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SSRT testing of Cu

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Update notice

The original report, dated April 2019, was found to contain factual errors which have been corrected in this updated version. The corrected factual errors are presented below.

Updated 2021-01

Location	Original	Corrected
Page 22, Figure 4-6	*Incorrect data used in figure*	*Figure updated with correct data* *Cu-OF, data point 122 and 126.8 MPa at 75 °C inserted* *Cu-6N, data point 149 MPa at 75 °C removed*
Page 22, Figure 4-7	*Incorrect data used in figure*	*Figure updated with correct data* *Cu-OF, data point 182.7 MPa at 75 °C inserted*
Page 23, Figure 4-8	*Incorrect data used in figure*	*Figure updated with correct data* *Cu-OF, data point 15.6 % at 75 °C inserted*
Page 23, Figure 4-9	*Incorrect data used in figure*	*Figure updated with correct data* *Cu-OF, data point 74.4 % at 75 °C inserted* *Cu-OFP, data point moved from 0 to 69.6 % at 75 °C*

Summary

Four different copper materials have been slow strain rate tensile tested (SSRT) at elevated temperatures. The temperatures used were 75, 175 and 215 °C, and the strain rate used approximately 5×10^{-7} s^{-1}. The four materials were an ultra-high purity copper (Cu-6N), an oxygen free copper (Cu-OF), a phosphorus doped copper with extra high hydrogen content (Cu-H) and a standard phosphorus doped copper (Cu-OFP). The results from the SSRT testing group the materials into two main groups. The materials with phosphorus exhibit a test ductility of approximately 35 % elongation at failure for all temperatures. The materials without phosphorus exhibit an elongation at failure of approximately 12 % for the two higher temperatures. At the lower test temperature of 75 °C the materials with and without phosphorus show the same, higher, elongation at failure. Yield strength and tensile strength are similar for all materials at each temperature.

Mechanical properties within each material group, with and without phosphorus, are similar. No effect of either the raised hydrogen content in Cu-H or the ultra-high purity copper (Cu-6N) is evident when compared to Cu-OFP and Cu-OF respectively.

Contents

1 Introduction

To fulfil the requirements of the KBS-3 method, copper must exhibit a high degree of ductility. The copper provides corrosion resistance and must also have sufficient creep ductility to withstand the manufacture of the canisters and pressure at the repository depth.

Initial designs were based on an oxygen free copper, but this was found to have insufficient creep ductility (Andersson-Östling and Sandström 2009). To increase the ductility, oxygen free copper has been doped with phosphorus. However, the role of phosphorus in the creep properties of copper is insufficiently understood but it is known from empirical studies in a short timescale, up to 20 years, that it has a beneficial effect on the elongation at failure which increases from less than 0.3 % (Cu-OF) to over 50 % (Cu-OFP) (Henderson and Sandström 1998).

The work presented in this report aims at studying the slow strain rate properties of different copper qualities to investigate if the difference in properties can be seen in short term tests such as slow strain rate tensile testing (SSRT). If they do, it might be possible to reduce the testing time for batch acceptance to a few weeks instead of a few years of creep testing. SSRT tests were performed on material that had, after being annealed, been pre-strained to 120 MPa. This was done to give the material a defined deformation history. The stress of 120 MPa was also chosen to give a material hardness approximative of the real canister after manufacturing.

Two materials, Cu-6N and Cu-H, were also hot tensile tested to provide comparisons with the other materials where such data was available (Danielsson and Andersson-Östling 2018).

2 Material and specimen preparation

Four different copper materials were tested, see Table 2-1.

Table 2-1. The four different materials and their quality.

Material no.	**Copper quality**	**Description**	**Charge no**
1	Cu-6N	Ultra-high purity, 99.9999 % Cu	Luvata LOT# 116292-2
2	Cu-OF	Oxygen free	SKB KME G221
3	Cu-H	Oxygen free, with phosphorus and high level of hydrogen (1.03 wt.ppm)	Luvata LOT# 117129-1
4	Cu-OFP	Oxygen free, with phosphorus	TX 89-126

Material 1 and 3 were received in the form of rectangular rods cut from forged 50 mm thick discs. Material 4 was extruded tube and weld metal from a weld previously studied (Danielsson and Andersson-Östling 2018). Material 2 was received as hot formed and drawn copper rods, with diameter 50 mm and length 3 000 mm (Danielsson and Andersson-Östling 2018). All of the materials had comparable grain sizes.

During manufacturing, material 3 was originally meant to be the same as material 4 (oxygen free with phosphorus) but elevated H content (1.03 wt.ppm) was discovered in the material and it was judged that it could be of interest to test this material as well. Thus, two material groups were tested: one without phosphorus (material 1 and 2) and one with phosphorus (material 3 and 4).

The composition of the four materials is shown in Table 2-2.

Table 2-2. Material composition of all four materials in wt.ppm and grain size in mm. Grain size is specified for as forged condition. Data for Material 1 and Material 3 from the suppliers chemical analysis, Material 2 and 4 from (Danielsson and Andersson-Östling 2018). Elements in bold are the relevant for this investigation.

	Cu	**Ag**	**Al**	**As**	**B**	**Bi**	**Cd**	**Co**	**Cr**	**Fe**
Material 1	bal	< 0.2	< 0.08	< 0.2	< 0.3	0.4	< 0.3	< 0.1	< 0.05	0.3
Material 2	bal	16		1		< 0.5	< 0.5	< 0.5	< 0.5	3
Material 3	bal	9.2	< 0.08	< 0.2		< 0.3	< 0.3	< 0.1	< 0.05	< 0.3
Material 4	bal	13		< 1		< 1	< 1	< 1	< 1	2

	H	**Mg**	**Mn**	**Ni**	**O**	**P**	**Pb**	**S**
Material 1	**0.09**	< 0.1	< 0.1	< 0.3	**4.1**	**< 0.3**	< 0.7	0.8
Material 2			0.5	1	**1**	**1**	1	2
Material 3	**1.03**		< 0.1	< 0.3	**0.9**	**74**	< 0.7	2.4
Material 4			< 0.5	2	**1–2 (O_2)**	**45–60**	< 1	5

	Sb	**Se**	**Si**	**Sn**	**Te**	**Ti**	**Zn**	**Zr**	**Grain size**
Material 1	< 1	< 0.6	< 0.2	< 0.6	< 2	< 2	< 0.1	< 0.1	0.09
Material 2	2	< 1		1	< 1		1		0.114
Material 3	< 1	< 0.6	< 0.2	< 0.6	< 2		< 0.1	< 0.1	0.05
Material 4	1	< 1		< 0.5	< 1		< 1		0.1–0.2

2.1 Specimen geometry

Figure 2-1 and Figure 2-2 show the design of the test bars and a manufactured specimen. The gauge length is the same within each material but has varied between the materials. The reason behind this variation is that material 2 and 4 specimens were reused from previous projects and these had different gauge length. The difference is not thought to have affected the SSRT strain data as the gauge lengths used have been within the permissible variation for creep testing.

This type of specimen has been used frequently in creep testing of copper at Swerea KIMAB. Blanks from Material 1, 2 and 3 were processed using spark erosion while blanks from material 4 were manufactured by sawing and milling. The reason for this was simply that the spark erosion machine was not available at the institute (KIMAB) when specimens from material 4 were produced.

From the blanks the specimens was machined by turning to obtain cylindrical specimens with 10 mm diameter.

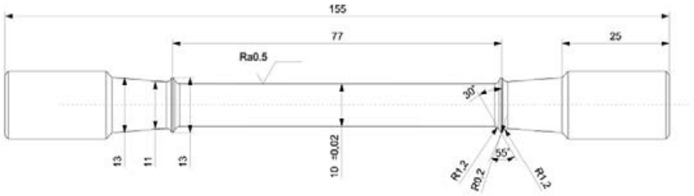

Figure 2-1. *Creep test specimen dimensions.*

Figure 2-2. *A manufactured creep test specimen.*

2.2 Material 4 specimens

Figure 2-3 shows the positions from where the material 4 specimens were cut (Andersson et al. 2007). The material had previously been used for creep testing of different weld components, and spare specimens were used in this study to speed up the completions of this work. Only two base metal specimens (TUB position) could be found and to complete the test matrix a weld metal specimen (WMI position) was substituted. In creep testing at 75 °C the TUB and WMI positions showed identical results. The microstructure was also similar and therefore the SSRT-properties should also be similar.

