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621.165-233.1:539.377

Study on the Heat Indication Test of Turbine Rotor Forgings*

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A lot of problems concerning the heat indication test were settled by the use of a model apparatus of heat indication test and by the application of some advanced techniques of metallurgical experiments.

Main points are as follows.

- (1) Proposal of type C' deflection.
- (2) Two kinds of type C deflection which are caused by the non-uniform distribution of Mo dissolved in matrix could be eliminated only by heat treatments.
- (3) Types A, D and C' of deflection which are considered attributable to the non-uniform thermal emissivity of forging surface could be completely remedied by the coating of a mixture of flake graphite powder and heat resistance paint. Consequently, no heat treatment is necessary to eliminate these three types of deflection.
- (4) Introduction of a new specification concerning the heat indication test.

At the heat indication test, only types B and C should be examined closely. The rotor forgings showing other types of deflection i. e. A, D and C' are not considered unsuitable as turbine or generator rotors.

1. Introduction

A few papers have hitherto been published concerning the heat indication test which is applied to steel forgings to be used as steam turbine rotors† for the purpose of securing quiet operation in actual running at high temperatures. The heat indication test has played an important role in the manufacture of turbine rotors, but most of the problems

concerning this test are still left unsolved⁽¹⁾. Consequently, even a rotor forging that had passed a tensile test, a transition temperature test as well as an ultrasonic inspection, etc. frequently failed in a heat indication test. And in this case, a re-heat treatment or a re-test was required. This trouble was not limited to Japan, and it was reported that the General Electric Company in the U. S. A. had rejected 27 rotors in twenty years up to 1958 due solely to the unsatisfactory results of the heat indication test⁽²⁾.

Also, there are some phenomena that can not be explained by the previous studies. The contradiction of opinion between steel forging makers and turbine or generator makers is frequently revealed

* Received 4th, April, 1962.

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† The same test is also required for turbo-generator rotor forging, but the test temperature is low and does not exceed 250°C.

at the time of evaluating the result of heat indication test.

The deflections in the heat indication test will be divided into two major groups by their causes, so far as the condition of the present test of heating by radiation is considered; i. e. the deflections caused by metallurgical defects of inner physical properties of the rotor forging, and the deflections by non-uniform thermal properties of the rotor forging surface. From these points of view, the authors have pursued complete and systematic studies on the heat indication test for several years.

2. Reviews of the past studies

2.1 Equipment and procedure of the heat indication test

Fig. 1 is an example of the equipment for heat indication test. There is no remarkable difference in the equipment and the procedure of the test among the makers. The rotor to be tested is supported horizontally by the journals and only the body is inserted into the furnace, and rotated at 2 rpm or 4 rpm. The deflections are measured at several positions (in this case, the number of the position depends on the length of the rotors) during

the whole period of test; the periods of warming up, constant temperature and cooling. The deflections can be expressed in vector diagram form.

2.2 Various forms of deflection, and previous studies

The deflections observed during the heat indication test show varieties of form in each individual rotor forging. If these deflections are to be considered as a combination of basic types of deflection, the studies about the cause of deflection would be simplified.

The deflections were divided into three types A, B, and C by Caplan and his co-workers⁽³⁾, and another type D was proposed by Timo and his co-worker⁽²⁾ in 1958. In the present study, a type similar to type C caused by entirely different origin is proposed, which is tentatively named type C'.

These basic forms of deflection are shown in Fig. 2.

Type A : According to Weaver⁽⁴⁾, type A deflection is caused by the asymmetrical thermal conductivity of the machined layer of rotor forging. He says that type A deflection disappears as the recrystallization of machined layer proceeds by

Fig. 1 The equipments of heat indication test in the Japan Steel Works Ltd. Arrows in (b) and (d) show the dial indicators which are used to measure the deflection

heating at the heat indication test or annealing for stress relieving. Sedille⁽⁵⁾ also stated a similar concept and it was vaguely conceived that the cause would lie in the physical and metallurgical properties of the machined layer.

Fuchs and his co-worker⁽⁶⁾ and Timo and his co-worker⁽²⁾ have concluded that type A deflection is caused by non-uniform thermal emissivity of rotor surface. Fuchs and his co-worker made an experiment on a rotor with a surface of asymmetrical pitting. Timo and his co-worker performed a study on a rotor with a painting of dark lacquer on its half periphery.

Kerversau and Rcques state in their correspondence to the papers by Burton and his co-worker⁽⁷⁾ that type A deflection appearing several times in the test consecutively repeated may have been caused by the non-uniform fall-off of the thick scale which occurred during heat treatment.

Type B: Asymmetrical residual stress originated by the heat treatment was pointed out as the cause of type B deflection by Caplan and his co-workers⁽⁸⁾.

Type C: By Caplan and his co-workers⁽⁸⁾, type C deflection is attributed to the disagreement between the axis of ingot and the axis of forging, because the segregation zone that is inevitable in heavy forging eccentrically distributes in respect to the axis of forging, whereby the thermal expansion coefficient at various parts of the forging shows tangentially non-uniform distribution (Segregation theory).

Burton and his co-worker⁽⁷⁾ discovered in a

turbine rotor forging of Mo steel (0.30% C, 0.50% Mo) that the thermal expansion coefficient of the convexly deflected side (bainitic structure) is larger by $0.2 \sim 0.4 \times 10^{-6}/^{\circ}\text{C}$ than that of the concavely deflected side (Pearlitic structure). Barker and his co-worker⁽⁸⁾ reported the same conclusion as above. Further, with regard to the cause of this difference, Barker and his co-worker disclosed an opinion that the main carbide contained in the forging at the convexly deflected side is M_3C (M denoting metal), while M_{23}C_6 with a coefficient of thermal expansion of only one half of M_3C is the main carbide contained at the concavely deflected side. Thus, the difference of main carbide induces the difference of thermal expansion coefficient even though the chemical composition of both sides is quite similar (Carbide theory).

Besides the above, some reports⁽²⁾⁽⁹⁾ are available concerning type C deflection, but in brief, they belong to either the segregation theory⁽⁸⁾ or the carbide theory⁽⁸⁾. At present, the carbide theory seems to be generally accepted.

Type D: On the basis of the experimental result that the thermal conductivity of the concavely deflected side during the cooling period is larger by 2 to 2.5% than that of the convexly deflected side, Timo and his co-worker⁽²⁾ insist that tangentially non-uniform distribution of thermal diffusivity in the rotor forging is the cause leading to the deflection of this type.

Important previous studies described above are summarized in Table 9.

3. Experimental procedure and model test apparatus

In order to perform heat indication tests ten times with an actual rotor (rotors weighing more than 20 t are not rare), one year would be required at least. It may be considered that some of the previous studies were incomplete due to the impossibility of repeating the test sufficiently and due to the conclusions being derived from a limited number of tests. The authors took this fact in mind and prepared a small-sized model apparatus of heat indication test to promote efficiency of the test as well as to simplify the test condition.

The conclusions obtained by summarizing about 130 times of testing which was performed on the model apparatus were ascertained to be true by actual tests. Therefore, it becomes possible to solve the various problems concerning deflections in a limited duration of time.

The model test apparatus is shown in Figs. 3:

Fig. 2 The fundamental deflections of five types

and 4. An unbonded strain gauge type of transducer and an auto-balancing recorder are used in the measurement of deflection in the model test apparatus. Fig. 5 is an example of record chart obtained from the model apparatus, on which the deflection can be determined. The magnification of measurement was 2500 times and the precision of relative measurement of $\pm 0.5\mu$ was readily obtained.

