Execution and reliability of slip resistant connections for steel structures using CS and SS (SIROCO)

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Research Locations:	**Outokumpu Stainless AB Avesta R&D Center SE-77422 Avesta, Sweden**
Contact person:	**Dr. Johan Pilhagen, Outokumpu Stainless AB Avesta R&D Center SE-77422 Avesta, Sweden**
Report authors:	**Johan Pilhagen**

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Mechanical properties and stress relaxation of stainless bolts

Johan Pilhagen

Abstract

Room temperature stress relaxation testing has been performed on stainless steel bars within the RFCS Execution and reliability of slip resistant connections for steel structures using carbon steel and stainless steel project (SIROCO). The aim of the testing was to investigate the stress relaxation behavior of stainless steel bolts in preloaded connections. Bars were used for the greater availability and ease of testing. The conclusions were that the two tested duplex grades in the “annealed” state had less stress relaxation compared to the tested austenitic grade in the “annealed” state. Cold drawn bars had less stress relaxation compared to bars in the “annealed” state. The cold drawn austenitic bar had less stress relaxation compared to the cold drawn duplex bars.
Applying the test results of the bars to preloaded bolt connections, the result indicates that most of the stress relaxation in preloaded bolts occurs within the first hour after the preloading and that machined bolts are likely to have higher stress relaxation compared to cold forged bolts.

Key words: Stress relaxation, room temperature, austenitic stainless steel, duplex stainless steel, SIROCO-project.

Distribution internal: Marie Louise Falkland, Erik Schedin, Cecilia Lille, Lena Wegrelius, Hans Groth, Anders Groth, Jan Y Jonsson, Timo Manninen.

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1. Introduction

In a slip-resistant bolt connection the preloaded bolts give the clamping force necessary to obtain the necessary friction level between the plates that gives the integrity of the connection. Due to time dependent dislocation glide [1] a phenomenon called stress relaxation may occur in the bolts in which the elastic strain (ε_e) with time converts to inelastic strain (permanent deformation), see Figure 1. The consequence of this is that the stress in the bolts decreases and may therefore cause slip in the connection which is regarded as a failure of the connection.

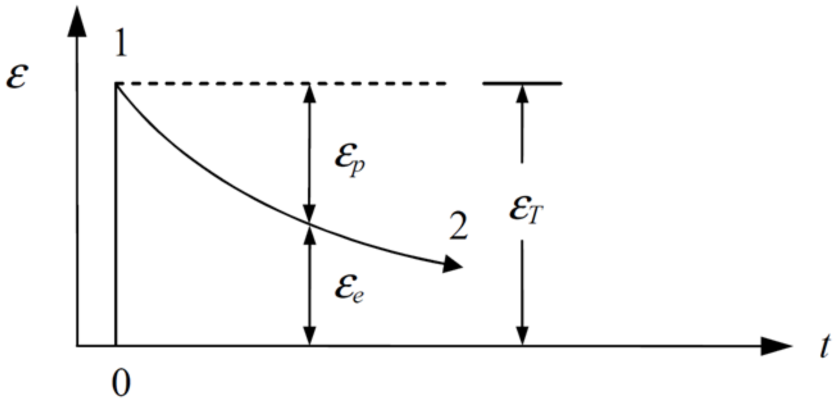


Figure 1 Stress relaxation due to increasing amount of inelastic strain (ε_p) with time under constant strain condition.

There are in general three types of stainless steel bolts, machined bolts, cold forged bolts and hot forged bolts. Machined bolts are preferred for small volume series, when high tolerances are needed, for complex geometries or when the bolt dimension is too large to be cold forged. Metals that are difficult to cold forge are usually machined. Cold forging is preferred for high volume series as the production rate is significantly higher than for machining. For austenitic and duplex stainless steel, the cold forging also results in significantly increased mechanical strength due to the cold work. Hot forged bolts are used for very large bolt dimension, sometimes with machining as a final step.

The use of stainless steels in slip-resistant bolt connection has traditionally been low due to lack of experience and at present date no design and execution rules exist for preloaded stainless steel connections. There may also be a preconception that stainless steels have unacceptable high rate of room temperature creep and stress relaxation which makes stainless steel ill-suited for this kind of application.

This report is about the stress relaxation testing of stainless steel bars that was performed within the RFCS project Execution and reliability of slip resistant connections for steel structures using carbon steel and stainless steel (SIROCO). Testing in actual slip resistant connections is reported in other reports within the project.

Bars were chosen instead of bolts due to the greater availability and ease of testing. Rebar and annealed bar was to represent machined bolts (low amount of cold work) and cold drawn bars to represent cold forged bolts (large amount of cold work).

2. Materials

The bar materials used were the austenitic grade EN 1.4436 (316), the duplex grades EN 1.4162 (Forta LDX 2101) and EN 1.4462 (Forta DX 2205). Three types of bars were used, rebar, annealed bar and cold drawn. The difference between rebar and annealed is that rebar is in condition as-rolled, while annealed is in solution annealed state after rolling. Both these conditions are regarded as potential to use for machined bolts.

