FATIGUE LIMIT OF INDUCTION HARDENED RAILWAY AXLES

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Abstract

The level of fatigue damage in railway wheel sets is one of limited parameters of rail vehicles reliability. Then new design methods of axles improving fatigue strength, is proposed. Using induction hardening high compression stresses into sub-surface layers of the axle are introduced, which prevents propagation of short fatigue cracks. The positive effect of axle induction hardening on fatigue limit has been already found earlier, however the reasonable industrial technology has been not yet developed. This paper presents axle induction hardening technology developed in BONATRANS GROUOP a.s. The basic mechanical properties and fatigue characteristics of induction hardened axles made of EA4T (25CrMo4) steel, commonly used in Europe in high-speed rail vehicles are compared, with fatigue behaviours of induction hardened axles made of S38C (AISI 1038) steel used in the Shinkansen high-speed trains. Positive effect of induction hardening on axle fatigue characteristics using newly developed method has been unambiguously proved.

Keywords: Fatigue limit, fatigue crack propagation, fatigue design, railway axles, induction hardening

1. INTRODUCTION

The degree of fatigue damage of railway wheel set axles is one of the rolling stock limiting safety factors [1-5]. This is the main reason for developing new concepts of axle design with higher resistance to initiation and propagation of fatigue cracks. Since it has been clearly demonstrated that the final fracture instability can be in the case of giga-cycle fatigue, i.e. after a long time in service, initiated under significantly lower stress amplitude than the fatigue limit defined for 10^7 cycles, the concept of fatigue limit must always be complemented by fatigue damage tolerance considerations in order to guarantee the axle safety [8]. The fatigue damage tolerance is based on an assumption of existence of fatigue micro-cracks in the axle, which may develop during the service into dangerous long fatigue cracks. Therefore fatigue damage tolerance includes, besides the minimum crack size detectable by NDT, also corresponding intervals of inspections, depending on localisation and the time in service. To increase fatigue strength of axles, the technology of surface induction hardening was developed and implemented firstly in Japan. This technology is also deployed by the railway wheel set manufacturer BONATRANS GROUP, the objective being to satisfy requirements of its clients, especially for deliveries of powered axles intended for high speeds, with high degree of safety against fatigue damage and with long service life. The technology of surface hardening allows the operators also to reduce the number of ultrasonic service inspections, thus saving them considerable amounts of money incurred in regular rolling stock side tracking and inspections.

2. TECHNOLOGICAL ASPECT OF INDUCTION HARDENING

The technology of induction hardening of railway axles was for the first time used in Japan in Shinkansen trains back in 1964. The objective of introducing induction hardening was to prevent fatigue failure of axles, which was to be achieved by inducing high residual compressive stresses in the axle surface. The resultant residual stress in the axle surface, including surface hardness and its sub-surface gradient is, from the technological point of view, very much dependent on the applied hardening frequency of the inductor. With lower inductor frequency, hardening reaches to a greater depth below surface and higher hardness values are achieved in greater depths below the hardened surface. Application of lower inductor frequency also leads to higher values of residual compressive stresses [1, 2]. Development of the induction hardening technology by BONATRANS GROUP for steel grade EA4T (25CrMo4 equivalent) defined in the EN 13261 standard [18] also pointed out at the necessity of using lower inductor hardening frequency about 1 kHz and lower tempering temperature about 200 °C. The actual quality of induction hardening is affected also by changes in the speed of the inductor shift and by possibility of temporary local increase of the inductor intensity, which has a positive effect on heating to the hardening temperature and hardening of problematic parts of transition radii, such as between the wheel seat and the axle body. In these parts, due to an increased air gap between the inductor and the material of the axle body, heat transfers towards the edge of the wheel seat at the expense of heating of the transition radius. **Fig. 1** further shows the effect of the air gap manifesting itself by reduced surface hardness of the steel grade EA4T axle body compared to the surface hardness measured on the motor seat, where the air gap between the inductor and the hardened material is the smallest. Higher surface hardness of the S38C grade steel illustrated in **Fig. 1** is due to a different chemical composition of the hardened axle, primarily higher carbon content.

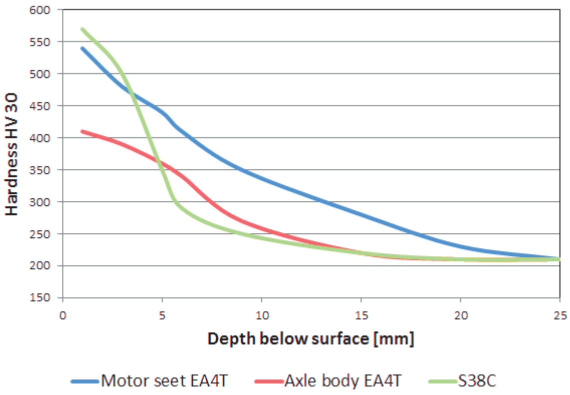

Fig. 1 The effect of the inductor air gap illustrated as the hardness curve in the motor seat with 218 mm diameter and in the axle body with 178 mm diameter, compared with the hardness curve of the S38C steel grade from literature [1]

Because of the large air gap, journals of the tested axles could not be hardened. Therefore complete axles from the wheel seat through the axle body to the opposite wheel seat were selected for testing. The surface which was induction hardened is shown in **Fig. 2** and indicated by dark grey.