The shapes and the chemical composition of model rotors used in these studies are respectively shown in Fig. 6 and Table 1.

Further experiments were principally performed by metallurgical techniques, for instance:

- (1) high precision measurement of thermal expansion coefficient,
- (2) studies concerning the carbides by electrolytic isolation,

Fig. 3 Model apparatus of heat indication test

(a) Whole view

(b) Furnace cover removed

(Numbers in photos are same as Fig. 3)
Fig. 4 The model apparatus of heat indication test

Fig. 5 An example of the experimental record by the model apparatus of heat indication test

X-ray diffraction, high temperature X-ray diffraction, extracted replicas and electron diffraction and others.

4. Experimental reappearance of deflections attributable to the metallurgical properties

At first, the deflections reappearing in the model rotors to which such treatments as will produce metallurgical non-uniformity had been applied are discussed in this chapter.

Tangentially non-uniform cooling was applied after tempering to two model rotors (1% Cr-1% Mo-V steel and 3% Ni-Mo-V steel). Only type B deflection was observed in the heat indication test of these model rotors, as shown in Fig. 7. Thus, Caplan and his co-workers' theory⁽⁸⁾ is confirmed; type B deflection is due to the relaxation of tangentially non-uniform residual stress.

Model rotor No. 1 in Table 1 was purposely machined in such a manner that the central axis of ingot and the axis of model rotor would be dislocated from each other and that a ring ghost would exist only on one side of certain diameter. The central axis of ingot was located, in this case, at the opposite side of the diameter. Thus, even the model rotor which had tangentially non-uniform segregation and forging effect showed no deflections in the heat indication test which was performed after applying normal heat treatment and finish machining.

Tangentially non-uniform normalizing and tan-

gentially uniform tempering were applied to six model rotors from No. 2 to No. 7 in Table 1. Type C deflection convex to faster cooling side was apparent in model rotors of Nos. 2, 3 and 4. Meanwhile, model rotors of Nos. 5, 6 and 7 which did not contain Mo as alloy element were found to be free from any deflection. As an example, type

Fig. 6 Machining shapes of model rotors

Test for the model rotor to which tangentially non-uniform cooling from tempering temperature was applied

Fig. 7 Reappearance of type B deflection (3% Ni-Mo-V steel)

Table 1 Chemical composition of model rotors

Model rotor	C	Si	Mn	P	S	Ni	Cr	Mo	V	Remarks
No. 1	0.28	0.36	0.43	0.020	0.019	2.88	0.07	0.39	0.08	{ Eccentric segregation Type C deflection which was caused by non-uniform normalizing was observed
No. 2	0.32	0.27	0.58	0.012	0.018	0.12	1.14	1.06	0.22	
No. 3	0.27	0.28	0.96	0.015	0.018	0.13	1.16	1.14	0.27	
No. 4	0.28	0.28	0.65	0.017	0.015	3.02	0.07	0.45	0.12	
No. 5	0.40	0.35	0.70	0.018	0.018	0.80	0.13	0.09	0.09	{ Type C deflection was not observed
No. 6	0.25	0.25	0.53	0.012	0.011	3.32	0.80	0.02	—	
No. 7	0.36	0.28	0.50	0.013	0.014	0.01	0.04	0.02	—	
No. 8	0.28	0.28	0.96	0.015	0.018	0.13	1.16	1.14	0.27	{ Eccentric tempering
No. 9	0.28	0.28	0.96	0.015	0.018	0.13	1.16	1.14	0.27	
No. 10	0.28	0.36	0.43	0.020	0.019	2.88	0.07	0.39	0.08	
1%Cr-1%Mo-V steel	0.27/0.37	0.15/0.35	0.70/1.00	<0.035	<0.035	<0.50	0.85/1.25	1.00/1.50	0.20/0.30	
3%Ni-Mo-V steel	0.25/0.35	0.15/0.35	0.60/0.80	<0.035	<0.035	2.50/3.00	<0.50	0.40/0.60	0.03/0.12	
Carbon steel	0.36	0.28	0.50	0.013	0.014	0.13	0.04	0.02	—	

C deflection reappearing in the model rotor No. 2 is shown in Fig. 8.

A deflection attributable to tangentially non-uniform tempering can be assumed from the result⁽¹⁰⁾ of the basic research concerning the relation between the thermal expansion coefficient of low alloy steels and the heat treatment.

Tangentially non-uniform tempering after uniform normalizing was applied to the model rotor No. 8 shown in Table 1.

In this case, only type C deflection was substantially observed as will be seen in Fig. 9 (b). Type A deflection in Fig. 9 (c) will be explained later in chapter 6.

It is one of the most important conclusions that only types B and C of deflection appear in the model rotors given all sorts of non-uniform metallurgical properties. And the other results are as follows:

(1) Model rotors to which the non-uniform residual stress was applied showed only type B deflection.

(2) Tangentially non-uniform segregation and forging effect can not be the case for any type of deflections.

(3) Model rotors to which the tangentially non-uniform normalizing was applied showed only type C deflection, if Mo was contained as one of alloy elements.

(4) Model rotor to which tangentially non-uniform tempering was applied showed only type C deflection.

(a) Test for the rotor to which normal tempering and machining with finishing tool were applied after normalizing in tangential non-uniformity
(b) Successive test after 1st test

Fig. 8 Reappearance of type C deflection (model rotor No. 2)

5. The cause of type C deflection by non-uniform normalizing

5.1 Tested forging

The rotor forging of 66MW high pressure turbine shown in Fig. 10 was selected in this study. Since type C deflection of 0.06 to 0.08 mm at 575°C was observed in 9 consecutive heat indication tests

(a) Test for the model rotor which was normally quenched and tempered (1000°C×5 hrs, A.C., 620°C×20 hrs, F.C.) and was machined with finishing tool
(b) Test for the same one which was added non-uniform re-tempering (A side: 690°C×20 hrs, C side: 620°C×20 hrs) and was grinded after 1st test
(c) Successive test for the same one which was re-machined with finishing tool after 2nd test
(d) Successive tests of two times after 3rd test
(e) Successive test for the same one which was plated with Ni on its finishing re-machined surface (Compare with the result of 3rd test)

Fig. 9 Test results of model rotor No. 8 which showed the tangentially non-uniform distribution of hardness due to eccentric tempering

several years ago, the rotor forging was preserved for the metallurgical experiments.

5.2 Metallurgical properties of tested forging

If there is a difference of $10^{-7}/^{\circ}\text{C}$ at least in the thermal expansion coefficient between the convexly deflected side and the concavely deflected side (merely to be referred to convex side and concave side hereafter), it can be presumed from a simple calculation that the type C deflection in question would naturally be obtained. Measurements of thermal expansion coefficients at the convex and concave sides were performed by the thermal dilatometer of high precision prepared specially for this purpose. This dilatometer is the improved one which was introduced by Masumoto and his co-worker⁽¹¹⁾. It is confirmed that the thermal expansion coefficient at any position of the convex side is larger by 0.15 to $0.20 \times 10^{-6}/^{\circ}\text{C}$ than that of the concave side as shown in Table 2.

Concerning the radial distribution of hardness of the convex and the concave sides, no appreciable difference was found between the two sides. The only difference, if any, is that the convex side can be judged just slightly harder than the concave side in the inner part near the axis more than 150 mm from the forging surface.