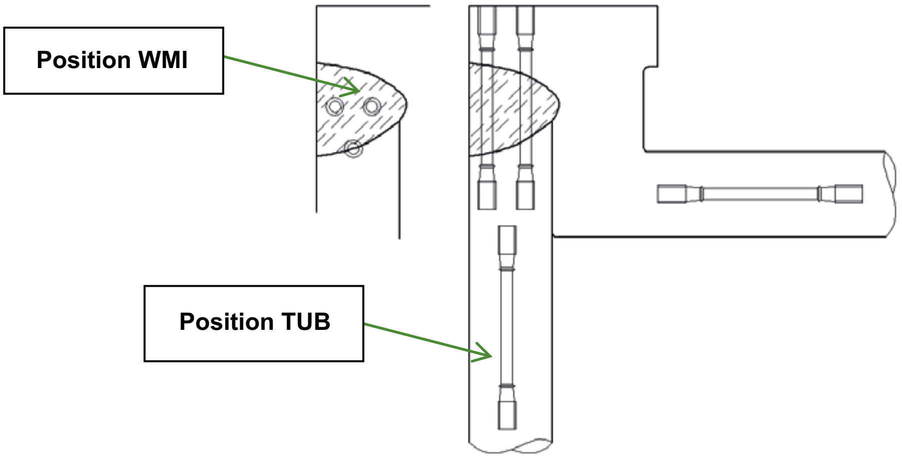

***Figure 2-3.** Specimen extraction positions in cross-weld, weld metal and heat affected positions.*

2.3 Annealing

The specimens were annealed in liquid salt, a neutral salt with the composition optimised for tempering of metals, for ten minutes in 600 °C, followed by water quenching. This is an annealing procedure that has been used to produce soft copper at Swerea KIMAB previously without grain coarsening. Figure 2-4 shows three (oxidized) specimens after annealing. Annealing was done to eliminate the effect that previous cold work might have on the results.

Figure 2-4. *Creep test specimens after annealing.*

3 Experimental

3.1 The tensile testing machines

For the testing, both the pre-loading and SSRT, three different machines were used. The machines are called SSRT-1, SSRT-2 and MTS-2. SSRT-1 and -2 are servo mechanical test rigs where the test is controlled by the displacement of the lower grip. MTS-2 is a servo-hydraulic test rig where the test can be either strain controlled of displacement controlled. The SSRT test rigs are equipped with resistance heated furnaces with a maximum temperature of 1 100 °C, and MTS-2 is equipped with a hot air chamber with a maximum temperature of 300 °C. The extensometer used in MTS-2 has a maximum temperature of 180 °C, which has meant that only the lower temperature tests can be performed in this test rig.

3.2 Testing conditions

3.2.1 Extensometer and logging SSRT-1 and SSRT-2

The specimen was installed in the test rig with an extensometer device. The extensometer was linked to one dial indicator with an accuracy of 10 µm and one capacitive position sensor with an accuracy of 0.1 µm. The dial indicator has a stroke of 25 mm and was used throughout the whole test. The position sensor only has a stroke of 3 mm and was therefore used for the first 3 mm strain. For the logging of the test, three different computer programs were used with logging intervals compatible with each other so that the data could be compiled.

3.2.2 Extensometer and logging MTS-2

In MTS-2 a standard Instron 25 mm gauge length clip on extensometer was used both to control and to record the testing.

3.2.3 Load cell

Calibrated load cells were used for all experiments. Calibration is performed annually. The raw data obtained by the load cell was exactly a fourth of the actual load. The correct load was then calculated and used in the analysis of the results.

3.2.4 Temperature control

Thermocouples were used for monitoring the temperature of the specimens, one pair for each specimen. The thermocouples were positioned at approximately 25 % and 75 % of the gauge length of the specimen. The temperature was measured occasionally until it was stable, minimum soaking time 30 minutes. Steady state conditions were then assumed, which was reasonable considering that the oven temperature reading was uniform throughout the testing and that the constant temperature zone was much larger than the specimen gauge length, see Figure 3-1.

3.2.5 Measurement of specimen dimensions

The diameter and length of the specimens were measured using a calibrated Vernier caliper. The measurements were made before preloading, after the preloading and also after the SSRT testing. The measurements were performed according to the creep testing standard SS-EN ISO 204:2009.

Figure 3-1. Approximate positioning of the thermocouples on the specimen. The thermocouples are tied to the specimen using a stainless steel wire.

3.3 Testing procedures

3.3.1 Hot tensile testing

The hot tensile tests were conducted in the MTS-2 at Swerea KIMAB. The temperature for the hot tensile tests was 75 °C and the strain rate 10^{-4} s^{-1}. Only Cu-6N and Cu-H were hot tensile tested in this study.

3.3.2 Preloading to 120 MPa for the SSRT tests

The test specimens were first installed in the test rig and the furnace was heated to 75 °C without any load on the specimen. When the temperature was stable the specimen was pre-loaded with 120 MPa. The reasons for choosing this preloading stress was to give the materials a defined degree of cold deformation after annealing had removed any previous effects of cold work, and to have a stress that is higher than what is actually expected in field use. Also the same preloading had been used in a previous project and specimens were readily available. This preloading stress gives the material a higher degree of cold deformation than what is expected in as-received lid or tube material used in the KBS-3 system, which makes the results in this study conservative.

The temperature was kept also during unloading after the preloading.

3.3.3 SSRT testing

The SSRT testing was conducted at three different temperatures; 75, 175 and 215 °C. All tests in the SSRT test rigs were displacement controlled. This means that the elastic part and the plastic part of the strain curve have different effective gauge lengths. For the elastic part, the effective gauge length is equal to the length (1 m) from the upper to the lower joint (Figure 3-2) while for the plastic part, the effective gauge length is only equal to the actual specimen gauge length (0.1 m). Thus, the motor speed – and in consequence, the strain rate – was slowed down by a factor of 10 for the plastic part of the strain curve in order to maintain a constant effective strain rate as close to 5×10^{-7} s^{-1} as possible.

Two different strain rates were thus used to compensate and keep the strain rate as close to 5×10^{-7} s^{-1} as possible. After finishing the test, the pins which were holding the sample in the tensile testing machine were taken away to avoid stress from cold shrinkage of the specimen when the temperature was lowered.

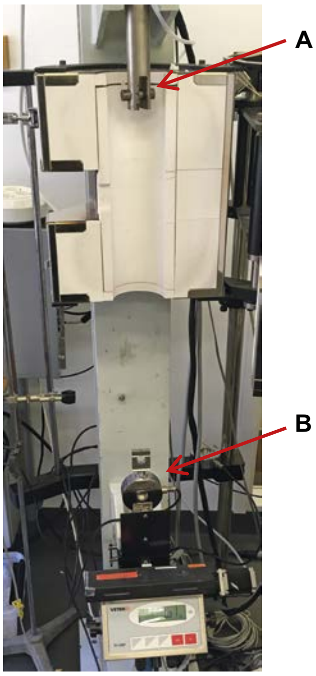

Figure 3-2. Slow strain rate testing machine, showing the upper joint (A) and lower joint (B).

4 Results

The test matrix and results for the hot tensile test are given in Table 4-1 and the graphs in Figure 4-1. The Cu-6N test did not rupture since the displacement reached maximum travel before rupture. Since the material was tested in annealed condition the yield stress, R_{p02}, when measured according to the standard procedure, was very low. This is since there is no straight elastic part in the early part of the curve to apply a tangent to.