The dimensions were 25 mm diameter rebar for the 1.4436 and 1.4162 and 20 mm annealed bar for the 1.4462. The cold drawn bars were all 12 mm in diameter.

The rebar and annealed bars were machined to round tensile specimens with 12.5 mm diameter and 80 mm parallel length in compliance with ISO 6892-1. The cold drawn bars were tested as-received.

3. Experimental technique

The testing system consisted of an electromechanical servo controlled machine from Dartec. The console was Doli EDC 120 and the testing software was Cyclic v8.11.02 from the Swedish company Inersjö Systems AB. The load cell used was a 250 kN class 0.5. The LVDT for the position had class 0.5. The extensometers used were class 0.5 macro extensometer from Zwick/Roell and class 1 clip-on extensometer from Instron. Hydraulic grips were used.

The tensile testing was based on EN ISO 6892-1:2009 method B. The initial stress rate was 11 MPa/s until the calculated parallel strain rate was 0.00075 1/s then the system switched to position control and pulled with 0.0001 1/s up to 2 % strain and then increased the strain rate to 0.008 1/s. For the cold drawn bars, no increased strain rate to fracture was used. The macro extensometer gauge length was of proportional length (macro extensometer).

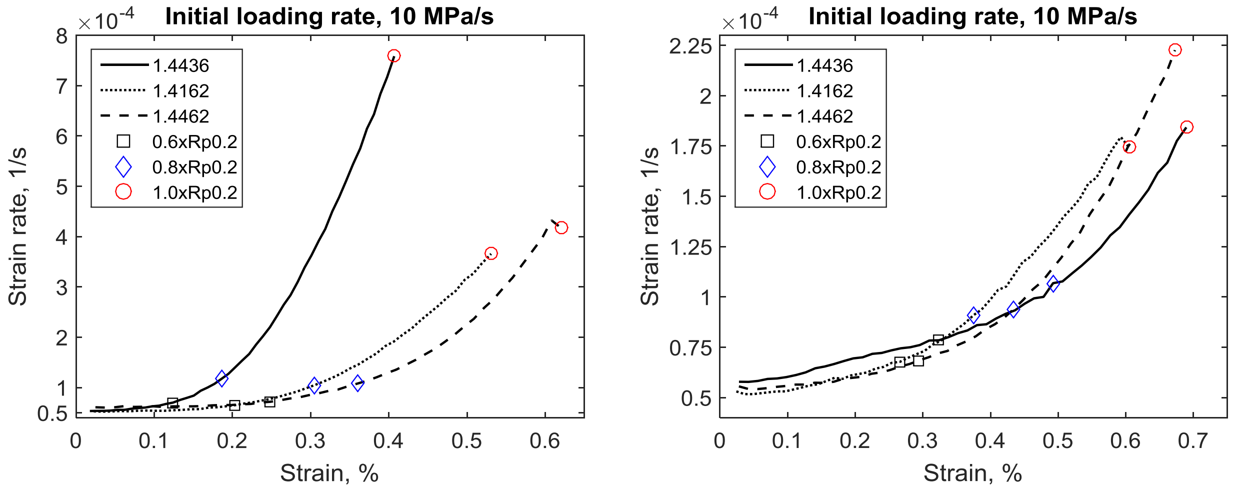
The tensile properties of the bar material can be seen in Table 1 together with the tensile properties of cold forged bolts from BUMAX (BUMAX 88, BUMAX 109, BUMAX LDX and BUMAX DX). For the bar material three tensile tests were performed on each type.

Table 1 Mean tensile properties of the tested bar material in comparison with cold forged bolts.

Material	Type	$R_{p0.2}$, MPa	$R_{p1.0}$, MPa	R_m, MPa	A_{gt}, %	$R_{p0.2}/R_m$
1.4436	Rebar	357	394	644	33	0.55
1.4162	Rebar	613	683	813	18	0.75
1.4462	Annealed	642	689	787	16	0.82
1.4436	Cold drawn	823	963	966	2	0.85
1.4162	Cold drawn	776	951	974	3	0.80
1.4462	Cold drawn	856	981	988	3	0.87
1.4436	M16-bolt ISO4017	869		993		0.88
1.4436	M16-bolt ISO4017	1060		1142		0.93
1.4162	M16-bolt ISO4017	992		1111		0.89
1.4462	M16-bolt ISO4017	1033		1128		0.92
1.4436	M20-bolt ISO4017	973		1033		0.94
1.4436	M20-bolt ISO4014	977		1077		0.91
1.4162	M20-bolt ISO4017	1009		1075		0.94
1.4462	M20-bolt ISO4017	1011		1072		0.94

For the relaxation testing the same testing machine was used as for the tensile testing. The extensometer used was the Instron clip-on with 60 mm extensometer gauge length.