Microstructure is tempered bainite as a whole. As an example, typical microstructures at the convex side and concave side of the test piece No. 5

C	Si	Mn	P	S	Ni	Cr	Mo	V
0.30	0.29	0.44	0.022	0.027	0.07	0.95	1.03	0.28

▽ : Position measured the deflection
Fig. 10 Chemical composition and shape of 66MW high-pressure turbine rotor forging which showed the type C deflection of 0.06~0.08 mm

in Fig. 10 are shown in Fig. 11. However, a ferritic transformed product is present in the inner part. The presence of this product was observed to be more evident at the concave side than at the convex side by measuring with the point counting method⁽¹²⁾. Thus, relatively speaking, the microstructure of the convex side may be called bainitic and the microstructure of the concave side may be called pearlitic as was stated by Barker and his co-worker⁽⁸⁾.

Examination of the carbides contained in the rotor forging by means of combined extraction replica⁽¹³⁾ and electron diffraction of selected area, and combined electrolytic isolation and X-ray diffraction revealed that the carbide distribution was exactly the same both in the convex side and the concave side as shown in Fig. 12, and the main carbide in this rotor forging was M_3C with VC and Mo_2C contained as the co-existing carbides.

The chemical composition of carbide electrolytically isolated by the hydro-chloride method⁽¹⁴⁾ is shown in Fig. 13. The concentration of each alloy element in matrix is shown in Fig. 14. This result was calculated from the chemical composition of carbide. While Mn and Cr were dissolved in carbide and matrix, V totally concentrated in the carbide did not dissolve in the matrix to any appreciable amount. It is one of the important results that the concentration of Mo in the matrix at the convex side was approximately 0.3 %, and the concentration of Mo in the matrix at the concave side was 0.1 to 0.15 %.

5.3 Thermal expansion coefficient of Fe-Mo alloy

It is notable that the quantity of Mo dissolved in the matrix is large at the convex side (approximately 0.3 %), and is small at the concave side (0.1~0.15 %). Fe and Fe-Mo alloys containing 0.005 to 0.006 % C and little impurities respectively were prepared as test materials, so that the effect of carbides and others on the thermal expansion coefficient would be avoided. A dilatometer of 10 000 magnification was used for the measurement of

Table 2 Thermal expansion coefficients of convex and concave sides of rotor forging, with type C deflection, which is shown in Fig. 10

Test piece	No. 2		No. 4		No. 6	
	Convex side	Concave side	Convex side	Concave side	Convex side	Concave side
	$12.32 \times 10^{-6}/^{\circ}\text{C}$	$12.20 \times 10^{-6}/^{\circ}\text{C}$	$12.36 \times 10^{-6}/^{\circ}\text{C}$	$12.07 \times 10^{-6}/^{\circ}\text{C}$	$12.31 \times 10^{-6}/^{\circ}\text{C}$	$12.12 \times 10^{-6}/^{\circ}\text{C}$
	12.26 "	11.96 "	12.15 "	12.04 "	12.33 "	12.06 "
	12.19 "	12.09 "	12.45 "	12.06 "	12.30 "	12.09 "
	12.13 "	12.14 "	12.36 "	12.00 "	12.36 "	12.18 "
			12.35 "	12.23 "	12.23 "	12.12 "
Mean value	12.23 "	12.10 "	12.33 "	12.08 "	12.31 "	12.12 "

thermal expansion coefficient of these alloys. This dilatometer is almost the same with the one introduced by Doonley and his co-worker⁽¹⁵⁾ in its principle of operation and its recording device of temperature and elongation by an X-Y recorder

with the aid of a differential transformer. Fig. 15 shows the external view of the dilatometer. The effect of dissolved Mo on the thermal expansion coefficient of pure Fe is shown in Fig. 16. It was found that the thermal expansion coefficient of

Fig. 11 Comparison of microstructures between convex side and concave side of rotor forging showing type C deflection (An example of test piece No. 5 in Fig. 10), $\times 80$

Fig. 12 Comparison of X-ray diffraction pattern of carbide between convex side and concave side of rotor forging showing type C deflection (Result of test piece No.5 in Fig.10)

Fig. 13 Comparison of alloy elements in carbide between convex side and concave side of rotor forging showing type C deflection

Fe-Mo alloy increased by approximately $0.5 \times 10^{-6}/^{\circ}\text{C}$ as 0.5 % Mo dissolved in Fe.

5.4 Thermal expansion coefficient of carbides M_3C and M_{23}C_6

In the case of 1%Cr-1%Mo-V steel, it has

Fig. 14 Comparison of alloy elements in matrix between convex side and concave side of rotor forging showing type C deflection

been ascertained that the main carbide of tempered martensite and tempered bainite is M_3C and the main carbide of pearlitic structure is M_{23}C_6 ⁽¹⁰⁾. The X-ray diffraction patterns of carbide M_3C and M_{23}C_6 at high temperatures which were electrolytically isolated from the 1%Cr-1%Mo-V steel are shown in Fig. 17. The thermal expansion coefficients of carbide M_3C and M_{23}C_6 determined from the X-ray diffraction patterns at high temperatures are presented in Table 3. These values were calculated by extrapolating the diffraction angle

Table 3 Thermal expansion coefficients of M_3C and $M_{23}C_6$, isolated electrolytically from 1%Cr-1%Mo-V steel, which were calculated from high temperature X-ray diffraction patterns

Carbide		Mean value of thermal expansion coefficient	
		Room temp. $\sim 200^\circ\text{C}$	Room temp. $\sim 400^\circ\text{C}$
M_3C (Orthorhombic)	Direction of a	$10.0 \times 10^{-6}/^\circ\text{C}$	$8.3 \times 10^{-6}/^\circ\text{C}$
	Direction of b	9.8 "	15.0 "
	Direction of c	12.6 "	12.6 "
	Volume thermal expansion coefficient : β	32.3 "	35.9 "
	Linear thermal expansion coefficient : $\alpha \approx \beta/3$	10.8 "	12.0 "
$M_{23}C_6$ (Cubic)	Volume thermal expansion coefficient : β'	60.0 "	64.9 "
	Linear thermal expansion coefficient : $\alpha' \approx \beta'/3$	20.0 "	21.7 "

- ① Detector of elongation and temperature
- ② Elongation-temperature X-Y recorder
- ③ Elongation-time recorder
- ④ Voltage stabilizer

Fig. 15 Electronic dilatometer

Fig. 16 Effect of dissolved Mo on the thermal expansion coefficient of pure Fe (Carbon content: 0.005~0.006 wt %)

Fig. 17 High temperature X-ray diffraction patterns of carbides M_3C and $M_{23}C_6$ which were electrolytically isolated from 1%Cr-1%Mo-V steel

of 2θ up to 180° with the least square method which was introduced by Cohen⁽¹⁶⁾ in order to compensate the theoretical and systematic errors contained in the technique of X-ray diffraction.

A comparison between the thermal expansion coefficients of M_3C and $M_{23}C_6$ shows that the coefficient of $M_{23}C_6$ is twice as large as that of M_3C , contrary to the opinion of Barker and his co-worker⁽⁸⁾ that the thermal expansion coefficient of M_3C is approximately twice as large as that of $M_{23}C_6$.

5.5 Summary

It can be concluded from the experimental results described above in this chapter that the carbide theory is not acceptable as the explanation of type C deflection.

(1) Type C deflection appears even if the carbides in convex and concave side are exactly the same.

(2) The trend of thermal expansion coefficients of carbides M_3C and $M_{23}C_6$ in the carbide theory⁽⁸⁾ can not be accepted.

