RESIDUAL FORCE IN HIGH-STRENGTH BOLTS SUBJECTED TO HEAT

—Part II Long Soak Time Test at Relatively Low Temperatures—

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Abstract

It has been shown that the slip resistance of a high strength bolted connection is reduced when it is subjected to certain temperature environments.^{1), 2), 3), 4)} In a recent report,^{5), 6), 14)} it was further shown that the reduction of the residual clamping force is likely to be the primary reason for the phenomenon. The parameters varied in that study included; 1) relatively short soak time of 1 to 8 hours, 2) bolt grade, 3) bolt diameter, 4) bolt length and 5) cooling method.

In this report, the behaviour of high-strength bolted joints subjected to relatively low temperatures particularly below 350°C is investigated. The value (350°C) has been reported to be a safe limit for allowable heating temperature. The soak time (1 to 500 hours) and repeated heating hysteresis are additional features of these tests.

In these tests, several types of bolted specimen were used to study the effect of grip length on the residual clamping force.

The clamping force of h.s. bolts subjected to the temperature environments of this study was reduced considerably at lower maximum temperature than the limit which was currently expected to be safe.

The results and recommendation of this investigation provide information necessary for the design of h.s. bolted joints which may be subjected to fire or the severe temperature found in industrial operation such as steel making and power generation.

1. Description of the Experiments

The experiments consisted of two types of heat cycling on identical bolted assemblies and are referred here as Experiment I and Experiment II.

1.1 Experiment I; Cyclic Heating Test

To determine the effect of repeated heating on the residual clamping force at a relatively low maximum temperature, specimens identical to those reported previously^{5), 6), 14)} were subjected to repeated heating hysteresis. One type of bolted specimen was used, that is, F 11 T M 22 L=100.

1.2 Experiment II; Long Soak Time Test

To determine the effect of the long soak time, four types of long soak time experiment were scheduled. These are shown in the following notes.

a) Experiment-II A; Accumulative Long Soak Time Test

To obtain basic data on the residual clamping force, the same specimen types as used in Experiment I were performed for the long soak time at relatively low maximum temperature range. The object of Experiment II-A was to compare the effect of the long soak time with the effect of the cyclic heating. For this purpose, the soak time was chosen as 10 hours and 50 hours which were accumulated maximum soak time in Experiment I. In addition to these soak time, 500 hours soak was executed.

b) Experiment II-B; Grip Length Test

A previous study^{9), 10)} showed that an elastic effect of joint material called "elastic follow-up" phenomenon affects on the residual clamping force. This is such effect that the elasticity of joint

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material may keep the clamping force longer than those of no elasticity if creep phenomena don't occur in joint material.

Meanwhile, the behavior of joint material at elevated temperature¹³⁾ is not clear and the increased bolt relaxation would occur because of the creep or flow of joint material under sustained high clamping pressures. In these tests, three types of bolted specimen were used, that is, F 10 T M 16 $L=85$ (Grip length=65 mm), F 10 T M 16 $L=60$ (Grip length=39 mm), F 10 T M 16 $L=50$ (Grip length=27 mm).

The condition of heating hysteresis was the same as Experiment II·A except 500 hours.

c) Experiment-II C; Threads under Nut Test

Due to the high stress level in the threaded part of an installed bolt, the number of plies as well as the grip length would be factors that influence the amount of bolt relaxation. Increasing the number of plies for a constant grip length might lead to an increase in bolt relaxation. For this reason, threads under nut was adopted as an experimental parameter. To obtain the effect of threads under nut on the residual clamping force after long soak time, five types of bolted specimen were used, that is, F 10 T M 22 $L=90$, F 10 T M 22 $L=95$, F 10 T M 22 $L=100$, F 10 T M 22 $L=105$, F 10 T M 22 $L=110$. Grip length was 68 mm and it was common to all specimens. The tightening condition is shown in Fig. 3-(b). The length of threads and shank in grip are tabulated in Table 5. In this table, l_n shows the length of threads and l_1 shows the length of shank. The condition of heating hysteresis was the same as Experiment-II B.

d) Experiment-II D; SM 50 A Joint Material Test

The relaxation characteristic of assemblies of galvanized plates is such a remarkable example that the influence of joint material affected on residual clamping force is great. Such being the case, joint material would be an important factor affected on relaxation characteristic because of the creep or flow under sustained high clamping pressures. In this experiment, SM 50 A was used to examine the effect of joint material on the residual clamping force as compared with SS 41. One type of bolted specimen was used, that is, F 10 T M 22 $L=100$.

1.3 Experimental Procedure

In summary the testing was of two types:

Experiment I ; repeated heating hysteresis test

Experiment II ; long soak time test subjected to simple hysteresis

In Experiment I, the test was performed by heating for one hour followed by cooling using a fan outside of a furnace. This process of heating and cooling is defined as one cycle; data were recorded after one, ten and fifty such cycles. This testing procedure is shown conceptually in Fig. 1(a).