The stress relaxation testing was based on EN 10319-1:2003. The specimens were loaded to an initial stress (σ_0) of 60, 80 or 100 % of the measured $R_{p0.2}$ (Table 1) and thereafter held at constant strain (ε_0) for 12 h at room temperature conditions and then unloaded. The initial loading rate was 10 MPa/s.
Due to the initial nonlinear deformation behavior of stainless steel the initial strain rate was not constant when subjected to constant stress rate, as seen in Figure 2. The initial strain rate for the stress relaxation testing and tensile testing was similar (10 MPa/s compared to 11 MPa/s).



a) b)

Figure 2 Strain rate as a function of strain during the initial loading for the stress relaxation testing. a) rebar or bar, b) cold drawn bar. The square, diamond and circle markers indicate the strain and strain rate at the start of the relaxation testing.

4. Results

The initial stress and constant strain for the stress relaxation testing can be seen in Table 2. The residual (inelastic) strain after 12 h of constant strain is also shown. Two stress relaxation tests were performed for each initial stress level. The stress relaxation was defined as:

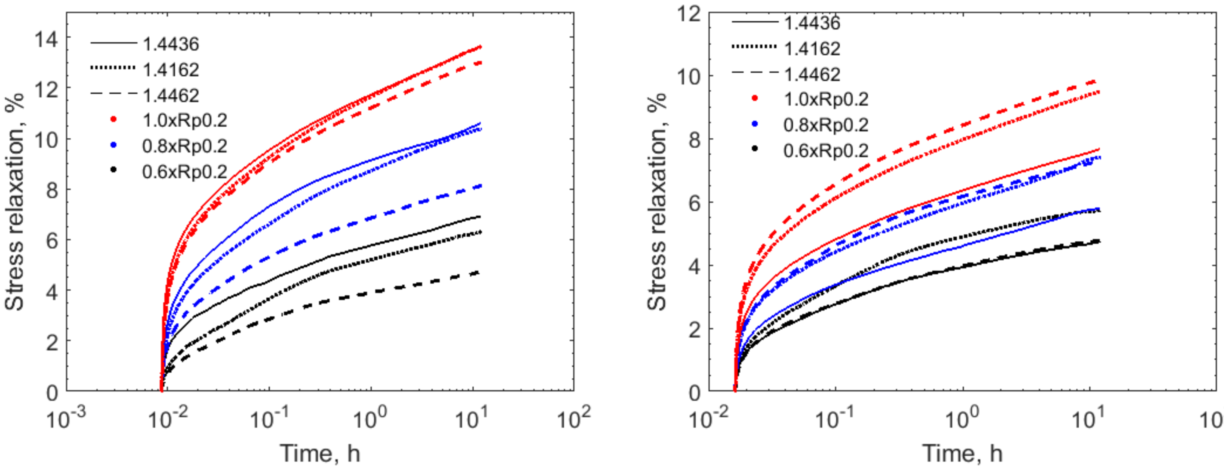
$$\sigma_r = \left(1 - \frac{\sigma}{\sigma_0}\right) * 100 \tag{1}$$

where σ was the measured stress during testing and σ_0 the initial stress.

Table 2 Mean values for the initial stress (σ_0) and constant strain (ε_0) for the 12 h stress relaxation (σ_r) testing together with the standard deviation (SD) of the stress relaxation and the residual plastic strain ($\varepsilon_{res.}$) after 12 h.

Material	**Type**	**σ_0, % of $R_{p0.2}$**	**σ_0, MPa**	**σ_r, %**	**SD, %**	**ε_0, %**	**$\varepsilon_{res.}$, %**
1.4436	Rebar	60	215	6.9	0.4	0.13	0.02
		80	285	10.6	0.2	0.19	0.05
		97	347	13.7	0.2	0.40	0.22
1.4162	Rebar	60	369	6.3	0.1	0.20	0.02
		80	490	10.4	0.0	0.31	0.07
		99	607	13.6	0.6	0.54	0.24
1.4462	Bar	60	386	4.7	0.1	0.25	0.02
		80	514	8.1	0.1	0.36	0.06
		99	633	13.0	0.2	0.62	0.26
1.4436	Cold drawn	60	495	4.7	0.0	0.33	0.04
		84	690	5.8	0.4	0.50	0.09
		100	821	7.7	0.1	0.69	0.19
1.4162	Cold drawn	60	466	5.7	0.5	0.26	0.02
		80	621	7.4	0.1	0.38	0.06
		100	773	9.5	0.1	0.60	0.18
1.4462	Cold drawn	60	514	4.8	0.0	0.30	0.02
		80	685	7.3	0.2	0.44	0.07
		100	853	9.8	0.2	0.67	0.21

The stress relaxation as a function of time can be seen in Figure 3. The time was adjusted for removing the difference in time due to initial loading times. The stress relaxation was high in the beginning but quickly slowed down with increasing time. Most of the stress relaxation occurred within the first minutes of testing.



a) b)

Figure 3 12 h stress relaxation of stainless steels, a) rebar or bar, b) cold drawn bar.

For the rebar/bar specimens the stress relaxation was similar between the 1.4436 and 1.4162 while 1.4462 showed lower stress relaxation at all stress levels. For the cold drawn bars, the two duplex grades showed similar stress relaxation except at the lowest stress level. The austenitic cold drawn grade showed less stress relaxation compared to two duplex cold drawn grades. The stress relaxation was higher for the rebar/bar compared to the cold drawn bars.