The test matrix and results for the SSRT tests are given in Table 4-2. It is evident that the two material groups, with and without phosphorus, have fairly similar properties within each group. That is to say, Cu-6N and Cu-OF have the same type of behaviour at the same temperature, as do Cu-H and Cu-OFP. It is also evident that the SSRT test ductility is high for phosphorus containing coppers at all temperatures and for non-phosphorus containing coppers at 75 °C. It is however low for non-phosphorus containing coppers at 175 and 215 °C.

Table 4-1. Test matrix for the hot tensile tests.

Specimen	Material	Strain rate	Temp.	R_{p02}	R_m	A	Z
Description				**Yield stress**	**Nom. ultimate tensile stress**	**Elongation at failure**	**Reduction in area**
Unit		**(s^{-1})**	**(°C)**	**(MPa)**	**(MPa)**	**(%)**	**(%)**
SKB-113	Cu-6N	1.00×10^{-4}	75	19	183	> 49*	> 27*
SKB-133	Cu-H	9.98×10^{-5}	75	31	193	58	67.5

** The test rig maximum travel was reached before final fracture of the specimen.*

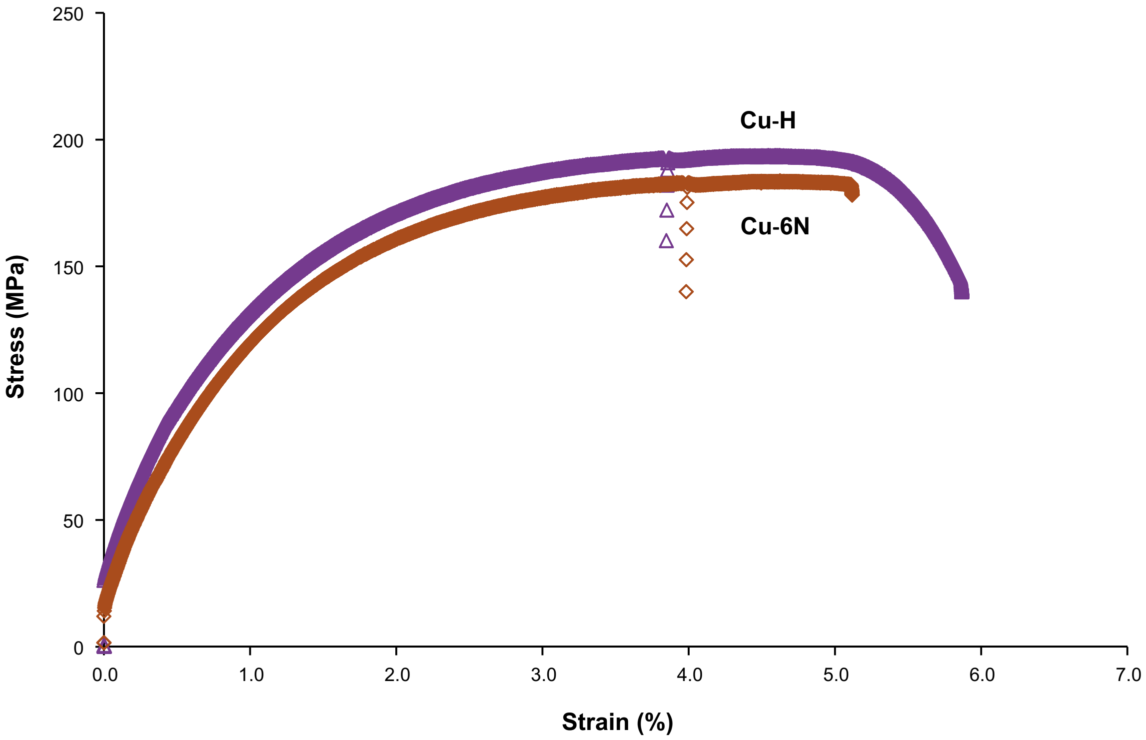

***Figure 4-1.** Hot tensile tests at 75 °C. The drops in stress at approximately 40 % strain are due to the extensometer being reset.*

For Cu-6N and Cu-OF two specimens each was tested at 75 °C. The results, visible in Figure 4-2 to Figure 4-5 where the individual stress-strain graphs are given, are similar even though the strain rates, given in Table 4-2 are different. Engineering strain and stress are used in all graphs. It appears that the straining rate does not have a large influence on the results if it is kept within an order of magnitude from the target straining rate of 5×10^{-7} s^{-1}.

Cu-H and Cu-OFP display higher area reduction than the other tests, especially at 175 and 215 °C. This can be seen in Figure 4-6 and Figure 4-8 where the yield strength, ultimate tensile strength, elongation at failure and area reduction for all tests are collated. Furthermore, Cu-6N and Cu-OF stand out with low ductility properties.

The different ductility properties for phosphorus and non-phosphorus coppers are evident in Figure 4-10 to Figure 4-12, where all the SSRT curves obtained for a specific temperature are collected. But so are the similarities of the general shape of the curves. It can for instance be seen that the ultimate tensile strength is reached at roughly the same strain for comparable materials, and also that the ultimate tensile strength itself attains the same value for comparable materials at the same temperature.

Comparisons can also be made with previously published results from the open literature. Pettersson (2010), Sandström and Hallgren (2012), Sui and Sandström (2016) produced SSRT-curves for Cu-OF and/or Cu-OFP. The results from these studies are summarized below.

Pettersson (2010) presented SSRT results for OF and OFP copper at temperatures ranging from 52 to 200 °C and strain rates ranging from 2.2×10^{-6} to 4.4×10^{-4} s^{-1}. The specimens had been extracted from two 40 mm thick hot-rolled plate whose composition only differed in the content of phosphorus, which was 35 ppm in the OFP material and < 10 ppm in the OF material. Both materials had a grain size of about 100 µm. Additional results from a previous study which the author had conducted with a guest student was also included in the study results. The results for the OFP material, evaluated at 100, 150 and 200 °C and at strain rates 2.2×10^{-6}, 4.4×10^{-6} and 4.4×10^{-4} s^{-1}, showed that all curves had an elongation of about 40 %. Comparing to the OF material, which had been tested at similar strain rates and temperatures, a reduced ductility was shown for all curves except two: the 52 °C 2.2×10^{-6} s^{-1} curve and the 100 °C 4.4×10^{-4} s^{-1} curve. It was thus observed that an increase in temperature and a decrease in strain rate reduced the fracture strain for OF copper. At the lower strain rates on the order of 1×10^{-6} s^{-1}, the ultimate tensile strengths were about 180 MPa at 200 °C and just above 200 MPa at 150 °C for phosphorus-enriched material.

Sandström and Hallgren (2012) presented SSRT results for Cu-OFP with specimens manufactured from plate, lid and tube at temperatures ranging from 20 to 175 °C and strain rates ranging from 1×10^{-7} to 5×10^{-3} s^{-1}. The rolled formed plate was oxygen free copper with 58 ppm phosphorus and had a cold work of 10 % and a grain size of 180 µm; the forged canister lid material had a grain size of 100 µm and the extruded tube material had a grain size ranging from 28 to 80 µm. The canister and the lid were in hot worked soft condition during testing. The results showed that for Cu-OFP lid material, at both 20 and 175 °C, at strain rates of 1×10^{-4} and 1×10^{-5} s^{-1} for 20 °C and 1×10^{-6} and 1×10^{-7} s^{-1} for 175 °C, the strains at failure were between 30 and 35 %. At 175 °C for the lid material, the ultimate tensile strengths were about 180 MPa at a strain rate of 1×10^{-6} s^{-1} and 170 MPa at a strain rate of 1×10^{-7} s^{-1}.