In Experiment II the specimen was soaked continuously for a time equal to the accumulated soak time of Experiment I.

This testing procedure concept is shown in Fig. 1(b). The maximum soaking temperatures used in Experiment I and II were 250°C, 300°C and 350°C; this later value had been suggested as an allowable maximum temperature¹⁾ for relatively short soak time like a fire.

Fig. 1 (a) Concept of Heating Procedure for Experiment I

Fig. 1 (b) Concept of Heating Procedure for Experiment II

2. Specimens

The specimens used in these experiments consisted of two elements, which are bolt sets and joint material. The dimensions of plate size and hole diameter are shown in Fig. 2. Details of each element are shown in the following notes.

2.1 Bolts

Bolt specimens were F 11 T M 22, F 10 T M 16 and F 10 T M 22; the mechanical properties and the

chemical composition are shown in Table 1 (a),(b). The total number of specimens tested for each combination of the soak temperature and cycles (or accumulated time) are shown in Table 2.

Table 1 (a) Chemical Composition of Bolt, Nut, Washer and Joint Material

Specimen	Experiment	Grade	Chemical Component, Weight(%)											
			C ($\times 10^2$)	Si ($\times 10^2$)	Mn ($\times 10^2$)	P ($\times 10^3$)	S ($\times 10^3$)	Cu ($\times 10^2$)	Ni ($\times 10^2$)	Cr ($\times 10^2$)	Ti ($\times 10^3$)	Al ($\times 10^3$)	B ($\times 10^6$)	Ceq ($\times 10^2$)
Bolt	Ex.-I, IIA	F11T M22 L=100	21	14	75	17	13	—	—	68	—	69	23	47.7
		F10T M16 L= 85	21	18	80	23	13	2	2	66	—	73	18	48.3
	Ex.-IIB	F10T M16 L= 60	19	19	78	16	15	1	2	68	—	54	12	46.4
		F10T M16 L= 50	19	16	86	15	11	1	2	70	—	56	14	48.1
		F10T M22 L= 90	20	15	80	16	13	—	—	68	—	70	18	47.6
	Ex.-IIC	F10T M22 L= 95	21	15	73	16	6	—	—	70	—	60	12	47.8
		F10T M22 L=100	20	16	77	21	14	—	—	68	—	65	14	47.1
		F10T M22 L=105	21	15	75	16	10	—	—	68	—	62	16	47.7
		F10T M22 L=110	20	16	77	21	14	—	—	68	—	63	14	47.1
	Ex.-IID	F10T M22 L=100	20	13	78	15	12	—	—	70	14	59	14	47.5
Nut	Ex.-I, IIA	F10(M22)	41	22	79	17	21	2	1	3	—	—	—	55.7
	Ex.-II B	F10(M16)	29	23	76	15	19	1	1	2	—	34	—	43.1
	Ex.-II C	F10(M22)	39	20	76	19	19	1	2	4	—	—	—	53.4
	Ex.-II D	F10(M22)	39	20	78	22	23	1	1	5	—	—	—	53.9
Washer	Ex.-I, IIA	F35(M22)	22	30	74	23	18	30	4.2	108	50	42	24	57.3
	Ex.-II B	F35(M16)	22	25	110	10	7	2	1	2	—	45	22	41.8
	Ex.-II C	F35(M22)	23	23	115	12	14	—	—	—	17	—	23	43.1
	Ex.-II D	F35(M22)	25	25	114	27	13	—	—	—	—	—	18	45.0
Joint Material	Ex.-I, IIA	SS41	16	16	62	22	17	—	—	—	—	—	—	27.0
	Ex.-II B	SS41	13	20	52	13	16	18	8	4	—	5	—	23.0
	Ex.-II C	SS41	13	20	47	16	22	—	—	—	—	—	—	21.7
	Ex.-II D	SM50A	17	37	137	22	19	—	—	—	—	—	—	41.4

Table 1 (b) Mechanical Property of Bolt Sets

Mechanical Property of Bolt Sets							
Bolt Specimen	Experiment	Tensile Strength (kg/mm ²)	Elongation (%)	Reduction of Area (%)	Hardness (HRC)	Nut Hardness (HRC)	Washer Hardness (HRC)
F11T M22 L=100	Ex.-I, IIA	119	16	61	37	27	40
F10T M16 L= 85		113	17	64	34	25	40
F10T M16 L= 60		110	18	67	32	23	40
F10T M16 L= 50	Ex.-IIB	112	18	67	33	24	41
F10T M22 L= 90		109	18	65	33	24	41
F10T M22 L= 95		109	18	67	33	25	39
F10T M22 L=100	Ex.-IIC	109	17	66	32	25	41
F10T M22 L=105		110	18	68	33	25	39
F10T M22 L=110		110	18	66	33	25	41
F10T M22 L=100	Ex.-IID	109	17	66	32	25	41