Fig. 2 The dark grey indicates axle areas that are induction hardened

3. TESTING MATERIAL AND EXPERIMENTAL PROCEDURE

All experiments presented in this paper were performed on samples of commercially produced EA4T grade steel used for manufacture of railway wheel set axles.

3.1 Axle material and its mechanical properties

All experiments presented in this paper were performed on samples of commercially produced EA4T grade steel used for manufacture of railway wheel set axles. The steel chemical composition that meets the requirements of EN 13261 [18] is presented in **Table 1**. For comparison purposes, chemical composition of the S38C grade steel used for manufacture of induction hardened axles in Japan [3] is also presented in **Table 1**. After the standard heat treatment, the axles were rough-machined, leaving a minimum technology material allowance necessary for induction hardening.

Table 1 Chemical composition of an EA4T steel grade axle and of an S38C steel grade axle used in Japan for comparison purposes. Values are in weight percentages

Grade	*C*	*Si*	*Mn*	*Cr*	*Mo*
EA4T (25CrMo4)	0.26	0.27	0.72	1.0	0.23
S38C (AISI 10038)	0.41	0.27	0.76	-	-

Response to cyclic stressing of the material was investigated on cylindrical test with 10 mm diameter. Because of the small thickness and steep gradient underneath the surface of the induction hardened axle, the test bodies were subjected to laboratory heat treatment which simulated the process of induction hardening used in the treatment of axles, in order to be able to quantify the effects of induction hardening. The resulting basic mechanical properties obtained through the tensile test and fatigue characteristic obtained from standard EA4T steel grade axles after standard heat treatment, are presented in **Table 2**. The table contains also results of the same mechanical characteristics obtained after heat treatment simulating induction hardening, i.e. after heating of the axle to the hardening temperature of 840°C, quenching in water and then tempering to the low tempering temperature (identified as IH). For comparison purposes, the mechanical properties of S38C axles used in the Shinkansen high-speed trains are again presented in **Table 2**.

Table 2 Basic mechanical and fatigue characteristics of the studied EA4T material and the compared S38C material

Grade	R_{fL} [MPa]	R_{fE} [MPa]	$q=R_{fL}/R_{fE}$ [-]	R_e [MPa]	R_m [MPa]	A_5 [%]
EN13261 EA4T	350	215	1.63	>420	650-800	18
EA4T	387	297	1.303	611	795	19.8
EA4T-IH	660	420	1.571	852	1563	13.2
S38C	-	-	-	325	612	33.8

Basic mechanical characteristics are presented in **Table 2**, where R_{fL} is the statistically assessed mean value of the bending fatigue strength determined on a rotating smooth sample of 10 mm diameter, R_{fE} is the statistically assessed mean value of the bending fatigue strength determined on a rotating sample with a 0.1 mm deep notch with the radius in the notch root 0.04 mm and top angle 30°, $q = R_{fL}/R_{fE}$ is the coefficient of notch sensitivity, R_e is the yield point, R_m is the tensile strength and A_5 is the elongation to fracture of the material as required by the EN 13261 standard [18].

Rotating bending fatigue tests were performed at the loading frequency $f = 35$ Hz and the coefficient of cycle variability (aspect ratio) $R = -1$, on smooth and on notched specimens. Mean values of the fatigue strength, determined from 18 smooth and 18 notched test bodies, were assessed in compliance with the ISO 12107 standard, using the staircase method [20].

By comparison of the fatigue tests' results of 10 mm diameter specimens made of steel grade EA4T axles and subjected to standard heat treatment with specimens of the same grade that were subjected to heat treatment in order to simulate the strength of an induction hardened surface, a conclusion can be made that increase of the tensile strength (R_m) from 795 MPa to 1563 MPa does not increase the coefficient of notch sensitivity q.

A tensile test of a specimen taken from the seat of the induction hardened axle was performed in order to investigate changes of the yield point R_e, tensile strength R_m, elongation to fracture A_5 and contraction Z, in a section of the induction hardened axle in the direction from surface to centre (**Table 4**). The tensile test was conducted on specimens of 10 mm diameter, taken from the wheel seat in accordance with the EN 13261 standard [18]. If we compare the results of the tensile tests with the requirements of the EN 13261 standard we see that the only non-compliant value was elongation to fracture of the specimen that was taken from a position that partly reached into the induction hardened surface.

Investigations in order to establish what effect hardening of the wheel seat surface would have on impact values was not less important. For this purpose, specimens were taken, in compliance with the standard [18], for a three-point bending test with a U-notch in the longitudinal and transversal directions, performed at it was tested at the temperature of 20 °C. The specimens that that reached into the induction hardened sub-surface layer and whose centreline was 15 mm below the outside surface, did not meet the impact values required by the standard. These values that did not meet requirements of the standard are shown in **Table 3** in red.