Sui and Sandström (2016) conducted SSRT of OFP copper at 75 and 125 °C, at strain rates of 1×10^{-6} and 1×10^{-7} s^{-1}. The phosphorus content was 54–56 ppm. The authors tested both uniaxial and multiaxial stress states, the latter by introducing two notches on the gage length. For uniaxial tests at 75 °C at 1×10^{-6} and 1×10^{-7} s^{-1} and 125 °C at 1×10^{-6} s^{-1}, the strains at failure were virtually identical: ca 48 %. The uniaxial 125 °C 1×10^{-7} s^{-1} test was slightly higher, about 52 %. The area reductions (ductility) were around 85 to 90 %. Ultimate tensile strengths were around 170 MPa at 75 °C and 155 MPa at 125 °C, with lower strain rates (1×10^{-7} s^{-1}) having slightly higher ultimate tensile strengths than higher strain rates (1×10^{-6} s^{-1}).

Comparing the results from these references with the results from this study (Table 4-2), the following becomes evident:

For the phosphorus-enriched copper material in this study (Cu-OFP and Cu-H), the elongation values at failure at temperatures of 75, 175 and 215 °C and strain rates on the order of 1×10^{-7} s^{-1} were rather similar to the OFP lid material in Sandström and Hallgren (2012) which had tested at 175 °C and strain rates of 1×10^{-6} and 1×10^{-7} s^{-1}: within a range of 30–40 % in this study and 30–35 % in Sandström and Hallgren (2012). In Pettersson (2010) which had tested OFP at 100, 150 and 200 °C and at strain rates on the order of 1×10^{-6} and 1×10^{-4} s^{-1}, the elongation values were similarly within a span of 35 to 40 %. Sui and Sandström (2016) had comparatively higher elongations, about 50 %.

For the phosphorus-lacking copper material, Pettersson (2010) had tested Cu-OF at 52, 100, 150 and 200 °C, at strain rates on the order of 1×10^{-4} and 1×10^{-6} s^{-1}. It was observed that an increase in temperature and a decrease in strain rate reduced the fracture strain for OF copper. In the present study, this temperature effect is also observed: as the temperature increases, the fracture strains of Cu-6N and Cu-OF decrease. The elongation values ranged from about 5 to 35 % in this study where temperatures of 75, 175 and 215 °C were tested at strain rates on the order of 1×10^{-7} s^{-1}; in Pettersson (2010) they ranged from about 10 to 40 %.

Ductility, measured as area reduction, was only recorded in Sui and Sandström (2016) and this study. For phosphorus-enriched copper, Sui and Sandström (2016) showed values within a range of 85–90 % for 75 and 125 °C at strain rates of 1×10^{-6} and 1×10^{-7} s^{-1}. This study had a range of 70–80 % for phosphorus-enriched copper at 75, 175 and 215 °C and at strain rates on the order of 1×10^{-7} s^{-1}.

Pettersson (2010) showed ultimate tensile strengths (UTS) for phosphorus-enriched copper just above 200 MPa at 150 °C and at about 180 MPa at 200 °C tested at strain rates on the order of 1×10^{-6} s^{-1}. At the higher temperatures in this study for phosphorus enriched copper, the ultimate tensile strengths were about 160 and 150 MPa for 175 and 215 °C respectively. Sandström and Hallgren (2012) showed UTS of about 170 MPa for 175 °C at 1×10^{-7} s^{-1}. Sui and Sandström (2016) showed UTS at 75 C at 1×10^{-7} s^{-1} of about 175 MPa, compared to this study where the corresponding value was approximately 180 MPa. It should be noted that the yield strengths in this study were quite large compared to the references given above. This is due to pre-straining at 120 MPa.

For phosphorus-lacking copper, Petterson showed UTS of ca 175 MPa at 100 °C, 150 MPa at 150 °C and 100 MPa at 200 °C at strain rates on the order of 1×10^{-6} s^{-1}, while this study showed values of ca 180 MPa at 75 °C, 125 MPa at 175 °C, 110 MPa at 215 °C at strain rates on the order of 1×10^{-7} s^{-1}.

In summary, the results of this study are largely similar to results obtained in the references above. The only caveats are the large difference in yield strength due to cold deformation, as well as a difference in elongation compared to Sui and Sandström (2016).

Figure 4-13 shows the appearance of the test specimens after the SSRT testing, all four materials are represented.

Table 4-2. Test matrix for the SSRT-tests.

Specimen	Material	Strain rate 1	Strain rate 2	Temp.	R_{p02}	R_m	A	Z
		(s^{-1})	(s^{-1})	(°C)	(MPa)	(MPa)	(%)	(%)
SKB-812[f]	Cu-6N	3.33E-07	4.99E-07	75	129.4	175.8	28.7	55.9
SKB-112[f]	Cu-6N	1.51E-07	1.50E-06	75	(149)*	183	34.5	53.5
SKB-811[f]	Cu-6N	5.30E-07	5.84E-07	175	111.3	121.6	5.7	16.7
SKB-111[f]	Cu-6N	1.24E-07	1.13E-06	215	104.1	112.7	7.9	12.7
Cu-OF-04[f]	Cu-OF	7.03E-08	7.03E-08	75	122	**	**	**
Cu-OF-08[f]	Cu-OF	2.52E-07	6.31E-07	75	126.8	182.7	15.6	74.4
Cu-OF-07[f]	Cu-OF	7.03E-07	6.82E-07	175	112.8	132.4	13.8	22.5
Cu-OF-05[f]	Cu-OF	1.92E-07	7.03E-07	215	100.7	110.9	8.9	13.2
Cu-OF-06[f]	Cu-OF	7.56E-07	7.05E-07	215	108.8	115.6	7.4	21
SKB-832	Cu-H	5.12E-07	5.08E-07	75	130	187	32.6	67.2
SKB-132	Cu-H	5.04E-07	5.28E-07	175	111.1	156.2	33.9	72.7
SKB-131	Cu-H	5.30E-07	5.84E-07	215	108.9	146.2	34.8	74.3
TUB-10[f]	Cu-OFP	3.40E-07	6.38E-07	175	112.5	156.1	37.7	81.6
TUB-11[f]	Cu-OFP	6.57E-07	7.70E-07	215	112	147.5	37.2	68.8
WMI-10	Cu-OFP	8.50E-07	8.48E-07	75	123.3	187.5	39.1	69.6

* Start-up problems with specimen, $R_{p0.2}$ only estimated.