5. Discussion

5.1 Precision of keeping constant strain and room temperature conditions

The stress relaxation test consisted of different programming blocks in the software used for controlling the electromechanical testing machine. The initial loading rate was 10 MPa/s up to a specified stress (0.6, 0.8 and 1.0x$R_{p0.2}$). When the specified stress was reached, the software proceeded to the next block which keeps the strain constant. However, during the initial time of the constant strain block the strain decreased until constant strain was achieved, see Figure 4a. This may have caused the stress to drop as seen in Figure 4b. For the 0.6x$R_{p0.2}$ stress level this stress drop was not significant but for the 0.8 and 1.0x$R_{p0.2}$ stress levels this stress drop could be significant as seen in Figure 4b.

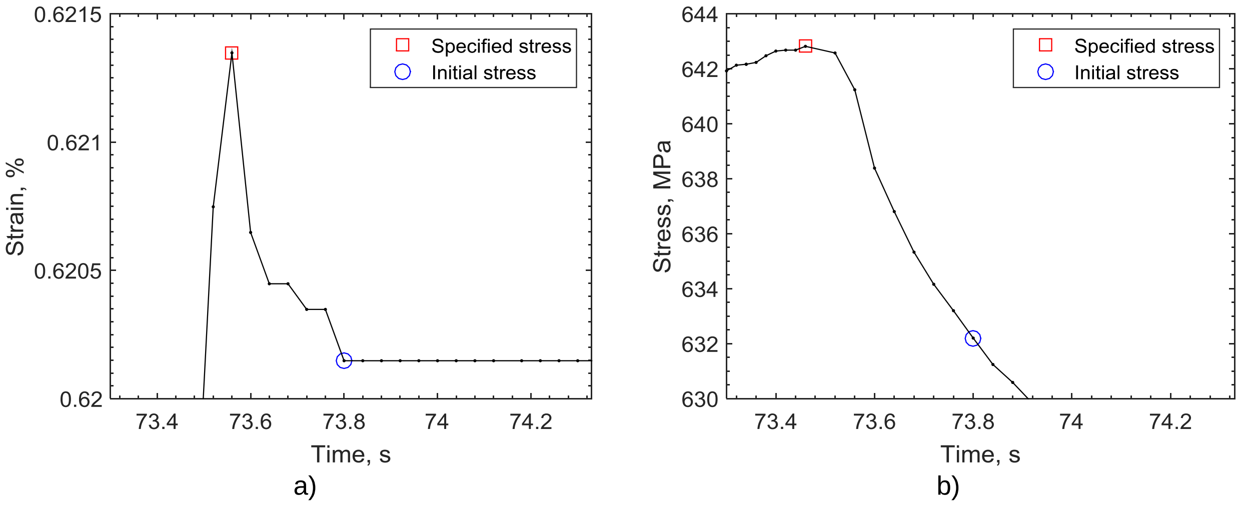


Figure 4 The definition of initial stress, a) strain as function of time, b) stress as function of time.

Due to the possible stress drop due to the decrease in applied strain, the stress relaxation result in Table 2 and Figure 3 was calculated from the initial stress (start of constant strain) according to Figure 4 and not from the specified stress.

Table 3 shows the average precision of the strain during the 12 hours of constant strain for each group tested. The result indicates high precision for maintaining constant strain for the used test setup.

Table 3 Precision of the constant strain during the stress relaxation testing.

Material	Type	Max-min strain, %	SD, %
1.4436	Rebar	3E-04	3E-05
1.4162	Rebar	4E-04	3E-05
1.4462	Bar	5E-04	5E-05
1.4436	Cold drawn	3E-04	3E-05
1.4162	Cold drawn	4E-04	4E-05
1.4462	Cold drawn	3E-04	4E-05

Hydraulic grips were used for clamping the specimen where the pressure was maintained from a hydraulic pump. The configuration was such that the pump increased the pressure to 200 bar and then was idle until the pressure had decreased to 190 bar at which the pump becomes active again. This cycle took approximately 30 s. When the retightening occurred the stress temporarily decreased on the specimen. This stress drop was estimated to be 0.5 MPa.

The stress relaxation testing was performed in room temperature condition where the ambient temperature in the room changed with the day-night cycle and outdoor condition. No climate chamber was available so no control over the ambient temperature was possible.
Due to the active strain control the distance between the extensometer knives were constant independent of any thermal expansion/contraction of the specimen. However, the load cell measures the load in the entire system and the thermal expansion/contraction of the remaining parts of the specimen may have influenced the load cell.

For short times and high initial stress levels no interference in the stress data could be observed. However, at longer times when the stress rate had decreased to very low levels, interference was observed for the two lowest stress levels after some hours of testing. One may conclude that for stress relaxation testing at room temperature conditions, pin-loaded specimen is preferred and that the ambient temperature needs to be controlled, especially for testing for long periods of time or low initial stress levels.