Table 1 (c) Mechanical Property of Joint Material

Mechanical Property of Joint Material				
Specimen	Experiment	Yield Stress (kg/mm ²)	Tensile Stress (kg/mm ²)	Elongation (%)
SS41	Ex.-I, IIA	29	43	28
SS41	Ex.-IIB	30	47	26
SS41	Ex.-IIC	30	45	30
SM50A	Ex.-IID	37	59	26

Table 1 (d) Mechanical Property of SM 50 A at Elevated Temperature

The Results of Tensile Test of SM50 at Elevated Temperature								
Temp.	Young's Modulus		Yield Stress		Tensile Strength		Elongation (%)	Reduction of Area (%)
	E(kg/mm ²)	A*	Oy(kg/mm ²)	A*	Omax(kg/mm ²)	A*		
Room	20.412	100.0	32.46	100.0	57.33	100.0	29.17	68.71
250°C	19.002	93.1	28.00	86.3	67.17	117.2	24.96	49.09
300°C	18.398	90.1	27.00	83.2	59.24	103.3	24.59	52.77
350°C	17.638	86.4	25.88	79.7	58.90	102.7	23.41	54.81
400°C	15.487	75.9	25.80	79.5	53.84	93.9	21.31	42.80
450°C	—	—	25.05	77.2	48.86	85.2	15.45	41.29
500°C	13.892	68.1	23.30	71.8	38.92	67.9	19.60	40.06

△ Young's Modulus : ($\times 10^8$)

Fig. 2 Dimensions of the Joint Material

Fig. 3 (a) The Method of Clamping Force Release

Fig. 3 (b) The Tightening Condition in Ex.-IIC (Threads under Nut Test)

2.2 Joint Material

The joint material was SS 41 and SM 50 A. It was fabricated as shown in Fig. 3 (a) and the tightening condition in the Experiment II-C was also shown in Fig. 3 (b). The chemical composition and the mechanical properties for the plate material are shown in Table 1 (a),(c),(d). The surfaces of the plates were prepared by removing the millscale using sand paper around the bolt holes.

3. Experimental Method

The conduct of the experiments proceeded according to the flowchart presented as Fig. 4. This procedure is essentially the same that used and reported in the previous studies^{5), 6), 7), 8), 14)} with the additional process of heat soaking or heat cycling added. Several specific aspects of the conduct of the experimental method are discussed here to give some insight on the experimental technique and the reliability of the data reported here.

3.1 Bolt Elongation

The measurement of residual force was done by the axial length of a bolt before or after releasing the clamping force. Therefore a spring constant of a bolt becomes important. These spring constants of bolts used in the experiments are summarized in Table 3. In order to measure the change of a bolt length with high accuracy, a rigid frame extensometer shown in Fig. 5 was used. To accept such an instrument, each end of a bolt specimen has a hole of 3.5 mm diameter and a depth of 2~3 mm. The bolts were installed with a torque testing machine. A universal testing machine (capacity 200 t) was to pull out a butt plate for clamping force release.

3.2 Heat Cycling

All specimens were heated in an electric resist-

Table 2 Specimen Table

Specimen Table						
Experiment	Bolt Specimen	Temp.	Soak Condition			
Cyclic Heating Test			1cycle	10cycles	50cycles	—
Ex.—I	F11T M22 L=100	250°C	3	3	3	—
		300°C	3	3	3	—
		350°C	3	3	3	—
Long Time Heating Test			1hour	10hours	50hours	500hours
Ex.—II A	F11T M22 L=100	250°C	3	3	3	3
		300°C	3	3	3	3
		350°C	3	3	3	3
Ex.—II B	F10T M16 L= 85	250°C	3	3	3	—
		300°C	3	3	3	—
		350°C	3	3	3	—
	F10T M16 L= 60	250°C	3	3	3	—
		300°C	3	3	3	—
		350°C	3	3	3	—
	F10T M16 L= 50	250°C	3	3	3	—
		300°C	3	3	3	—
		350°C	3	3	3	—
Ex.—II C	F10T M22 L= 90	250°C	3	3	3	—
		300°C	3	3	3	—
		350°C	3	3	3	—
	F10T M22 L= 95	250°C	3	3	3	—
		300°C	3	3	3	—
		350°C	3	3	3	—
	F10T M22 L=100	250°C	3	3	3	—
		300°C	3	3	3	—
		350°C	3	3	3	—
	F10T M22 L=105	250°C	3	3	3	—
		300°C	3	3	3	—
		350°C	3	3	3	—
F10T M22 L=110	250°C	3	3	3	—	
	300°C	3	3	3	—	
	350°C	3	3	3	—	
Ex.—II D	F10T M22 L=100	250°C	3	3	3	—
		300°C	3	3	3	—
		350°C	3	3	3	—
		400°C	3	—	—	—
		450°C	3	—	—	—
		500°C	3	—	—	—