** Test rig malfunction after 15.5 % strain. R_m, A and Z not available.

[f] Fracture

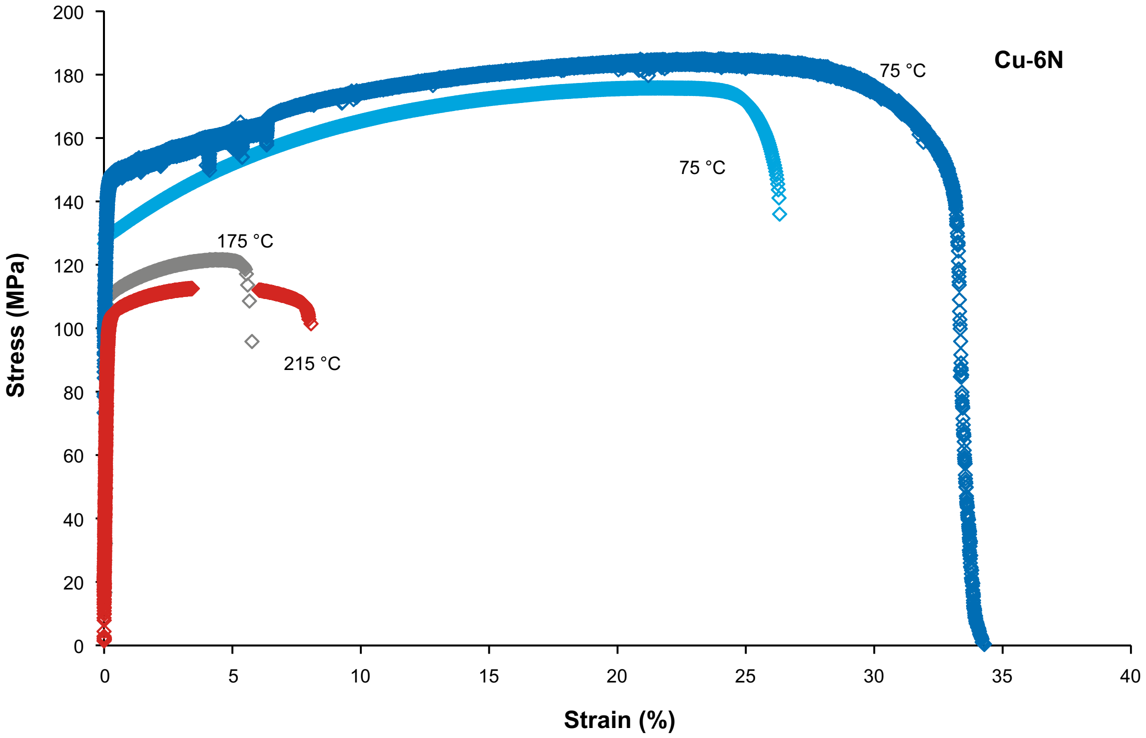

Figure 4-2. *Cu-6N SSRT tests engineering strain against engineering stress.*

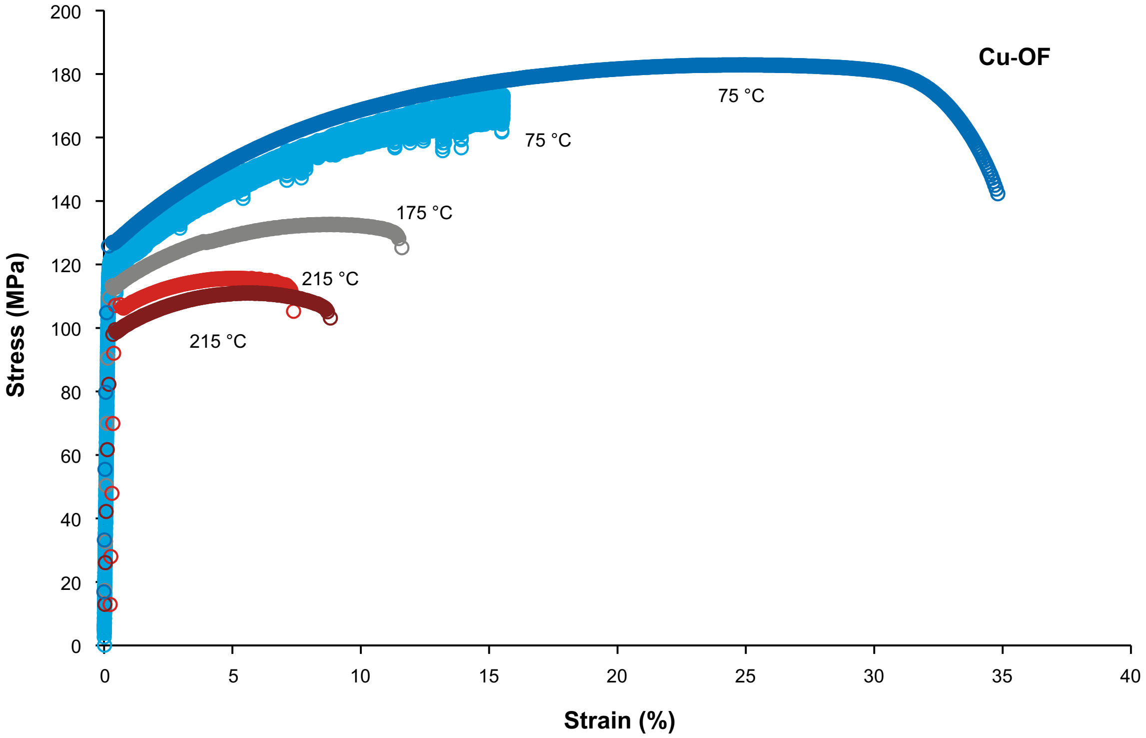

Figure 4-3. *Cu-OF SSRT tests engineering strain against engineering stress.*

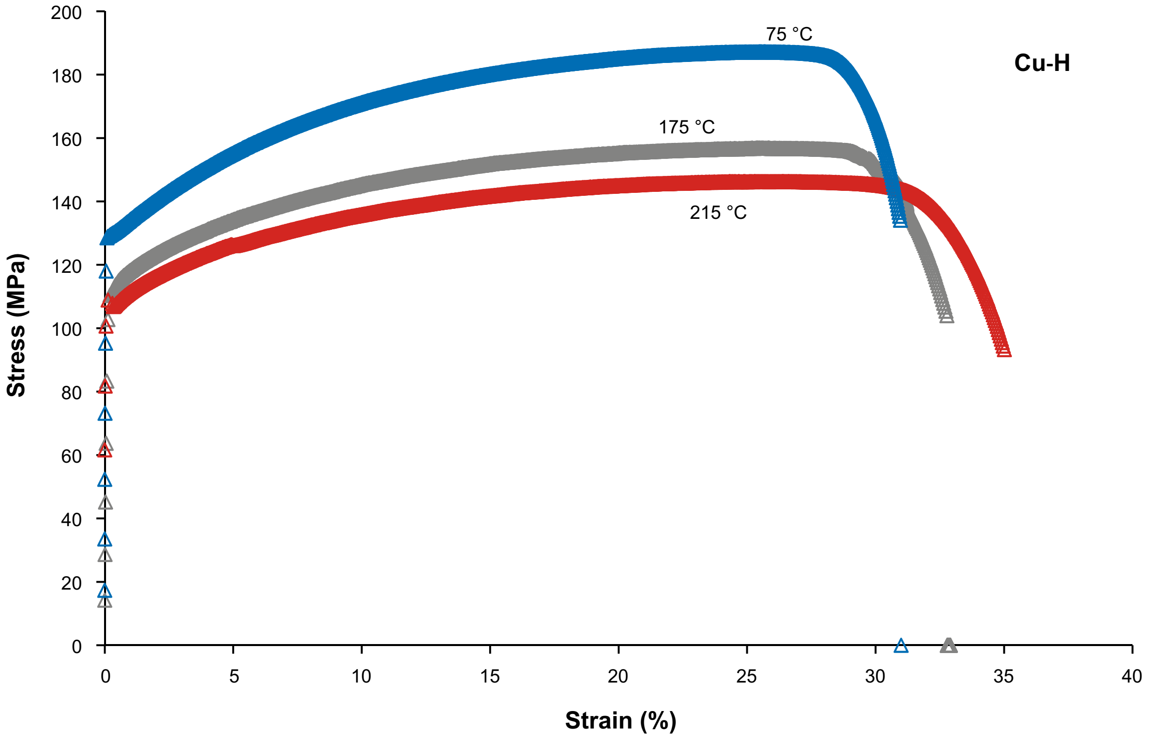

Figure 4-4. Cu-H SSRT tests engineering strain against engineering stress.