5.2 The stress relaxation rate

From the literature [1] it is often reported that for room temperature creep the primary creep rate can be described by the following empirical creep law:

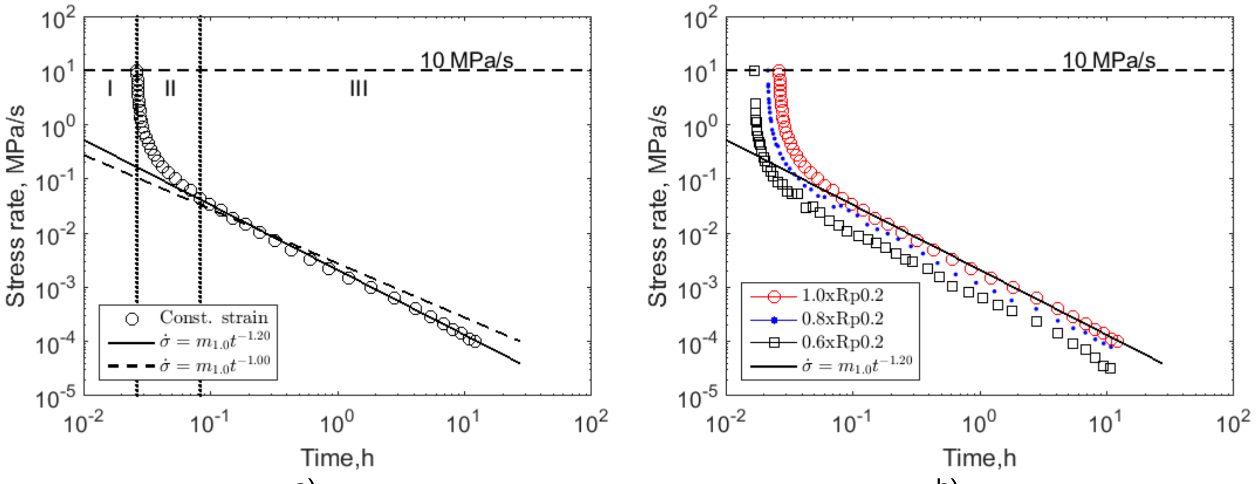
$$\dot{\varepsilon} = mt^{k} \tag{2}$$

where t is the time. If k = -1 the creep is defined as logarithmic, otherwise it is defined as power-law creep (not to be confused with the time independent power-law behavior during secondary creep). To investigate if the stress relaxation obeys an empirical logarithmic or power-law description the stress rate during the stress relaxation testing was calculated. The stress rate was defined as the time derivative of the stress. Equation (2) would then be expressed as:

$$\dot{\sigma} = mt^{k} \tag{3}$$

where $\dot{\sigma}$ was the stress rate. Figure 5a shows the mean stress rate for the two 1.4462 cold drawn specimens at the 1.0x$R_{p0.2}$ stress level. Three distinct regions could be found: the first region (I) was the initial loading which was held constant at 10 MPa/s, the second region (II) was the initial stress relaxation and the third region (III) was the stress relaxation region where the stress rate could be described by equation (3). The k values for the logarithmic case (k = -1.00) is plotted together with the found value of k from least square fitting of the data (k = -1.20). The result indicate that the stress relaxation had a power-law behavior and not logarithmic.

In Figure 5b the influence of different stress levels is shown and it was evident that the stress relaxation behavior was similar between the different initial stress levels. The k value was found to be independent of the initial stress level. The difference between lower initial stress level and higher initial stress level was that the start of the test was shifted to shorter times and that the start of the third region begins at lower stress rates (lower m value in equation (3)) for the lower stress level, this result in lower stress relaxation.



a) b)

Figure 5 The stress rate, a) power-law behaviour, b) influence of the initial stress.

Table 4 shows the linear square fitting for all tested specimens and the result was consisted with Figure 5. The austenitic 1.4436 rebar had k = -1.12 while the two duplex grades had k = -1.19, indicating a slight difference between austenitic and duplex stainless steels in the rebar/bar condition. For the cold drawn bars, the k values were similar between austenitic and the lean duplex while the duplex bar had slightly lower k value. In the work by Hannula et al. [2] the k was found to be -1.08 for AISI type 316 austenitic stainless steel compared to k = -1.12 found in this work.

Table 4 Found values for k and m for the tested bars according to equation (3).