Table 3 Spring Constant and Initial Elongation of Bolt

Spring Constant and Initial Elongation of Bolts			
Bolt Specimen	Experiment	Spring Const. (ton/mm)	Initial Elong. ($\times 10^{-3}$ mm)
F11T M22 L=100	Ex.-I, IIA	88.88	268
F10T M16 L= 85		51.46	227
F10T M16 L= 60		76.00	154
F10T M16 L= 50	Ex.-IIB	97.56	120
F10T M22 L= 90		87.77	257
F10T M22 L= 95		89.16	253
F10T M22 L=100	Ex.-IIC	90.39	250
F10T M22 L=105		91.55	247
F10T M22 L=110		93.03	243
F10T M22 L=100	Ex.-IID	90.39	250

Fig. 4 Flow Chart of Experimental Procedure

Fig. 5 Special Bolt Extensometer

ance type furnace. The temperature was measured to $\pm 3^{\circ}\text{C}$ with thermocouples and recorded with X-Y recorder. To minimize the difference between the temperature in the furnace and the temperature of the bolted assemblies, heating rates were maintained between $50^{\circ}\text{C}/\text{hour}$ and $100^{\circ}\text{C}/\text{hour}$.

3.3 Release of the Clamping Force

Previous study^{1),2)} has shown that at the time of releasing the clamping force there may be a scorching phenomenon between the nut and the bolt thread or at the washer resulting from the heating. For such a case the large torque on the bolt axis results in plastic deformations and the desired elastic rebound elongation can not be achieved. Therefore, the method used in reference⁶⁾ was adopted, and is shown diagrammatically in Fig. 3 (a). Specimens are composed of cover plates and two butt plates. These butt plates are separated at the center and so that the clamping force is released as the two plates are extracted by using a universal testing machine. The second butt plate is extracted by using the jig.

4. Experimental Results

4.1 The Effect of the Number of Cycles of Heating (Ex.-I)

The relationships between the number of heating cycles and nondimensional residual clamping force in cyclic heating tests are shown in Fig. 6. The nondimensional residual clamping force shown here is the measured residual clamping force divided by standard or initial clamping force. Since the soaking requires an hour per cycle, one can interchange the number of cycles with hours. On this figure the equations obtained by the least squares method are shown simultaneously. In general, the data shows that, the greater the number of heat cycles, or the higher heating soaking temperature, the more clamping force is reduced.

4.2 The Effect of Soak Time (Ex.-IIA)

The relationships between soak time and nondimensional residual clamping force for simple heating tests, Experiment IIA, are shown in Fig. 7. On this figure the equations obtained by the least squares method are shown simultaneously. As in the cyclic heating test, the longer the soak time, or the higher the temperature, the more clamping force is reduced.

4.3 Influence of Heating and Cooling on Residual Clamping Force (Ex.-I, IIA)

The coefficients of the equations obtained by the least squares method shown in Fig. 6~Fig. 7 are tabulated in Table 4 and these equations are shown to compare the results of Ex. I and Ex. IIA in Fig. 8. It can be concluded from this summary that heat cycling and heat soaking of the same cumula-

Fig. 6 Relationship between Non-Dimensional Clamping Force and The Number of Cycles

Fig. 7 Relationship between Non-Dimensional Clamping Force and Soaking Time

Table 4 The Coefficients of Equations by Least Squares Method

Test	Experiment-I			Experiment-II A		
Temp.	250°C	300°C	350°C	250°C	300°C	350°C
A	0.96	1.14	1.31	1.04	1.38	1.31
B	-0.02	-0.07	-0.15	-0.04	-0.17	-0.11
r	0.99	0.83	0.99	0.69	0.93	0.96

$Y/Y_0 = A + B \log X$
 Y : Residual Clamping Force (t) X : Soak Time (hour)
 Y_0 : Standard Bolt Tension (t)

Fig. 8 Comparison between Ex. I and Ex. IIA

tive duration produce essentially the same clamping force reduction and one could estimate the residual clamping force after cyclic heating by accumulative soak time test with small error.

4.4 Influence of Grip Length on Residual Clamping Force (Ex.-IIB)

The relationships between soak time and non-dimensional clamping force are shown in Fig. 9 (a), (b), (c) and grip length and nondimensional clamping force relations are also shown in Fig. 9 (d), (e), (f). The difference of the residual clamping force under the same soak time and heating temperature is within 5% of non-dimensional residual clamping force.

From this result, the effect of the grip length on the residual clamping force is seen to be negligible. This also coincides with the result obtained from relatively short soak time in the previous report¹⁴⁾.