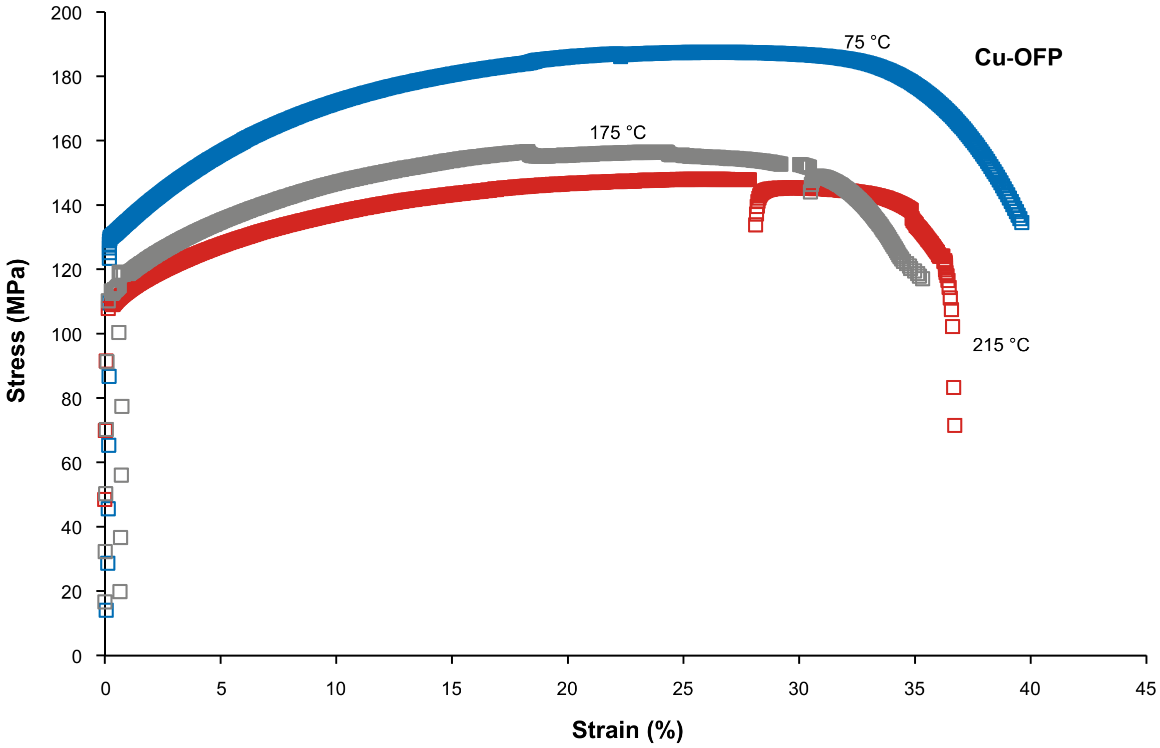

Figure 4-5. Cu-OFP SSRT tests engineering strain against engineering stress.