When the distribution of Mo dissolved in the matrix of actual rotor forging as explained in section 5.1, and effect of Mo on the thermal expansion coefficient of pure Fe as shown in section 5.3 are considered, type C deflection is attributable to the tangential non-uniformity of dividing rate of Mo to carbide and matrix, namely, to the tangentially non-uniform distribution of Mo dissolved in matrix. In the case of a steel containing approximately 1% Mo, type C deflection appears convexly to the side of high Mo concentration in matrix. Of course, the tangentially non-uniform normalizing is pointed out as the defect of production process of rotor forgings.

Such Mo theory concerning type C deflection explains the experimental results described in chapter 4 without contradiction.

6. Introduction of type C' deflection and the causes of type A, D and C' deflections

It was indicated in chapter 4 that only types B and C are the deflections attributable to the metallurgical defects of forgings. Concerning the condition of present heat indication test, the deflections attributable to the thermal blackness or thermal emissivity of forging surface in tangential non-uniformity are discussed in this chapter.

6.1 Introduction of type C' deflection

If there is any difference in the thermal blackness on the surface at the both ends of certain diameter and the average temperature of forging is kept at an elevated temperature, the temperature

distribution on the cross section including the diameter is considered to be as shown in Fig. 18. Consequently, it follows that there have to be a deflection which is similar in behaviour to type C deflection at the elevated temperature. However, this deflection is rapidly decreased when the cooling process is started. This type of deflection is tentatively named as C' by the authors. When the emissivity of forging surface is tangentially non-uniform, there exist quasi-steadily the side of high temperature and the side of low temperature. This is assumed to be the cause of type C' deflection.

6.2 Reappearance of types A, D and C' deflection

Model rotors No. 9 and No. 10 in Table 1 were

Fig. 18 Temperature distribution which is presumed the cause of type C' deflection

(a) Test for the model rotor which was eccentrically machined with finishing tool on purpose
(b) Test for the same one which was roughly machined
(c) Successive test after 2nd test
Fig. 19 Test results of normally quenched and tempered model rotor No. 9 to which two kinds of machining were applied

eccentrically machined with a finishing tool on purpose. Then the residual stresses by machining were determined by X-ray diffraction technique to

Table 4 Residual stresses of machined surface of model rotors which were measured by X-ray diffraction method

Model rotor	Position on periphery	Axial direction kg/mm ²	Tangential direction kg/mm ²	Result of heat indication test
No. 9	A	-24	-19	Fig.19 (a)
	B	-10	-10.5	
	C	-21	-11	
	D	-26	-16	
No.10	A	-3	-1	Fig.22 (a)
	B	-21	-18	
	C	-11	-13	
	D	5	9

- (a) Test for the model rotor which was plated with Ni of about 10 μ thickness on its half periphery of finishing machined surface
 (b) Successive test after 1st test
 (c) Successive test after 2nd test
 (d) Successive test for the model rotor on which scale of half periphery (D-A-B) was stripped by emery paper after 3rd test

Fig. 20 Test results of normally quenched and tempered model rotor (3%Ni-Mo-V steel) which was non-uniformly plated with Ni

confirm the tangential non-uniformity of machined surface layer. The results are shown in Table 4. However, these model rotors did not produce type A deflection and any other deflection, either. It was clarified that the eccentric residual stress caused by machining could not be the origin of any deflections [Fig.19 (a) and Fig.22 (a)]. Also, it was a significant result that type A deflection was caused in the model rotor which was machined roughly as shown in Fig.19 (b). But, it should be noticed that no deflection was observed in successive tests as shown in Fig.19 (c).

It is natural that non-uniform thermal emissivity of forging surface is one of the causes to some deflections. Three types of deflection were observed with a model rotor which was plated with Ni on its half periphery as shown in Fig.20. Therefore, heat indication model tests were performed by use of model rotors in which the conditions as close as

- (a) Test for the model rotor which was oiled on its half periphery of finishing machined surface
 (b) Successive test after 1st test
 (c) Successive test after 2nd test
 (d) Successive test after 3rd test

Fig. 21 Test results of the model rotor (3% Ni-Mo-V steel) in normal quenched and tempered condition which was non-uniformly contaminated with machine oil

possible to those of actual rotors were reproduced.

At first, it was confirmed that the model rotors, to which normal heat treatments and careful finish machining were applied, showed no deflection. Subsequently, type A, D or C' deflection appeared in such model rotors to which either one of the following conditions was applied.

(1) Tangentially non-uniform contamination of rotor surface by machine oil, paint, mud, dust or others.

(2) Partial removal of the scale on rotor surface.

(3) Non-uniform surface roughness.

The heat indication model tests were performed over 70 times by using model rotors to which the above non-uniform properties of surface were given. Some of the results are shown in Figs. 21, 22, 23,

- (a) Test for the model rotor which was eccentrically machined with finishing tool on purpose
(b) Test for the same one on which scale of half periphery (C-D-A) was stripped by emery paper after 1st test
(c) Successive test after 2nd test
(d) Successive test after 3rd test (stopped at 350°C as no deflection appeared)

Fig. 22 Test results of the model rotor No. 10 in normally quenched and tempered condition which was eccentrically machined or was eccentrically descaled

24 and 25.

In Fig. 20, two kinds of type D deflection are notable. One is the deflection in the opposite directions to each other at heating and cooling as

- (a) Test for the model rotor of which surface of half periphery was polished with #29 emery paper after finished grinding
(b) Successive test after 1st test
(c) Successive test after 2nd test

Fig. 23 Test results of the model rotor (3% Ni-Mo-V steel) in normally quenched and tempered condition which shows non-uniform surface roughness (Part 1)

- (a) Test for the model rotor which was polished its surface of half periphery (B-C-D) with #400 emery paper and its residual surface of half periphery (D-A-B) with #29 emery paper
(b) Successive test after 1st test

Fig. 24 Test results of the model rotor in normally quenched and tempered condition which shows non-uniform surface roughness (Part 2)

will be seen in Figs. 20 (a), (b) and (c), and the other is the deflection in the same directions at heating and cooling as shown in Fig. 20 (d).

Fig. 26 is the condition of rotor surface before the tests shown in Fig. 9 (b) and (c). From this difference in surface roughness, the cause of type A deflection in Fig. 9 (c) could be found. Consequently, the cause of type A deflection in Fig. 19 (b) could be similarly assumed. Type A deflection did not appear [Fig. 9 (e)] when the model rotor was uniformly plated with Ni even if the surface was in such a condition as shown in Figs. 26 (c) and (d).

Vibration marks by the cutting tool have to be considered as one of the causes of these three types of deflection in actual heavy rotor forgings.

Most of thermal emissivity in tangential non-uniformity attributable to the above conditions could be uniformly improved by heating of a short period. However, some of them could not be improved by heating of a short period.

Furthermore, types A, D and C' of deflection may differ only in their period of appearance and are essentially the same in respect of their causes. It is confirmed by the model tests that these three

types of deflection are sensitively affected by a slight non-uniformity of surface condition.