4.5 Influence of Threads under Nut on Residual Clamping Force (Ex.-IIC)

The relationships between soak time and non-dimensional residual clamping force are shown in Fig. 10 (a)~(e). On these figures the equations obtained by the least squares method are shown simultaneously. To compare the influence of threads under nut, the relationships between soak time and nondimensional residual clamping force under the same heating temperature are shown in

Fig. 9 (a) Relationship between Non-Dimensional Clamping Force and Soak Time ($L_g = 27$ mm)

Fig. 9 (b) Relationship between Non-Dimensional Clamping Force and Soak Time ($L_g = 39$ mm)

Fig. 9 (c) Relationship between Non-Dimensional Clamping Force and Soak Time ($L_g = 65$ mm)

Fig. 9 (d)

Relationship between Non-Dimensional Clamping Force and Grip Length (250°C)

Fig. 9 (e)

Relationship between Non-Dimensional Clamping Force and Grip Length (300°C)

Fig. 9 (f)

Relationship between Non-Dimensional Clamping Force and Grip Length (350°C)

Fig. 10(a) Relationship between Non-Dimensional Clamping Force and Soak Time ($L_n = 25.4$ mm)

Fig. 10(b) Relationship between Non-Dimensional Clamping Force and Soak Time ($L_n = 19.7$ mm)

Fig. 10(c) Relationship between Non-Dimensional Clamping Force and Soak Time ($L_n = 14.9$ mm)

Fig. 10(d) Relationship between Non-Dimensional Clamping Force and Soak Time ($L_n = 10.5$ mm)

Fig. 10(e) Relationship between Non-Dimensional Clamping Force and Soak Time ($L_n = 5.0$ mm)

Fig. 10(f) Relationship between Non-Dimensional Clamping Force and Soak Time (250°C)

Fig. 10(g) Relationship between Non-Dimensional Clamping Force and Soak Time (300°C)

Fig. 10(h) Relationship between Non-Dimensional Clamping Force and Soak Time (350°C)

Fig. 10 (f), (g), (h) with these equations. The difference of the residual clamping force on each figure is within 6% of non-dimensional residual clamping force. The effect of threads under nut on residual clamping force is found to be negligible.

4.6 Influence of Joint Material on Residual Clamping Force (Ex.-IID)

The relationships between heating temperature and non-dimensional residual clamping force in SM 50 A tests are shown in Fig. 11 (a) and those between soak time and non-dimensional residual clamping force are also shown in Fig. 11 (b).

The purpose of this experiment was to examine the influence of joint material on residual clamping force, therefore comparison of this experimental results with Ex.-IIC results, which were obtained by using the same bolted specimen except joint material, has been made in Fig. 11 (c).

It can be seen for the case of identical heating temperature and soak time, residual clamping forces obtained by using SM 50 A joint material are greater than those of SS 41 joint material and the difference is 3.7% (250°C; 1 hour soak), 8.7% (300°C; 1 hour soak) and 6.1% (250°C; 1 hour soak).

4.7 Evaluation of Clamping Force Reduction

In order to examine the reasons for reduction of bolt clamping force, plastic deformation* of bolt and that of the clamped material were compared.

For calculation of relative effects of the bolt length changes and the thickness changes in the connected parts the following assumptions are made:

- 1) There is no change in spring constant of bolt and clamped material as a result of heating.

NON-DIMENSIONAL RESIDUAL CLAMPING FORCE
VS. TEMPERATURE RELATIONSHIP
F10T M22 L=100
(SM50)

Fig. 11(a) Relationship between Non-Dimensional Clamping Force and Temperature

Fig. 11(c) Comparison between SS 41 and SM 50 A Joint Material

Table 5 Shank and Threads Length in Grip
(Ex.-IIC)

Shank and Threads Length in Grip					
	L=90	L=95	L=100	L=105	L=110
z1(mm)	42.65	48.28	53.09	57.52	62.99
zn(mm)	25.35	19.72	14.91	10.48	5.01
Grip Length; 68mm L; Bolt Length (mm)

Fig. 11(b) Relationship between Non-Dimensional Clamping Force and Soak Time

Fig. 12 Equivalent Model for Compression Behavior of Connected Material (Bolted Plates)

* plastic deformation=permanent deformation

Fig. 13 (a)

2) There is no change in the length between the bolt end and the free nut face.

3) The change of the bolt length in the clamped condition during heating corresponds to the change of the thickness of the clamped material.

4) The stress angle, or the assumed portion of the plate material in compression is shown in Fig. 12. It was assumed to be 18° for the purpose of calculating the effective spring constant of the connected parts.

Fig. 13 (a), (b) show, graphically the elongation of the bolt and shrinkage of the clamped material in the process of heating. In these figure, the upper (or right) half shows the characteristics of the bolt and the lower (or left) half shows the corresponding behavior of the clamped material. On the bolt side, elongation is positive and on the clamped material side, shrinkage is negative. The bolt length and the thickness of clamped material for each condition were prescribed as follows.