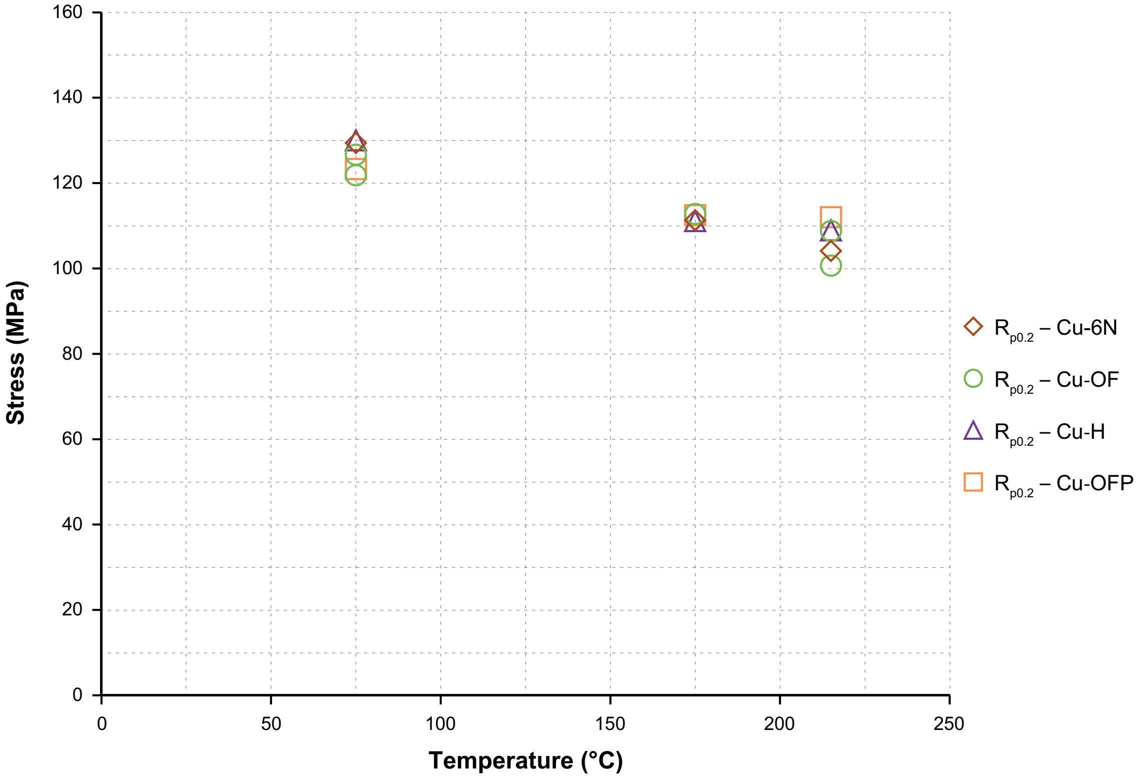

Figure 4-6. *$R_{p0.2}$ for all SSRT tests.*

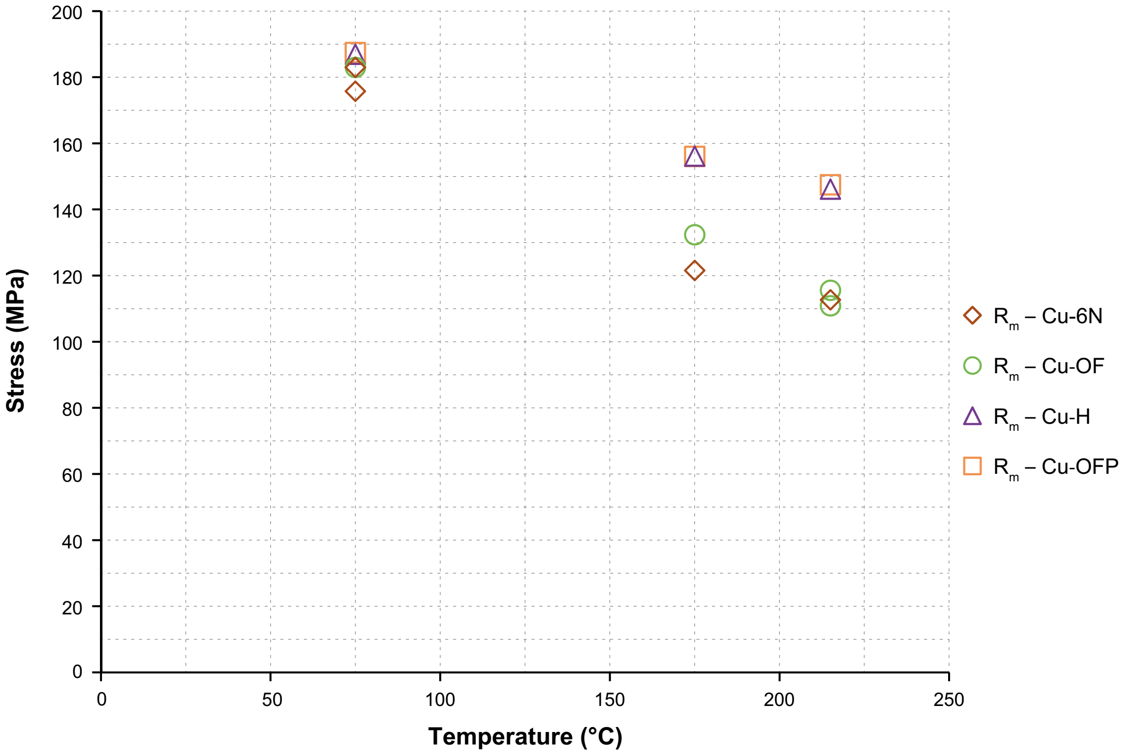

Figure 4-7. *R_m for all SSRT tests.*

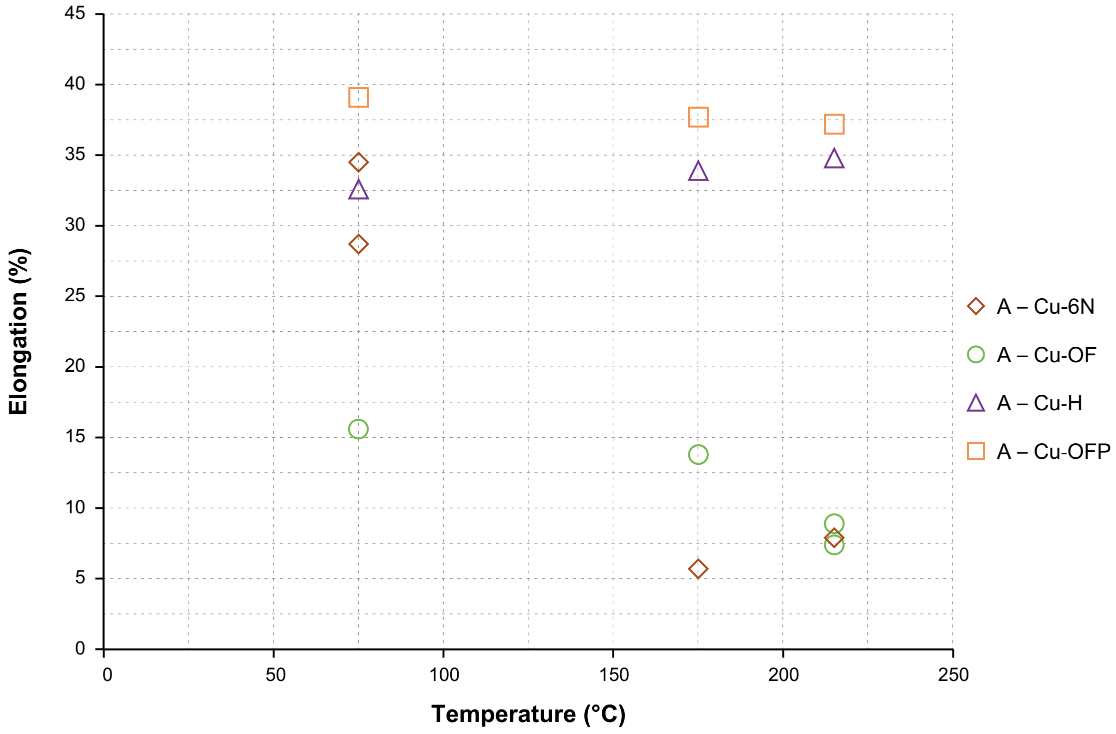

Figure 4-8. *A for all SSRT tests.*

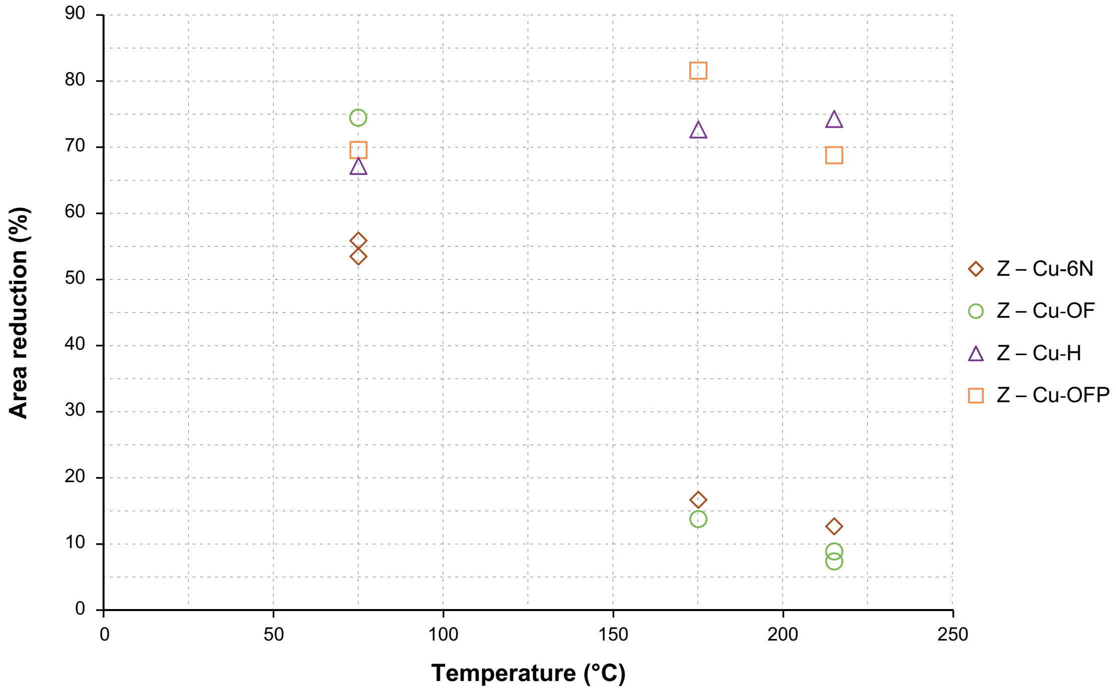

Figure 4-9. *Z for all SSRT tests.*

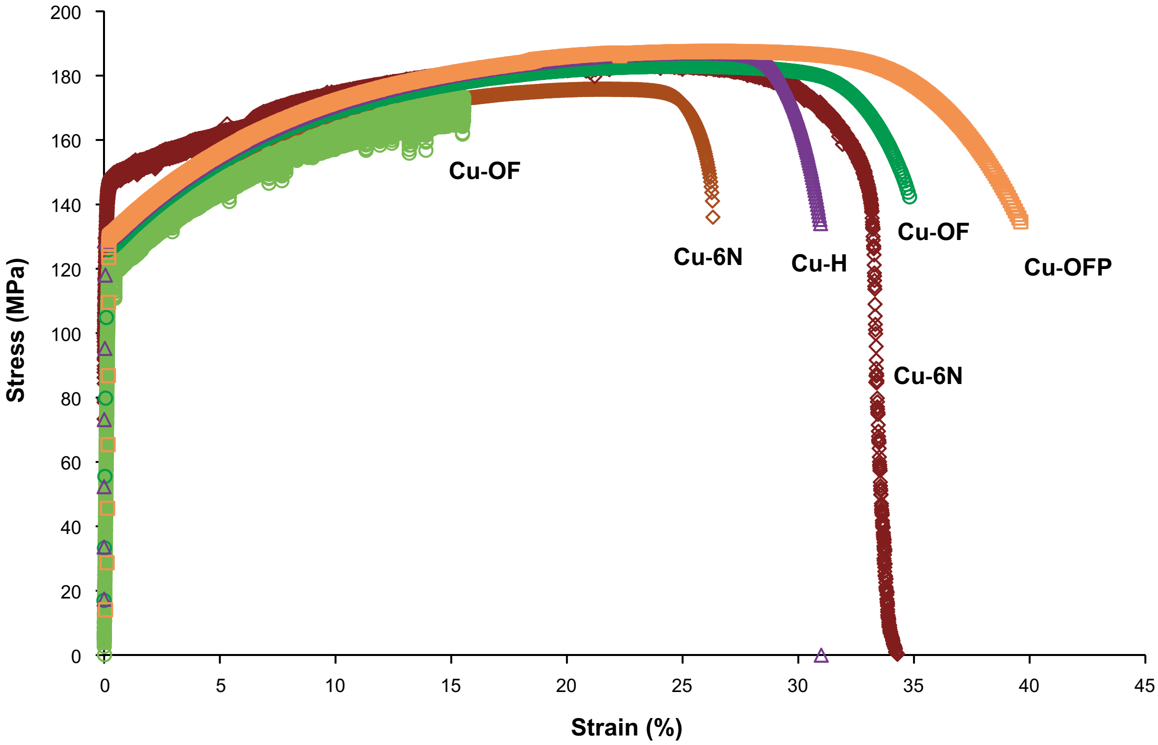

Figure 4-10. All curves for SSRT-tests at 75 °C.