Table 3 Results of the tensile strength test and the impact test of specimens taken from the induction hardened wheel seat

Grade EA4T-induction hardened	*Tensile test*				*Impact test*					
	Re [MPa]	*Rm [MPa]*	*A_5 [MPa]*	*Z [%]*	*KU5 - Longitudinal [J]*			*KU5 - Transversal [J]*		
EN 13261	≥ 420	650-800	≥ 18	-	≥ 40			≥ 25		
1 (A) near outer surface	778	1055	9.6	32	35	35	33	32	53	52
2 (B) wall centre	480	675	21.6	66	59	69	58	42	43	45
3 (C) near inner surface	474	706	20.7	64	52	58	70	43	43	47

3.2 Fatigue characteristic tested on full scale axles

Resistance against cyclic loading was tested on axles of selected designs that were subjected to standard heat treatment and after rough machining they were induction hardened and low-temperature tempered at 473 K. After subsequent final machining - taking a chip between 0.5 and 0.75 mm - and grinding of the required parts of the wheel seats and journals, the axles were fitted to clamping discs, and were prepared for the fatigue test in a form of standard test half-wheel sets. Special attention had to be paid to the final machining, particularly to grinding of the wheel seats and bearing journals that had to be, unlike the standard technology, performed in such a way that would not reduce the induced compressive stresses because of local heating of the ground parts [2, 14]. For this reason it is recommended in the paper [2] to reduce the final ground layer from 0.5 mm to 0.15 mm only. Requirements on fatigue characteristics of selected parts of axles are specified by standards EN 13261 [18] and EN 13260 [19]. The axles were tested on an Inova resonance test rig with a selectable stress amplitude level and the cycle asymmetry coefficient $R = -1$. Test frequency ranged, depending on the selected loading level, between 23 and 25 Hz. Local stress in the R75/R15 transition zone (parameter F1) was set by means of an HBM type 1-KY11-4/120 chain strain gauge. The strain gauge was attached to the area of the anticipated critical point, inside the zone of axle body and axle seat transition. Parameter F3 was set on the basis of analytical calculations and results of a static calibration, and it represents stress in the area of the wheel seat edge in the fitted joint. Feedback control strain gauges were attached to the axle body to the distance of 450 mm. Results of fatigue tests of these axles are presented in **Table 4** below.

Table 4 Test stress levels to which the tested axles were exposed

	Axle number	*Local stress [MPa]*	*Nominal stress [MPa]*	*Press fitted area stress [MPa]*	*Number of Cycles []*
St. req. [18, 19]		-	240	145	10 000 000 Without crack
Standard A4T	1	285	243	156	10 000 000
		310	264	170	10 000 000
		335	286	183	2 600 000
	2	310	266	171	10 000 000
		335	288	184	6 300 000*
A4T +IH surface	3	400	372	241	10 000 000
		450	418	271	10 000 000
		500	467	301	420 000**
	4	450	418	274	10 000 000
		500	465	305	690 000***

*) crack in the press fit area

**) Crack in the axle body area localised within the critical point area

**) High test stresses and raised temperature made it impossible to continue testing on the test assembly

4. DISCUSSION AND CONCLUSION

Induction hardening is one of perspective methods of increasing fatigue strength of rolling stock axles, which has already been used on a different steel grade in Japan for many years. The resulting fatigue strength of full size axles are presented in **Table 4**. The main reasons why the induction hardening technology should be further developed are:

✓ Fatigue strength increased by about 58% (418 / 264) compared to the standard EA4T steel grade and about 74% compared with EN 13261 standard, which cannot be achieved by any other technologies. This implies usability of application of the induction hardening technology on highly loaded powered axles made of EA4T steel grade.

✓ Price affordable technology, the costs of which is comparable to application of a molybdenum layer, the difference being that induction hardening provides a comprehensive protection of the entire axle from the wheel seat through the axle body to the opposite wheel seat.

✓ The coefficient of notch sensitivity, determined on the reduced specimens with 10 mm diameter, met the requirements of the standard for EA4T grade steel and was not significantly increased.

✓ Small disadvantage is reduction of the coefficient of notch strength and generally also of plasticity, measured as elongation at break, in the sub-surface induction hardened layers, which are outside of the requirement range of the European standard.

✓ After promotion of the induction hardening technology to the customer, BONATRANS GROUP has supplied powered and non-powered induction hardened axle for the prototype HEMU-430X high-speed train designed for speeds up to 430 km/h.

ACKNOWLEDGEMENTS

This article has been elaborated in the framework of the project Opportunity for young researchers, reg. no. CZ.1.07/2.3.00/30.0016, supported by Operational Programme Education for competitiveness and co-financed by the European Social Fund and the state budget of the Czech Republic.

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