Fig. 13 (b) Elongation of the Bolt and Shrinkage of the Clamped Material in the Procedure of Heating

- (Condition 0) Before heating and before clamping, bolt length : L_0 Thickness of the clamped material : δ_0
- (Condition I) Before heating and after clamping, bolt length : L_1
Thickness of the clamped material : δ_1
Clamping force : P_S
- (Condition II) After heat cycles and on the clamped condition, bolt length : L_2
Thickness of the clamped material : δ_2
Clamping force : P_R
- (Condition III) After heat cycles and after releasing the clamping force, bolt length : L_3
Thickness of the clamped material : δ_3

In conditions 0~III, the following nomenclature is used.

L_3-L_0 ; plastic elongation of the bolt

$\delta_3-\delta_0$; plastic shrinkage of the clamped material

L_2-L_3 ; residual elastic elongation of the bolt

$\delta_2-\delta_3$; residual elastic shrinkage of the clamped material

L_1-L_2 ; the change of bolt elongation during heating at the clamped condition

$\delta_1-\delta_2$; thickness change of clamped plates during heating, on the clamped condition

Now let

$$L_1-L_2=\delta_1-\delta_2 \dots\dots\dots (1)$$

and P_S is an initial clamping force and P_R is a residual clamping force, then

$$P_S=k_B(L_1-L_0)=k_p(\delta_0-\delta_1) \dots\dots\dots (2)$$

$$P_R=k_B(L_2-L_3)=k_p(\delta_3-\delta_2) \dots\dots\dots (3)$$

where, k_B and k_p are spring coefficients of bolt and the clamped material. From (1),(2),(3), following equation is obtained.

$$\delta_0-\delta_3=(P_S-P_R)/k_p+(L_1-L_2) \dots\dots\dots (4)$$

In equation (2),(3),(4), substitution of experimental values for L_0, L_1, L_2, L_3 yields change of clamping force of bolt and plastic shrinkage of the clamped materials. The spring coefficient of plate¹⁵⁾ is $K_p=EA_p/L$, and A_p is derived by integrating the stress cone. In this case the stress angle was 18° which was obtained by Nagai, then

$$D=\left[\frac{4d \cdot l \tan \theta}{\log \frac{(2l \cdot \tan \theta + B - d)(B + d)}{(2l \cdot \tan \theta + B + d)(B - d)}} + d^2\right]^{1/2}$$

where, D ; The diameter of equivalent stress cylinder

B ; The diameter of washer

d ; The diameter of bolt hole

l ; Half length of joint material

So, in the case of bolt M 22 $L=100$, as $A_p=1712 \text{ mm}^2$ and $K_p=642 \text{ ton/mm}$.

Fig. 14 (a) and Fig. 14 (b) show the plastic shrinkage of joint material in threads under nut test (Experiment-II C) and SM 50 A joint material test (Experiment-II D) and the ratio of the plastic shrinkage of joint material to the sum of the plastic elongation of the bolt and the plastic shrinkage of joint material; that is the ratio of the loss of clamping force attributable to the clamped plates to the total loss of clamping force.

If the comparison is made between SS 41 and SM 50 A, the shrinkage of SS 41 is greater than that of SM 50 A under the same heating temperature and the same soak time and the difference is between $3.5 (\times 10^{-3} \text{ mm})$ and $34.0 (\times 10^{-3} \text{ mm})$. The conclusion made in SM 50 A joint material test is likely related to the plastic shrinkage of clamped material.

As regards the quantity of shrinkage, the shrinkage of plate material has the tendency to increase

Fig. 14(a) Comparison of Connected Part Shrinkage (SS 41 and SM 50 A)

Fig. 14(b) Ratio of the Loss of Clamping Force Caused by Plate Shrinkage (SS 41 and SM 50 A)

with the increase of heating temperature and soak time. Meanwhile the ratio of loss of clamping force caused by the clamped material to the total loss of clamping force of bolt decreases with increasing maximum temperature.

5. Conclusions

The important aspects of the tests reported herein are summarized following conclusions.

1) The clamping force in a high strength bolted joint decreases with the increase of the soak time (or number of heat cycles).

2) From a comparison between the cyclic heating test and the accumulative heating test, it was found that the primary factor affecting residual clamping force in the cyclic heating test is not process of heating or cooling but the cumulative time and maximum temperature of soaking. Therefore, it is reasonable to estimate the decrease of clamping force in the cyclic heating test from the long-time accumulative heating test results.

3) The cause of the loss of clamping force, was found to be partially (approximately 80~50%) the creep of plate material and partially the creep of the bolt material for the 250°C maximum temperature and the relaxation of bolt contributes proportionately a larger amount with the increase of maximum temperature.