		Rebar/bar			Cold drawn		
Grade	**$xR_{p0.2}$**	**k**	**m**	**Mean R2**	**k**	**m**	**Mean R2**
1.4436	0.6	-1.11	3.5	0.87	-1.20	12.2	0.97
	0.8	-1.11	6.2	0.97	-1.15	13.6	0.96
	1.0	-1.13	10.6	0.99	-1.16	22.3	0.97
	Mean	-1.12		0.94	-1.17		0.97
1.4162	0.6	-1.20	13.2	0.92	-1.19	12.4	0.93
	0.8	-1.19	21.7	0.98	-1.14	14.4	0.96
	1.0	-1.17	28.6	0.98	-1.17	26.2	0.96
	Mean	-1.19		0.96	-1.17		0.95
1.4462	0.6	-1.21	10.3	0.83	-1.20	12.6	0.94
	0.8	-1.20	20.1	0.96	-1.21	26.3	0.98
	1.0	-1.17	28.8	0.98	-1.21	39.3	0.97
	Mean	-1.20		0.92	-1.20		0.96

5.3 The asymptotic stress relaxation

The strain rate during stress relaxation testing can be described by the following equation:

$$\frac{d\varepsilon}{dt}=\frac{d\varepsilon_{el.}}{dt}+\frac{d\varepsilon_{in.}}{dt} \tag{4}$$

where ε is the total strain, $\varepsilon_{el.}$ the elastic contribution and $\varepsilon_{in.}$ the inelastic contribution. If one assumes that Hooke's law applies, then equation (4) can be written as:

$$\frac{d\varepsilon}{dt}=\frac{1}{E}\frac{d\sigma}{dt}+\frac{d\varepsilon_{in.}}{dt} \tag{5}$$

As the total strain was kept constant during the stress relaxation testing, the inelastic change with time can be found from rearranging equation (5):

$$\frac{d\varepsilon_{in.}}{dt}=-\frac{1}{E}\frac{d\sigma}{dt} \tag{6}$$

It has been found for various metals that the inelastic response (at low homologous temperatures [3]) can be described by an equation of state [4],[5] where the mechanical properties that characterize the material plastic behavior can be identified by introducing a "hardness state" parameter which is related to the strength of barriers to dislocation motion. For an austenitic stainless steel, Yamada and Li [6] found out that the inelastic response followed an equation of state of the form:

$$\frac{d\varepsilon_{in.}}{dt}=K(\sigma-\sigma^*)^m \tag{7}$$

where K and m are material parameters, σ the stress and σ* is the "hardness state" parameter. K is related to the burger vector and mobile dislocation density while m is related to the dislocation velocity-stress exponent [3]. Equation (7) has been found to also describe the inelastic response for duplex and super duplex stainless steel [7]. By substituting equation (6) in (7) results in:

$$-\frac{1}{E}\frac{d\sigma}{dt}=K(\sigma-\sigma^*)^m \tag{8}$$

Which can be rearranged in to the following differential equation:

$$(\sigma-\sigma^*)^{-m}d\sigma=-EKdt \tag{9}$$

Integrating equation (9) results in:

$$\int_{\sigma_0}^{\sigma}(\sigma-\sigma^*)^{-m}\,d\sigma=\int_{t_0}^{t}-EKdt \tag{10}$$

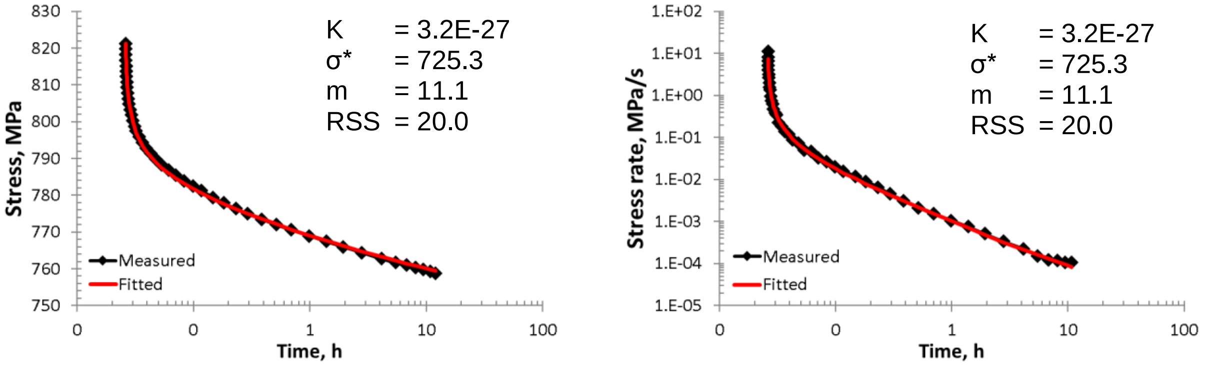
which has the solution:

$$\frac{1}{1-m}\left[(\sigma-\sigma^*)^{1-m}-(\sigma_0-\sigma^*)^{1-m}\right]=-EK(t-t_0) \tag{11}$$

solving for σ as a function of time yields:

$$\sigma(t)=\sigma^*+\left[(\sigma_0-\sigma^*)^{1-m}+EK(m-1)(t-t_0)\right]^{1/(1-m)} \tag{12}$$

By nonlinear curve fitting the measured stress relaxation with equation (12) by using the nonlinear solver in Excel, it was possible to determine the K, m and σ*, see Figure 6. The Young's modulus was assumed to be 200 GPa for all materials.



a) b)

