high strength steel is cast and cooled down in specific way. The material is heated and quenched, in order to gather high strength characteristics needed to high strength steel. After that, material is heated up once more and left to slowly cool (tempering) down and get back ductile properties [14].

These are all the forms that are created during the slow process of cooling down. If this process is faster and the cooling becomes rapid, the structure will not follow the above mentioned graph. Austenite will not transform into Pearlite but into new form. Fall of temperature sometimes can be very high and thus lasts very short period of time. New form will be created, and it is called **Martensite**. Once the steel of this kind is produced, there is still danger of undergoing the similar process of quenching one more time during the welding phase. On the local spot, the welding will bring huge amount of heat and once the welding is over, this region will cool down very fast, similar to quenching process described before. Cracks can happen in this situation so the welding should be done carefully. Martensite has high hardness and

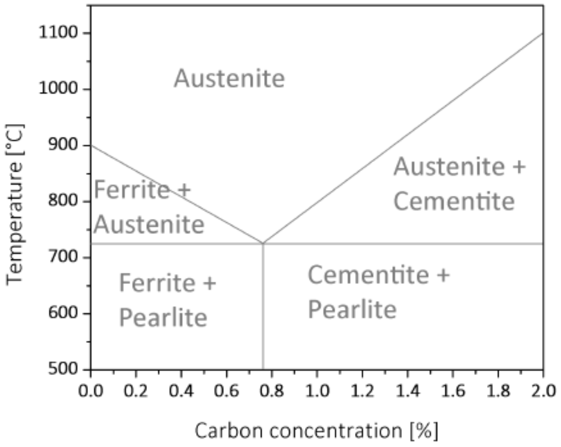

Figure 19: Simplified Fe-C phase diagram.

low toughness, so tempering has to be done in order to supply the material with better mechanical properties.

According to recent study [15], reasons for drop of strength in high strength steel (such is S960 tested in this Master's thesis) should be investigated by observing what happens with the microstructure of material during the experiment. At temperatures between 200 °C and 300 °C carbide that is in the steel due to the tempering process will form new carbides and take out any left carbon in Martensite [16]. In this process, the strength of high strength steel is reduced. If the initial strength has to be again reached, the quenching process should take place as well. After 350 °C the rest of the carbide will continue to coarsen and hence additionally drop down the strength of steel [17]. Martesite has feature that carbide particles coarsen very fast comparing to mild steels where carbide is much more stable (it consists of Ferrite grains and Pearlite grains). Martensite behavies differently at high temperatures [18] resulting in lower thermal stability of high strength steel.

5 Conclusions

The main goal of this Master's thesis was to investigate the behaviour of high strength steel S960 at elevated temperatures. Tensile tests were performed and the results were presented. Steady - state test was used at five different temperatures (20 °C, 400 °C, 550 °C, 700 °C and 900 °C) with two different strain rates (0,2 %/min and 1,0 %/min). Three specimens were assigned to the same temperature and strain rate, in order to have more accurate and reliable results.

Experimental results and EC3 recommendations are compared, since EC3 is known for usage in Europe for designing structures. Reduction of Effective yield strength is underestimated by EC3 which shows that high strength steel at elevated temperature will lose more of its initial strength. Reductions of Proportional limit and Young's modulus are overestimated. According to this, using EC3 to design structures with S960 steel is not recommended and suggestion is to do more testing of different grades of high strength steel, in order to obtain reliable results [19]. Difference in stress - strain graphs is noticed for different temperatures and different strain rates. At higher temperatures, difference between strain rates in terms of strength is higher.

Reasons why high strength steel behavies differently comparing to mild steel are briefly explained. According to research papers described in the part of Discussion, high strength steel has microstucture (which is the result of specific heat treatment of this material) of Martensite, which is not thermally stable, as forms of Ferrite or Pearlite in mild steel. Hence, loss of strength can be explained by faster degradation of this microstructure.

S960 high strength steel is material which nowadays practically has no use in structural engineering. However, this is the material that will be used in future. Hence, it is very important to do more tests with similar high strength steel. Interesting is to see how it will behave in fire, and from the point of fire safety engineers, is it safe enough to build structures with it. Perhaps testing of these materials will help other research related to fire safety engineering, especially in field of passive fire protection.

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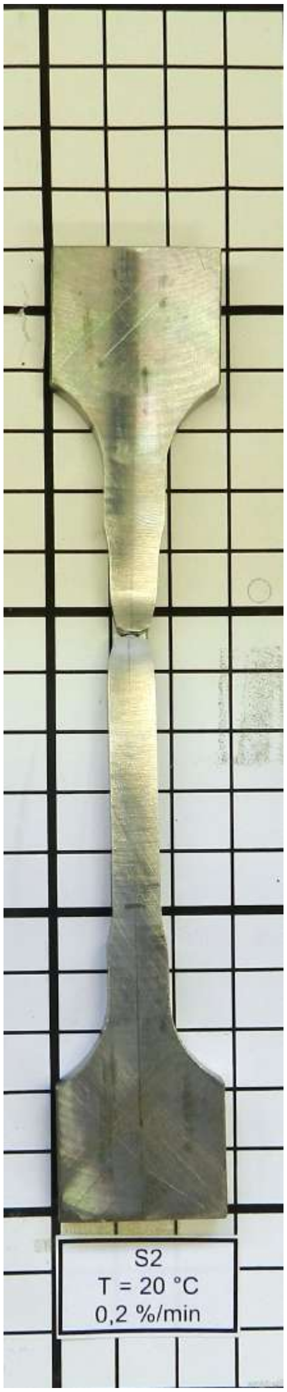
8 Appendix

At the following pages, photos of broken specimens after cooling process are shown.

Photos of all specimens are taken on the same background, for easier comparison between them. Specimen numbers, temperatures and strain rates are presented as well.


S1
T = 20 °C
0,2 %/min


S2
T = 20 °C
0,2 %/min


S3
T = 20 °C
0,2 %/min


S4
T = 400 °C
0,2 %/min


S5
T = 400 °C
0,2 %/min


S6
T = 400 °C
0.2 %/min


S7
T = 400 °C
1,0 %/min


S8
T = 400 °C
1,0 %/min


S9
T = 400 °C
1,0 %/min


S10
T = 550 °C
0,2 %/min


S11
T = 550 °C
0,2 %/min


S12
T = 550 °C
0,2 %/min


S13
T = 550 °C
1,0 %/min


S14
T = 550 °C
1,0 %/min


S15
T = 550 °C
1,0 %/min


S16
T = 700 °C
0,2 %/min


S17
T = 700 °C
0,2 %/min


S18
T = 700 °C
0,2 %/min


S19
T = 700 °C
1,0 %/min


S20
T = 700 °C
1,0 %/min


S21
T = 700 °C
1,0 %/min


S22
T = 900 °C
0,2 %/min


S23
T = 900 °C
0,2 %/min


S24
T = 900 °C
0,2 %/min


S25
T = 900 °C
1,0 %/min


S26
T = 900 °C
1,0 %/min


S27
T = 900 °C
1,0 %/min