4) The difference of the residual clamping force on three types of bolt grip length and five types of threads length under nut are within 6% of non-dimensional residual clamping force and the effect of grip length and threads length under nut are seen to be negligible.

5) For the case of identical heating temperature and soak time, residual clamping forces obtained by using SM 50 A joint material are greater than those of SS 41 joint material.

6) Comparing the plastic shrinkage of joint material which is closely related to the residual clamping force, the amount of SM 50 A has a tendency to be smaller than that of SS 41.

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熱履歴をうける高力ボルト残留軸力に関する研究†

—その 2 比較的低温域で長時間加熱をうける場合—

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1. 序

高力ボルト摩擦接合部が、熱履歴をうけるとすべり耐力が低下することが実験的に指摘^{1), 2), 3), 4)}されている。既報^{5), 6), 14)}ではこの主な原因である高力ボルト軸力の減少量を、比較的短時間の加熱条件で（熱履歴時間 1~8 時間）ボルト鋼種、径、首下長さ、冷却方法などをパラメータにとり実験的に明らかにした。

これは、火災のように比較的短時間の熱履歴をうける場合を対象としたのに対し、本報は、比較的低温域で長時間の熱履歴をうける場合、たとえば、製鋼所などの工場の熱源付近などのように、長期間にわたり熱の暴露をうける高力ボルト接合部の設計のための資料を提供することを目的としている。そのため、実験項目は上記の目的に合わせ、熱履歴温度は比較的低温域で長時間加熱される可能性のある 350°C 以下の温度域とした。また、熱履歴方法は実際の熱暴露条件を考慮し、熱繰返し及び連続長時間加熱とした。また、グリップ長さやグリップ長さの中のねじ長さの残留軸力に及ぼす影響をみるために、数種類のグリップ長さやボルト長さを持つ供試体を用いて、接合部材の残留軸力に及ぼす影響を明らかにした。

2. 実験概要

2-1 実験Ⅰ：熱的繰返し試験

ここでは、比較的低温域での熱的繰返しが高力ボルトの残留軸力に与える影響を明らかにするために、既報^{5), 6), 14)}で用いた供試体と同型のものに繰返し加熱の熱履歴を与えた。実験Ⅰは、熱履歴中の昇温、冷却の効果を明らかにするものであり、昇温（3~4 時間）→均温（1 時間）→冷却（炉外に取り出しファンで風を当て空冷約 15 分間）を 1 cycle とし、これを 1 回、10 回、50 回繰返した。その模式図を Fig. 1 (a) に示す。

2-2 実験Ⅱ：長時間加熱試験

ここでは比較的低温域で長時間にわたって熱履歴をう

ける高力ボルトの残留軸力を推定するための資料を得るために、連続長時間加熱の熱履歴を与えた。実験Ⅱは、高温リラクセーション現象による軸力低下量を明らかにするために、実験Ⅰの加熱最高温度での保持時間を積算し、連続的に加熱した。その模式図を Fig. 1 (b) に示す。実験Ⅰ及びⅡにおいて均熱温度（最高温度）は、鋼構造部材の高温時の機械的性質や接合部のすべり耐力から求めた許容温度付近の 350°C, 300°C, 250°C とした。

実験Ⅱでは、以下に示す 4 種類の実験を行い、残留軸力量を求めた。

実験Ⅱ・A：積算加熱試験

実験Ⅰ：熱的繰返し試験に用いたのと全く同様のものを用い、熱履歴は実験Ⅰの加熱最高温度での保持時間を積算し、連続加熱を与えて軸力を求めた。

実験Ⅱ・B：グリップ長さ試験

本実験は、グリップ長さの変化の残留軸力に及ぼす影響を明らかにするために行ったものであり、供試ボルトに F 10 T M 16 を用い、グリップ長さを $l_g = 65 \text{ mm}$, 39 mm , 27 mm に変化させて行った。

実験Ⅱ・C：遊びねじ長さ試験

本実験は、グリップ長さ中に占めるボルトねじ部の多寡の残留軸力に及ぼす影響を求めるために行ったものであり、ボルト供試体は、グリップ長さを一定とし、ボルト全長が 90 mm から 110 mm の 5 種類の異なるボルトを用いることにより、グリップ長さ中のねじ長さを変化させた。

実験Ⅱ・D：接合部材に SM 50 材を用いた場合

残留軸力に及ぼす要因の 1 つとして、接合部材のクリープが挙げられ、高温中のこれら素材のクリープ特性¹³⁾も序々に明らかにされつつあるが、ボルト接合部に用いられた場合の挙動については、未だ明らかにされていない。実験Ⅰ~実験Ⅱ・C は、接合部材に最も一般的な SS 41 を用いているが、ここでは、接合部材に SM 50 A 材を用いて実験を行い、接合部材の材質の残留軸力に及ぼす影響を明らかにした。