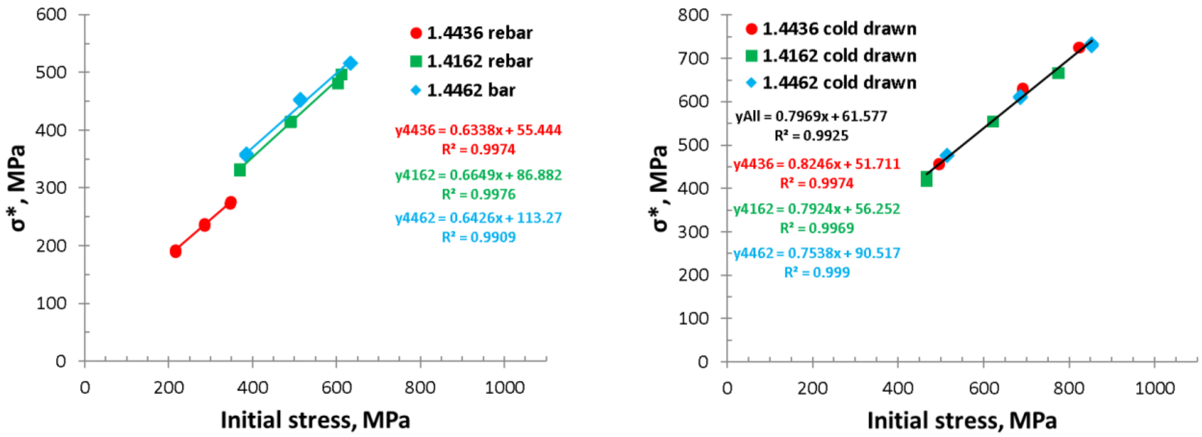
Figure 6 Fitted parameters according to equation (12), a) stress relaxation of the 1.4436 cold drawn at 1.0xR$_{p0.2}$ (48 data points), b) the stress rate. RSS is the lowest residual sum of squares.

However, the number of local minimum in the parameter space of equation (12) was vast so the following practice was used for determining the K, m and σ*: Hannula et. al [3] reported no significant dependence between m and strain so the K, m and σ* was first determined for the 1.0xR$_{p0.2}$ stress level (as these had the "smoothest" curve, recall chapter 5.1). The average m of the two tests at this stress level was then used for evaluating the K and σ* at the lower stress levels for each type of material. Table 5 shows the determined values of K, m and σ* from the nonlinear fitting of the tested bars according to equation (12).

Table 5 Found parameter values from solving equation (12), mean value of two measurements.

Grade, EN	State	xR$_{p0.2}$	m	K	σ*, MPa	SD σ*, MPa	RSS, MPa^2
1.4436	Rebar	0.6	12.1	3.8E-22	191.5	1.6	2.3
		0.8	12.1	1.8E-25	236.9	2.0	11.9
		1.0	12.1	3.2E-27	274.8	2.1	1.7
	CD	0.6	11.2	1.4E-23	456.7	0.4	9.7
		0.8	11.1	2.2E-25	629.5	2.2	18.3
		1.0	11.1	3.2E-27	725.4	0.2	33.4
1.4162	Rebar	0.6	10.3	3.2E-22	331.3	1.4	11.6
		0.8	10.3	1.5E-24	414.8	0.8	16.7
		1.0	10.2	5.7E-26	489.3	7.6	23.4
	CD	0.6	10.3	1.2E-22	422.5	5.1	21.1
		0.8	10.3	3.0E-24	554.7	0.4	17.2
		1.0	10.3	5.3E-26	666.3	0.3	25.6
1.4462	Bar	0.6	10.3	5.0E-21	357.2	1.5	4.8
		0.8	10.3	1.0E-23	452.6	0.8	8.6
		1.0	10.3	5.7E-26	515.6	0.2	10.4
	CD	0.6	10.1	7.2E-22	476.4	0.9	7.4
		0.8	10.1	2.6E-24	610.8	1.7	16.3
		1.0	10.1	5.7E-26	731.3	2.9	15.6

Figure 7 shows σ* as a function of initial stress for the tested bars and the σ* was found to be a linear dependence of the initial stress (which was consistent with the literature [2],[7]). For the cold drawn bars, the σ* as a function of the initial stress was similar for the three tested grades.



a) b)

Figure 7 σ as a function of the initial stress. a) Rebar/bar, b) cold drawn bars.*

It is assumed that the inelastic deformation during stress relaxation testing proceeds only as long as the stress exceeds the threshold determined by the state variable σ* and that the value of the state variable σ* characterizes the asymptotic lower bound for the stress in the relaxation experiments (i.e. the stress at infinite time). Figure 8 shows the asymptotic stress relaxation (defined according to equation (1) where σ*, from Table 5, was used instead of σ) as a function of the initial stress. The results show that for the tested specimens the duplex grades, in the “annealed” state, has less stress relaxation than the austenitic grade in the “annealed” state at all initial stresses. However, for the cold drawn bars the austenitic grade has less stress relaxation compare to the two duplex grades at higher stress. Figure 8 was consistent with Figure 3. The $F_{p,C}$ correspond to the estimated stress in the bolts for the used preload levels used in this project.