- (a) Test for the model rotor which was polished its surface of half periphery (D-A-B) with #180 emery paper and its residual surface of half periphery (B-C-D) with #29 emery paper
(b) Successive test after 1st test

Fig. 25 Test results of the model rotor (3% Ni-Mo-V steel) in normally quenched and tempered condition which shows non-uniform surface roughness (Part 3)

Finish by grinding, surface condition before the test in Fig. 9 (b)

Finish by turning, surface condition before the test in Fig. 9 (c)
Fig. 26 Microscopic surface roughness of the model rotor, ($\times 60$)

7. Further factors affecting the magnitude of type A, D and C' deflections

7.1 Effect of geometrical shape of rotor body on the magnitude of types A, D and C' deflections

Table 8 (b) shows the results of heat indication test conducted during 1958~1961 in the authors' plant. In spite of the improved heat treatment by which most of types B and C deflections are eliminated, type A and D deflections are still observed. The magnitude of type A deflection of turbine rotor forging decreases in the order of high-, medium- and low-pressure ones. Type D deflection appears only in high- and medium-pressure rotor forgings, and does not in low-pressure ones. This tendency has been generally accepted, and has led to a proposal of explaining the cause of type D deflection; 1%Cr-1%Mo-V steel for a rotor

Table 5 Characteristics of shape of rotor forging in the heat indication test

Rotor forging	Depth of slit Width of slit
High-pressure turbine	0.5~2.0
Medium-pressure turbine	1.5~2.5
Low-pressure turbine	2~3
Marine turbine	3~5

Test conditions are as follows

- (1) Scale only on the surface of half periphery was stripped after baked at 575°C
- (2) Surface of half periphery was oiled after finished machining
- (3) Scale only of slit bottom of half periphery was stripped after baked at 575°C
- (4) Scale only on the top of disk (external surface of disk) of half periphery was stripped after baked at 575°C

Fig. 27 Effect of the body shape of model rotor (Fig. 6 (b)) on the magnitude of type A deflection

forging of high- and medium-pressure turbine is more susceptible to type D deflection than 3% Ni-Mo-V steel for a rotor forging of low-pressure turbine.

Fig. 6 (b) shows the machined shapes of the model rotors (carbon steel in Table 1) with six different diameters; 320, 260, 220, 200, 180 and 160 (flat) mm. These model rotors were used in the following experiments.

Three kinds of surface conditions were applied to the six model rotors:

- (a) half periphery of body baked at 575°C was carefully descaled by emery paper,
- (b) half periphery of body after finish machining was made dirty with machine oil,
- (c) half periphery of body baked at 575°C was descaled only along the slit bottom surface by emery paper.

The results of 18 experiments are summarized in Fig. 27; the magnitude of type A deflection is shown as a function of slit depth. The fact that the deflection decreases as the slit depth increases may presumably be explained by the following reasons.

(a) The difference of thermal blackness along the periphery of disks brings a tangential non-uniformity of temperature in the outer part of disks. But, the thermal distortion due to this temperature distribution decreases rapidly with increase of the disk depth.

(b) The temperature difference along the slit bottom surface decreases as the slit depth increases for the same thermal blackness of slit bottom. Consequently, the deflection decreases. These results for type A deflection is legitimate for types D and C' deflections having the same origin of appearance.

Table 5 shows an example of depth-width ratio of slit for actual rotors at the time of heat indication test. By considering these ratios in Table 5 and the result of Fig. 27, it is concluded that the rotor forging of high pressure turbine is the most susceptible to the deflections attributable to the surface emissivity, as the depth-width ratio of slit is the lowest.

7.2 Effect of rate and mode of heating on the magnitude of types A, D and C' deflections

Effect of heating rate: A model rotor of 3% Ni-Mo-V steel with standard shape [Fig. 6 (a)] was plated with Ni along its half periphery and baked at 575°C for 2 hours. It was already confirmed by the experiments in Figs. 20 (b) and (c) that the model rotor treated similarly to as the above shows the same deflections under the same test conditions. The model rotor was tested with heating and

cooling rate of $30^{\circ}\text{C}/\text{hour}$, of which the result is shown in Fig. 28 (a). Then two layers of asbestos for thermal shield were put between nichrome wire

for heating and the model rotor. The second test revealed small deflections of types A and C'. The third test was conducted with heating and cooling

rate of $120^{\circ}\text{C}/\text{hour}$ without a thermal shield of asbestos. In this case, the largest deflection was seen as shown in Fig. 28 (c).

Effect of heating mode: The same rotor was descaled with emery paper. An oil tank which was filled with lubricant oil was placed at the bottom of the furnace so that one third of rotor diameter (vertically) might be dipped in the oil. The results of oil-bath heating are shown in Fig. 29 (a). Then the oil tank was removed and a test by ordinary nichrome wire heating was performed with the same heating and cooling rates. The results are shown in Fig. 29 (b). Figs. 28 (a), (b) and Fig. 29 show that the types A, D and C' deflections become larger with increase of radiation to be replaced by thermal conduction and convection.

Effect of distance between the furnace heating source and rotor: Five disked rotors in Fig. 6 (b) were baked at 575°C , and

the scale was removed by emery paper only around the half periphery of the tops of disks. The result shows that the deflection becomes smaller with increasing disk diameter to some extent, and increases again with further increase of disk diameter as shown in Fig. 27. This latter fact comes from the shorter distance between the surface of rotor forging and the heating source which brings an increased view factor of radiation. Rise of nichrome wire temperature by rewinding brings similar result.

7.3 Summary

The magnitudes of types A, D and C' deflections are affected by the geometrical shape of rotor forging and the heating mode. Experiments described in this chapter offer a clear explanation for many phenomena in actual heat indication test practice.

8. A confutation to the thermal diffusivity theory as the cause of type D deflection

As introduced in chapter 2, papers concerning

The model rotor (3% Ni-Mo-V steel) of which surface of half periphery was plated with Ni was used after baked at 575°C , and test conditions are as follows.

- (a) Heating and cooling rates were $30^{\circ}\text{C}/\text{hour}$ under ordinary test condition
- (b) Two thermal shield plates of asbestos were placed between model rotor and nichrome wire heat source
- (c) Same condition as 1st test except heating and cooling rates of $120^{\circ}\text{C}/\text{hour}$

Fig. 28 Effects of test conditions on the magnitude of type A, C' and D deflections (Part 1)

The model rotor (3% Ni-Mo-V steel) of which surface of half periphery was plated with Ni was used, and test conditions are as follows.

- (a) Heating and cooling by deeping one third of diameter in oil bath
- (b) Ordinary heating and cooling by nichrome wire

Fig. 29 Effect of test conditions on the magnitude of type A, C' and D deflections (Part 2)

type D deflection are published only on the thermal diffusivity theory⁽²⁾, which points out some metallurgical defects of rotor forging. Meanwhile, every experiment in the previous chapters shows that type D deflection is attributable to the surface condition of rotor forging. In this chapter re-experiments and direct confutation to the thermal diffusivity theory are attempted.

8.1 Scope and precision of experiment

Timo and his co-worker⁽²⁾ observed a difference of 2 to 2.5 % in the thermal conductivity of convex and concave sides of rejected rotors due to type D deflection, from which their thermal diffusivity theory has been derived. For the complete criticism on this theory, a precision of $\pm 1\%$ in the measurements of thermal diffusivity is required, which means necessarily precisions of $\pm 0.5\%$ for thermal conductivity and specific heat and $\pm 0.1\%$ for specific weight. These measurements are one of the most difficult experiments, even if the best techniques of the present day are used.

8.2 Effect of tempering temperature on the thermal conductivity

Experimental method: A comparison method was adopted for the measurement of thermal conductivity from the standpoint of both feasibility and precision. The arrangement used in present experiments is shown in Fig. 30. This is a modification of the apparatus used by Powell and

his co-worker⁽¹⁷⁾.