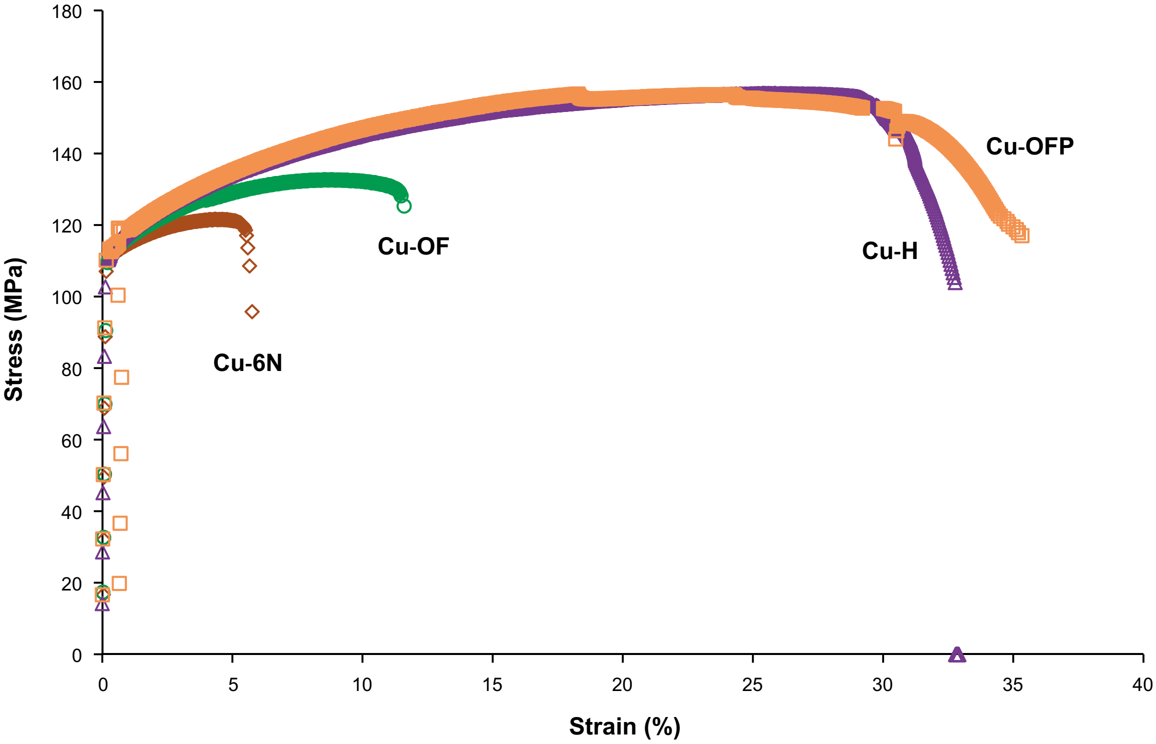

Figure 4-11. All curves for SSRT-tests at 175 °C.

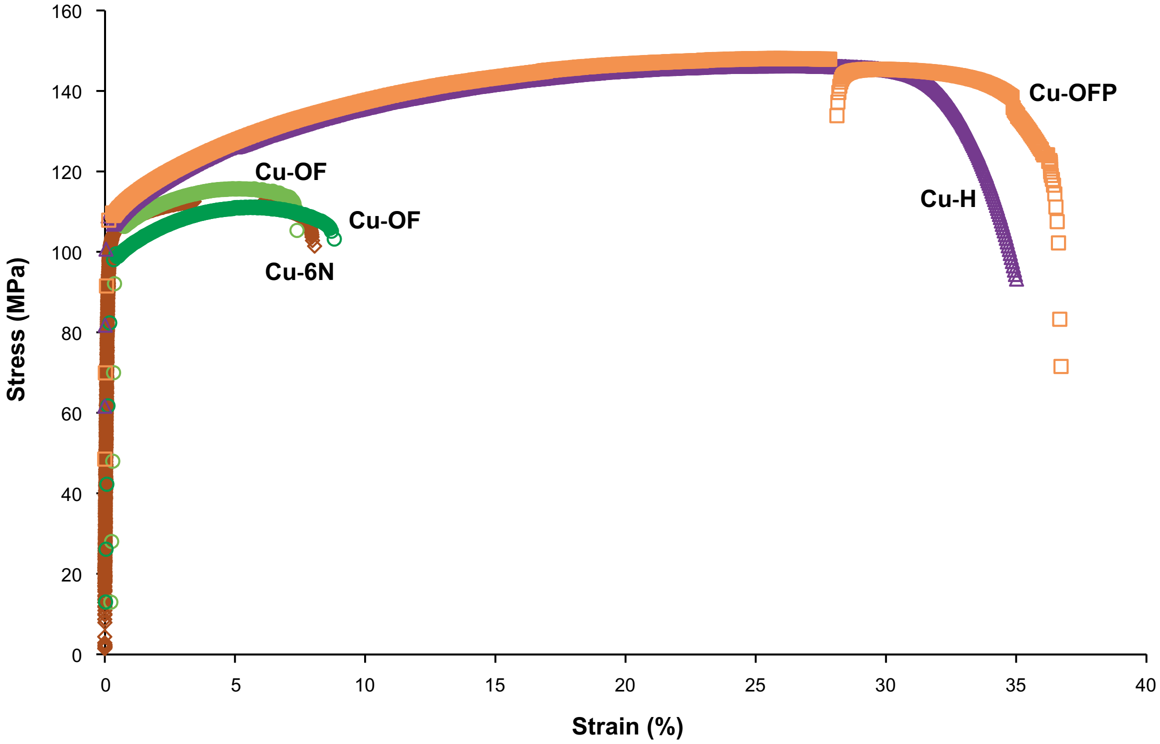

Figure 4-12. *All curves for SSRT-tests at 215 °C.*

Material 1 SKB-111	Material 2 Cu-OF-05	Material 2 Cu-OF-06	Material 3 SKB-131	Material 4 TUB-10
				

Figure 4-13. *Specimens after SSRT testing at 215 °C.*

5 Discussion

The results from the testing show that the two main material groups, with and without phosphorus, have within each group roughly similar properties. Cu-6N and Cu-OF both have lower ductility at 175 and 215 °C and higher ductility at 75 °C. Cu-H and Cu-OFP have the higher ductility for all tested temperatures and at 75 °C the ductility is comparable to that measured for the non-phosphorus materials. Overall, the results are similar to those found in the literature for similar materials, temperatures and straining rates.

Compared to creep properties for phosphorus and non-phosphorus coppers at the same temperature, the sharp division between ductile and brittle ruptures is not as distinct in this study (Andersson-Östling and Sandström 2009, Danielsson and Andersson-Östling 2018). At 175 and 215 °C there is a distinct difference, but not at 75 °C. This means that the method of slow strain rate testing is not immediately useful as a rapid sorting method at the lower temperature.

The strain rate in the testing was kept as close to 5×10^{-7} s^{-1} as possible. Due to machine considerations it was at times difficult to keep the straining rate at the desired level. The results at 75 °C show that the ductility results are similar for both faster and slower strain rates if the variation is kept within an order of magnitude from the target rate. The same behaviour has also been shown in the published literature (Sui and Sandström 2016). It is known from the literature that if the straining rate is increased to normal tensile test rates, 10^{-3} to 10^{-4} s^{-1}, there is almost no difference in properties depending on phosphorus content at room temperature up to approximately 100 °C (Lindblom et al. 1992). If the strain rate is lowered to that representative of creep rates, (10^{-10} s^{-1}) the influence of phosphorus is large, even at 75 °C (Andersson-Östling and Sandström 2009). Slow strain rate testing may therefore be regarded as an intermediate method between hot tensile and creep testing.

6 Conclusions

Slow strain rate testing has been performed on copper alloys with and without phosphorus. The materials from which specimens were obtained had been manufactured differently and received in different dimensions but all of them were annealed and then pre-strained under the same parameters. This causes more cold deformation in the soft phosphorus-free copper than the phosphorus-rich copper.

Conclusions to be made include:

- Ultra-pure copper and normal oxygen free coppers exhibit similar properties at all tested temperatures.
- Phosphorus containing coppers with different degrees of hydrogen contents exhibit similar properties.
- At 175 and 215 °C both non-phosphorus and phosphorus containing materials exhibit roughly similar properties. At 75 °C the properties are significantly different.

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