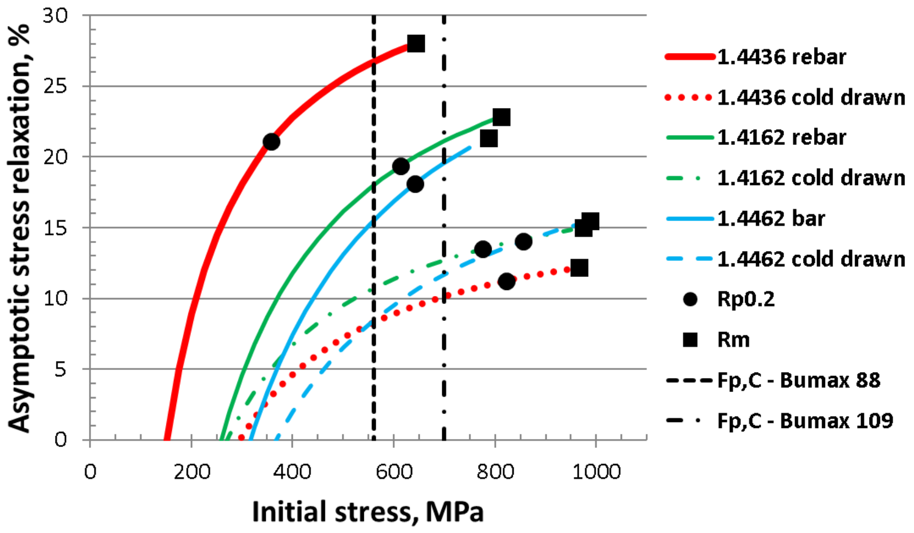


Figure 8 The asymptotic stress relaxation as a function of the initial stress for the tested bars. $R_{p0.2}$ and R_m were the measured strength of the tested bars, recall Table 1.

5.4 Conclusions for preloaded bolt connections

The stress relaxation testing has been performed on bars and as seen in Table 1 the cold forged bolts have higher proof stress compared to the cold drawn bars. This indicates higher amount of cold work in the bolts compared to the cold drawn bars. The stress relaxation seems to be sensitive to the amount of cold work. One may therefore assume that cold forged bolts will lie below the 1.4436 cold drawn line in Figure 8 and thus show less stress relaxation than the tested cold drawn bars in this report. One may therefore also assume that machined bolts will show more stress relaxation than cold forged bolts.
The stress relaxation testing shows that most of the stress relaxation occurs within minutes of applying constant strain. Roughly 50 % of the asymptotic stress relaxation occurs within the first hour of testing, see Figure 9. Instrumented bolt connects may be used for measuring the loss of preload in preloaded bolt connection. This setup is however expensive and time consuming. Figure 9 indicates that measuring the loss of preload for very long times may not give significant more accurate information about the stress relaxation than measuring for a relative short time.

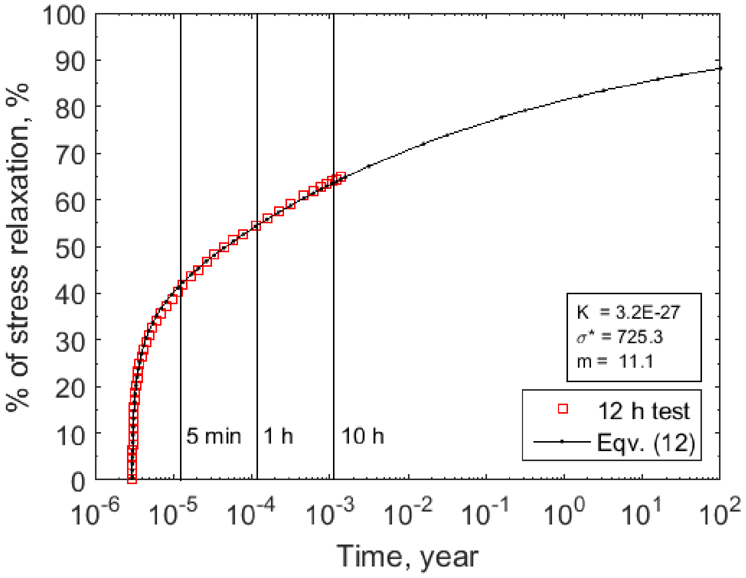


Figure 9 Comparison between 12 h stress relaxation test and the asymptotic stress relaxation. 5 min, 1 h and 10 h marks the respectively testing time. Cold drawn bar of 1.4436 at the 1.0xR$_{p0.2}$ stress level.

6. Summary

- The tested duplex stainless steels in the “annealed” state has less stress relaxation compared to the tested austenitic stainless steel in the “annealed” state.
- Cold drawn bars had less stress relaxation compared to bars in the “annealed” state.
- Cold drawn austenitic bar had less stress relaxation compared to cold drawn duplex bars.
- Most of the stress relaxation in preloaded bolts is likely to occur within the first hour after preloading.
- Machined bolts are likely to have higher stress relaxation than cold forged bolts.

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8. References

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