Denote the heat conductivity, length and temperature of test piece and standard piece, as λ and λ' , l_1 and l_2 , T_1 , T_2 , T_3 and T_4 , respectively (Fig. 30), then the heat which flows through the sectional area F in time Δt will be

$$Q = \lambda \frac{(T_1 - T_2) F \Delta t}{l_1} = \lambda' \frac{(T_3 - T_4) F \Delta t}{l_2},$$

so

$$\lambda = \lambda' \frac{l_1}{l_2} \frac{(T_3 - T_4)}{(T_1 - T_2)}.$$

Thus the heat conductivity λ of test piece can be calculated from the known and the measured values.

The precision of measurements is 0.1°C for temperature by the use of potentiometer and 0.05 mm for length by a micrometer. The temperature differences between 1 and 2, 3 and 4, 6 and 7 in Fig. 30 were controlled by external nichrome wire within 0.1°C . It took at least 24 hours in order to obtain the temperature difference within 0.1°C . Test piece was mated with the standard piece in cup-and-corn fit leaving a small space filled with molten wood's metal* (Fig. 31), so as to keep the

- ①~⑦ Thermo-couple ⑪ Nichrome wire heating coil
 ⑧ Copper rod ⑫ Porcelain cylinder
 ⑨ Test piece ⑬ Diatomite flak insulator
 ⑩ Standard piece

Fig. 30 Apparatus for measurement of thermal conductivity by longitudinal heat flow method

Fig. 31 Joining part of test piece and standard piece

* 12.5% Sn and Cd, 25% Pb and 50% Bi. In none of the experiments the joint space went down below the melting point of 61°C

smooth heat flow sufficiently uni-axial. It is estimated that the integrated precision is $\pm 0.7\%$ or so. And this estimation was proved to be true with slight deviation by the reproducibility of experiments. Thus, it is confirmed that the thermal conductivity can be obtained within a relative error of $\pm 1\%$.

1%Cr-1%Mo-V steel and 3%Ni-Mo-V steel in Table 6 were used as the test piece. Carbon steel in annealed condition in Table 6 was also used as the standard test piece, of which the thermal conductivity is referred to the value in Metal Handbook⁽¹⁸⁾.

Result: Figs. 32 and 33 are the results of conductivity measurement with the change of hardness. The diagrams show the influence of temperature and time of tempering on the thermal conductivity. The increase of conductivity is about 5% for the rise 50°C of tempering temperature in 1%Cr-1%Mo-V steel and 3.5% for 80°C in 3%Ni-Mo-V steel.

Since the tangential non-uniformity of tempering temperature of actual rotor forging in the authors' plant, and possibly in any plant in the free world is not over 10°C in practice, it could be stated that surveys on actual rotors will never show a conductivity difference over 1% along their periphery. Also, tangentially non-uniform normalizing

was only the cause of type C deflection as described in chapters 4 and 5. Consequently, Timo and his co-worker's observation⁽²⁾ is now doubtful.

8.3 Results of heat indication test on model rotors eccentrically tempered

The experiments in Fig. 9 were again referred to. The model rotor to which tangentially non-uniform re-tempering was applied showed a small type C deflection in the test with heating and cooling rates of 120°C/hour, but no type D deflection [Fig. 9(b)]. In this model rotor, the thermal conductivity of side A is higher than that of side C by more than 5%. According to Timo and his co-worker's result, the model rotor should have shown type D deflection convexly to side C during cooling.

8.4 Summary

The thermal conductivity theory⁽²⁾ (Thermal diffusivity theory, to be more exact) has been denied by the results of precise measurement of thermal conductivity followed by a corresponding heat indication model test. The confutation is also supported by both the experimental results in the preceding chapters and experience in our plant practice described in chapter 9.

Table 6 Chemical composition of test pieces of which thermal conductivity was measured and standard piece

	C	Si	Mn	P	S	Ni	Cr	Mo	V
Test piece : 1%Cr-1%Mo-V steel	0.30	0.35	0.80	0.017	0.019	0.45	1.06	1.18	0.25
Test piece : 3%Ni-Mo-V steel	0.30	0.32	0.56	0.016	0.014	2.88	0.11	0.35	0.08
Standard piece : Carbon steel	0.29	0.20	0.51	0.012	0.006	0.10	0.05	0.02	—

Fig. 32 Effect of temperature and time of tempering on the thermal conductivity and hardness of quenched 1%Cr-1%Mo-V steel

Fig. 33 Effect of temperature and time of tempering on the thermal conductivity and hardness of quenched 3%Ni-Mo-V steel

9. Improvement through the actual practice

Thus far, problems in the heat indication test have been clarified by the conclusion of fundamental studies that there are two groups of deflections: types B and C deflections which required some remedial treatments for improvement are attributable to the metallurgical defects of forging, while types A, D and C' deflections which are quite harmless and can be eliminated by simple procedure are attributable to the surface condition of forging.

We will now come back again to the starting point. We have been studying to settle the troubles in the heat indication test utilizing model rotors. Now the results of fundamental researches should be applied to actual test for improvement of the practice.

9.1 Recommendations on type B deflection

As a matter of general plant practice, a rotor which happened to reveal type B deflection would not show type B deflection any more, if the successive heat indication test was done without machining. However, it has to be noticed that a few exceptional cases exist. For example, a rotor forging of 150 MW medium-pressure turbine was tested with a 5 mm allowance of machining and no deflection appeared. However, type B deflection of 0.09 mm was observed in the second test after rough machining to a 2 mm allowance with a grooved labyrinth.

Even if the residual stresses are inevitable in

large forgings and type B deflection is discovered the test of a steel maker, a rotor forging has generally a sufficient allowance of finish machining. Remaining eccentricity can be eliminated by the finish machining at a turbine maker. In addition, the heat treatments are performed carefully to minimize type C deflection. Such heat treatments are expected at the same time to prevent type B deflection.

It can be safely mentioned that the appearance of type B deflection is remediable without re-heat-treatment, and no re-test is required at the steel plant.

9.2 Recommendation on type C deflection

As described in chapter 4, type C deflections are classified into two groups; one is caused by eccentric normalizing, the other by tangentially non-uniform tempering. In both cases the heat treatment is required to eliminate them, which

(a) A rotor forging of 156 MW turbo-generator

(b) A rotor forging of 175 MW high-pressure turbine

Fig. 34 Shapes of tested actual rotor forgings.

(a) Appearing of typical type C deflection
(b) Result of same forging after re-tempering (disappearance of type C deflection)

Fig. 35 Test results of 156 MW turbo-generator rotor forging

Table 7 Chemical composition of actual rotor forgings

Rotor forging	C	Si	Mn	P	S	Ni	Cr	Mo	V
156 MW turbo-generator rotor forging	0.25	0.30	0.57	0.012	0.021	2.94	0.09	0.31	0.08
175 MW high-pressure turbine rotor forging	0.32	0.31	0.50	0.014	0.024	0.50	0.96	1.08	0.27

means that the type C deflection is caused by the metallurgical defects of rotor forging. The results obtained through fundamental experiments are directly applicable to the actual practices, as follows.

(1) Repetition of the heat indication test is of no use for the rotor forging with type C deflection. Any additional heat indication test would result in the same magnitude and direction of deflection.

(2) The type C deflection due to eccentric

normalizing will presumably be eliminated by tempering 5 000 to 10 000 hours. As such a long period of tempering is impossible, of course, from the economical standpoint, re-normalizing is recommended to eliminate this type of deflection.