3. 供 試 体 本文参照

4. 実験方法 本文参照

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5. 実験結果及び考察

5-1 繰り返し加熱回数と残留軸力の関係

Fig. 6 に、繰り返し加熱試験における繰り返し回数と無次元化残留軸力*との関係を示す。これらより、1 cycle の均熱時間**が等しければ繰り返し回数が増加するほど、また熱履歴温度が高いほど、軸力の低下が大きいことがわかる。

5-2 加熱時間と残留軸力の関係

Fig. 7 に、積算加熱試験における均熱時間と無次元化残留軸力の関係を示すが、繰り返し加熱試験の場合と同様、均熱時間が長いほど、また熱履歴温度が高いほど軸力の低下が大きい。今回の実験では、最高加熱温度 350°C で 500 時間連続加熱すれば、軸力は 30% になることが明らかになった。

5-3 加熱及び冷却過程の残留軸力に及ぼす影響

Fig. 6~7 の結果から求めた、均熱時間または繰り返し回数 対 無次元化残留軸力の関係を最小自乗法により求め、Table 4 に示す。この結果より、繰り返し加熱試験におけるボルト軸力低下の原因は、昇温・冷却自体の効果はあまり大きくなく、均熱部分の温度と時間が大きな因子となっている。すなわち、繰り返し加熱試験における軸力低下量は、積算加熱試験より推定しても大きな誤差は生じないことが明らかになった。

5-4 グリップ長さとの残留軸力の関係

Fig. 9 (a)~Fig. 9 (c) に、グリップ長さをパラメータにとり、無次元化残留軸力—熱履歴時間関係を示すが、グリップ長さの残留軸力に及ぼす影響は、無次元化残留ボルト軸力で比較すると 5% 以内であり、あまり大きな要因ではないことがわかる。このことは、既報^{5), 6), 14)}の比較的短時間の場合に、求めた結果とも一致する。

5-5 グリップ長さ中のねじ長さとの残留軸力の関係

Fig. 10 (a)~(e) に、グリップ長さ中のねじ長さをパラメータにとり、無次元化残留軸力—熱履歴時間関係を示すが、これらのばらつきは、350°C 50 時間均熱で高々 2.7% であった。

5-6 接合部材の材質との残留軸力の関係

* 無次元化残留軸力とは、残留軸力を標準ボルト軸力 (= 初張力) で除した値である。

** 均熱時間とは、温度が定常に保持される時間を指す。

実験 II・C と II・D の結果より、F 10 T M 22, $L=100$ の高力ボルトを用いた場合の残留軸力を Fig. 11 (c) に示すが、接合部材に SM 50 を用いた方が軸力低下率は小さく、その差は 1 時間均熱において、250°C で 3.7%, 300°C で 8.7%, 350°C で 6.1% であった。

5-7 ボルト軸力低下の要因

接合部材の塑性縮み量を、実験で得られたボルト伸びの変化から求めるために、加熱前後のボルト伸び、及び接合部材の縮み関係を模式的に Fig. 13 に示す。ここで添字 0 は、ボルト締付け前、1 は締付け後、2 は加熱後締付け状態、3 は加熱後ボルト軸力解除状態を示す。今回の実験で得られたボルト伸びの変化より、式 (4) を用いて、SS 41 と SM 50 の塑性縮み量と、これらの軸力低下に占める割合を Fig. 14 (a), (b) に表す。これらの結果より、SM 50 の方が SS 41 よりも塑性縮み量が少なく、その差は最大 35×10^{-3} mm、最小 4×10^{-3} mm であり、軸力低下に占めるこれらの割合は、低温側ほど大きい。温度上昇につれて、ボルトのリラクセーションが大きな割合を占める。

6. 結 び

1) ボルト軸力は、均熱時間または繰り返し回数が増加するほど低下する (Fig. 6~11)。

2) 繰り返し加熱及び積算加熱試験の比較より、繰り返し加熱による残留軸力低下に及ぼす因子としては、昇温、冷却の過程の影響は少なく、均熱温度及び均熱時間が主因となっている。また、繰り返し加熱試験における軸力低下量は、積算加熱試験より推定しても、大きな誤差は生じない (Fig. 8)。

3) ボルトのグリップ長さやグリップ長さ中のねじ長さの残留軸力に及ぼす影響は、長時間熱履歴後も、あまり大きな要因でないことが明らかになった (Fig. 9, 10)。

4) 接合部材に SS 41 と SM 50 を用いた場合の残留軸力を比較した結果、SM 50 を用いた場合の方が残留軸力量は大きく現れた。この原因と推察される接合部材の塑性縮み量の比較をした結果、SM 50 の塑性縮み量の方が少なく、また、これらの塑性縮みの軸力低下に占める割合は、低温側ほど大きい。温度上昇につれて、ボルトのリラクセーションが大きな割合を占めることが明らかになった (Fig. 14)。