(3) The type C deflection due to eccentric tempering can be remedied by re-tempering at slightly higher temperature. For example, type C deflection of 0.075 mm was found at 156 MW generator rotor forging of which chemical compositions and shape in the test were shown in Table 7 and in Fig. 34 (a) respectively. However, this type C deflection was completely eliminated by re-tempering at slightly higher temperature than the nominal tempering temperature [Fig. 35 (b)].

(a) Scale which was partially stripped
(b) Scale which embossed partially and did not stick to forging surface
(c) Scale which adhered closely to forging surface

Fig. 36 Three types of scale which grew on forging surface during a test

(a) Forging surface on which scale was partially stripped
(b) Forging surface on which scale was almost stripped
(c) An example of covering with scale which did not stick to forging surface

Fig. 37 Forging surface conditions after the test which was started with little attention to the surface

Consequently, it is recommended that a rotor forging with type C deflection should be re-tempered at higher temperature at first, and when the deflection is not improved by re-tempering, a re-normalizing and tempering should be tried as a second step.

(4) Precautions should be taken with respect to the type C' deflection which shows the similar behaviour to that of type C and is originated by the condition of forging surface as described in section 6.1.

9.3 Trials to eliminate types A, D and C' deflections

Types A, D and C' deflections depend on the non-uniformity of thermal emissivity which is caused by little contamination and others summarized in Table 9. For example, three kinds of condition of scale as shown in Fig. 36 are observed on the forging surface after a test. As the actual rotor forging is heated for a long time in a heat

indication test, the change of scaling conditions; the local dropping-off and re-scaling phenomena as shown in Fig. 37, are recognized during and after the test. Type A deflection is the largest and type D and C' deflections get smaller in the order mentioned under the same condition of the test. This is qualitatively explained by the fourth power law of heat radiation. Thus, the experiments to eliminate the deflections are performed in the order of types C', D and A.

Elimination of types C' and D deflections: Even if a rotor forging showed type C' or D deflection, light machining to remove the scale of forging surface is sufficient in most cases to eliminate the types D and C' deflections in the next test. However, the following should be fully

- (a) Test forging which was machined with finishing tool
- (b) The forging just before 1st test, on which surface the silicaron graphite was coated by sprayer
- (c) The forging after 1st test

Fig. 38 The surface condition of the rotor forging of 175 MW high-pressure turbine before and after 1st test of which result was shown in Fig. 41 (a)

- (a) Test forging which was re-machined with finishing tool
- (b) The forging after 2nd test

Fig. 39 Surface conditions of the rotor forging of 175 MW high-pressure turbine before and after 2nd test of which result was shown in Fig. 41 (b)

Fig. 40 Coating practice of the silicaron graphite by sprayer

considered.

(1) Holding time at the temperature of over 500°C must be long enough in the test, because the surface of rotor forging should be covered sufficiently with uniform scale.

(2) It is inadvisable to strip or emboss the scale from the forging surface.

The two conditions stated above are contradictory and it is very difficult to conduct such a heat indication test as may satisfy concurrently the above conditions. The black uniform coating was devised to avoid the effect of the non-uniformity of thermal emissivity.

Elimination of type A deflection (also C' and D): An example will be shown to explain the new technique. A rotor forging of 175 MW high-pressure turbine (Table 7 and Fig. 34 (b)) was machined with ordinary finish (Fig. 38 (a)) and was coated uniformly with the silicaron graphite* by the sprayer while it was turned on the test equipment before the test starting (Fig. 38 (b)). Fig. 40 shows the practice of coating with the silicaron-graphite. The test of this rotor forging with heating and cooling rates of $100^{\circ}\text{C}/\text{hour}$ did not reveal any deflection (Fig. 41 (a)). Scale stripped from forging

surface could not be observed after the test as shown in Fig. 38 (c). Then the rotor forging was lightly machined again (Fig. 39 (a)), and the second test was started with no coating. Fig. 41 (b) is the result of the second test in which types A and D deflections are observed. Surface condition of forging after the second test is rough and non-uniform as shown in Fig. 39 (b).

Table 8 is the recent result of the heat indication test at the authors' plant. It is recognized from Table 8 that the treatment by the silicaron-graphite is one of the best techniques to eliminate the types A, D and C' deflections. Also, one of the most important conclusions in this study that there is no deflection of type A, D or C' attributable to the metallurgical defect of rotor forging has been confirmed from Table 8. It goes without saying that all of types A, D and C' deflections shown in Table 8 (b) were eliminated by applying the silicaron graphite process.

9.4 Summary

Experiments with actual rotor forging were intended here to confirm by the actual practice in works that the deflections should be and could be distinguished into two groups; one includes types A, D and C' deflections which are harmless in the rotor and the other does types B and C deflections which are caused by the metallurgical defects of rotor forging. It is necessary to consider that there are a lot of problems in the procedure and result of the heat indication test performed presently under the conditions dissimilar to those under which the steam turbine rotor and the generator rotor are operated.

10. Proposals for a modified specification of heat indication test

Researches in both laboratory and works practice have systematically solved almost all of the problems concerning the heat indication test. In this line a modified specification for the heat indication test is proposed. The items on which particular stress is laid are as follows.

(1) Types A, D and C' deflections should be permitted without any conditions. Because these deflections are not attributable to the substantial defect, and further could completely be eliminated by the silicaron graphite process, if necessary.

(2) If type C deflection is observed, re-heat-treatment and re-test are necessary

(3) When type B deflection is observed, notice type C deflection. If the type C deflection is not of harmful magnitude, or does not exist at all, type B deflection should be permitted, and no

- (a) Test for the forging which was coated with silicaron-graphite on its finishing machined surface
(b) Test for the same one which was re-machined with finishing tool after 1st test

Fig. 41 Test results of 175 MW high-pressure turbine rotor forging

* Tentative name by the authors. Mixture of flaky graphite under 200 mesh and "Silicaron" which is the trade name of a heat resisting paint of silicone plastic made by the Nihon Tokusyu Toryo Co. (The Japan Special Paint Co.)

Table 8 The recent results of heat indication test in authors' plant, HP, IP, LP and G.R mean the rotor forging of high-, medium-, low-pressure turbine and generator, others are rotor forging of special turbine except marine turbine.
* : Per cent to the grand total of test

(a) Test to which the silicaron graphite process was applied

Forging	The number of test	The number of satis- factory test	The number of unsatisfactory tests							Unknown
			Deflections attributable to the metallurgical properties			Deflections attributable to the surface thermal emissivity				
			Type B	Type C	Total	Type A	Type C'	Type D	Total	
HP	12	12 100%			0				0	
IP	9	9 100%			0				0	
LP	13	13 100%			0				0	
GR	17	17 100%			0				0	
Others	14	13 93%	1		1 7%				0	
Grand total	65	64 *98%	1 *2%	0	1 *2%	0	0	0	0	0

(b) Test by ordinary method

Forging	The number of test	The number of satis- factory test	The number of unsatisfactory tests							Unknown
			Deflections attributable to the metallurgical properties			Deflection attributable to the surface thermal emissivity				
			Type B	Type C	Total	Type A	Type C'	Type D	Total	
HP	68	37 55%	1		1 1%	21		9	30 44%	
IP	22	20 91%			0			2	2 9%	
LP	36	33 92%			0	3			3 8%	
GR	41	34 83%		1	1 2%	5		1	6 15%	
Others	23	20 87%			0	2		1	3 13%	
Grand total	190	144 *76%	1 *0.5%	1 *0.5%	2 *1%	31 *16%	0	13 *7%	44 *23%	0

Table 9 Previous views and the conclusions of present study concerning the causes of deflections and the practical method to eliminate the deflections

Deflection	Previous studies	Conclusions of present study	Practical treatment for solution	Suitability as rotor
Type B	Caplan and others ⁽³⁾ : Relaxation of residual stress	Relaxation of residual stress	No re-test is necessary at least at steel maker	Good
Type C	Caplan and others ⁽³⁾ : Eccentric segregation zone, Burton and other ⁽⁷⁾ : Asymmetrical austenitization during soaking at normalizing temperature, Barker and other ⁽⁸⁾ : Carbide theory; main carbide is M_3C in convex side and is $M_{23}C_6$ in concave side	(1) Origin in the process of production: normalizing or tempering in tangential non-uniformity, (2) Metallurgical origin: difference of thermal expansion coefficient due to the non-uniform distribution of Mo dissolved in matrix	Re-heat-treatment is necessary; (1) Re-tempering, or (2) Re-heat-treatment including normalizing	Good except the case of deflection over 0.05 mm
Type D	Timo and other ⁽²⁾ : Tangentially non-uniform thermal diffusivity	Caused by tangentially non-uniform thermal emissivity; (1) Non-uniform contamination by machine oil, paint, dust and others, (2) Non-uniform scale which grew on or stripped partially from forging surface, (3) Non-uniform surface roughness (consider the vibration marks by cutting tool)	(1) To the forging of insensitive shape to deflection; improvement of surface by re-machining (2) To the forging of shape liable to defect; improvement of surface by coating with the silicaron-graphite as one of the most practical treatments	Good
Type A	Weaver ⁽⁴⁾ : Tangentially non-uniform thermal conductivity of machined surface layer, Fuchs and other ⁽⁶⁾ : Emissivity theory (by experiment of forging pitted non-uniformly), Timo and other ⁽²⁾ : Emissivity theory (by experiment of forging painted with dark lacquer on its quarter periphery			
Type C'	A new type presented by authors			

re-heat treatment is required at least at the steel maker.

(4) Heating and cooling rates have not necessarily to be specified. Rather, smaller rates than the present are recommended unless there is any restriction otherwise.

(5) Measurements of deflection are to be limited only during steady stages; the first cold reading before heating, the hot reading during the holding at a specified test temperature and the second cold reading at room temperature after cooling. No transient reading is necessary unless the hot reading exceeds 0.05 mm, and also any clear discrimination between type C' deflection and type C deflection is not required.

11. Conclusions

The heat indication test of turbine and generator rotor forging has offered many problems in the past decade. In spite of confusions caused throughout the steel makers, turbine makers and relevant societies, little research has been done to solve these problems. The obstacles to the feasible experiments were primarily in the size of rotor forging which involves many difficulties such as large cost, long time of test, non-uniformity of test condition, etc. To minimize these difficulties, laboratory experiments with the model apparatus of heat indication test, the high magnification dilatometer and the advanced techniques in metallurgical experiments were attempted.

The causes of deflections were classified into two major groups; metallurgical defects in forging and non-uniform thermal emissivity of forging surface. The one group includes types B and C deflection and the other group does types A, C' and D deflection which could be eliminated without any heat treatment. The conclusions of the present study were successfully applied to the actual practice, and were finally confirmed to be reasonable. The conclusions are very simple and definite as summarized in Table 9.

Main points of result are as follows.

- (1) Proposal of a new type of C' deflection.
- (2) Molybdenum theory concerning type C deflection was advanced instead of non-uniform distribution theory of carbides.
- (3) Eccentric tempering was added to eccentric normalizing as another cause of type C deflection.
- (4) Type D deflection is attributable to thermal emissivity of forging surface, and the thermal diffusivity theory is presumably an illusion.
- (5) Of five fundamental types of deflection, types B and C deflections are originated from the metallurgical defects of rotor forging, and especially

re-heat treatment is required to eliminate type C deflection, while types A, D and C' deflections which can be eliminated completely by coating the rotor forging with suitable black material (e.g. the silicaron-graphite) are caused by the non-uniform thermal emissivity of forging surface.

(6) A rotor forging with type A, D or C' deflection, if such deflection is observed in the heat indication test, is not unsuitable for use as a rotor of turbine or generator.

Also, a heater box test⁽¹⁹⁾ of which the purpose is nearly the same as that of the heat indication test is performed at some turbine makers. Behavior of the rotor during this test was not discussed in this report.

The authors hereby express their profound gratitude to the Late Mr. Takamitsu Minakawa, former Managing Director and General Manager of Muroran Plant, and Mr. Katsutoshi Isaji, Managing Director and General Manager of Muroran Plant, for their valuable guidances extended to the authors in performing this study and for the permission of publishing the results of the study. This study was financed by the subsidy for the practical studies for the year of 1958 granted from the Ministry of International Trade and Industry. Acknowledgement is also made of the Government authorities concerned for their assistances and encouragement.

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534.11:624.072.33

Vibrations of Rectangular Frame Works*

By Shin TAKAHASHI**

The free vibrations of rectangular frame works in two groups of mode moving perpendicular and coplanar to its own plane are studied by the Lagrangian-minimizing-method. In the former group, flexural and torsional deformations must be considered, and in the latter, flexural and extensional ones must be. The frequency equations for both groups of vibration are derived explicitly, and numerical results of nondimensional frequencies in some special cases are demonstrated in graphs. The natural fact that the center of gravity of the frame in free vibration does not move is certified analytically.

1. Introduction

In the preceding papers⁽¹⁾⁽²⁾, the author investigated the vibrations of an L-bar. In them the boundary conditions and the conditions of continuity are used. In this paper the vibrations in the plane and in the direction perpendicular to the plane of rectangular frame works are discussed using the conditions of continuity only. Both opposite bars of the rectangular frame work are of the same dimensions and of the same materials.

In the frame works composed of many straight bars, each bar has eight boundary values at both ends, that is, the deflections and slopes in bending, the twisting angles in torsion and the extensions to the axial direction. By variation calculus to the Lagrangian integrated for a cycle of vibration, we obtain the lateral, torsional and extensional displacements represented by the boundary values. Using the boundary conditions and the conditions of continuity, some of the boundary values are represented by the other unknown ones. Again, the Lagrangian which is represented by the unknown boundary values only is minimized and we obtain the frequency equations and the ratios of the boundary values.

In the case of rectangular frame work which vibrates perpendicularly to its plane, there are the

lateral and torsional vibrations and no extensional one. In the case vibrating in its plane, there are only the lateral and extensional ones. In both cases, there are 24 boundary values of which 12 are represented by the other 12 using the conditions of continuity at each rigidly jointed corner.

There are three modes of vibrations in both cases, that is symmetric and antisymmetric vibrations of all four bars, and symmetric vibration of a pair of bars and antisymmetric one of the other pair. It is also shown that the center of gravity does not move in the vibrations which satisfy the frequency equations and modes obtained in this paper. Numerical calculations are carried out and comparison is made between the results of calculations, experimental data and the results by the Rayleigh method.

2. Nomenclature

Suffix n denotes the quantity of the n -th bar.

L : Lagrangian

F.E. : frequency equation

x : coordinate starting at one end of bar and running along its axis

l : length of bar

EI , C' , ES , γS : bending, twisting and longitudinal rigidities and weight per unit length of bar, respectively. All are independent of x .

u , θ , w : lateral, twisting and longitudinal displacements. All are the functions of x only.

A , B , C , D , F , G , J , K : boundary values (constants)

* Received 19th July, 1961.

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