THE EFFECT OF INDUCTION HARDENING ON FATIGUE BEHAVIOR OF RAILWAY AXLES

FAJKOŠ Rostislav[1, 2], ZIMA Radim[1], STRNADEL Bohumír[2]

[1]*BONATRANS GROUP a.s., Bohumín, Czech Republic, EU*
[2]*Center of Advanced Innovation Technologies - VSB - Technical University of Ostrava, Ostrava, Czech Republic, EU*

Abstract

A new surface induction hardening technology was for the first time in Europe developed in BONARTANS GROUP Company for the purpose of increasing the safety and resistance of railway axles to fatigue damage. The operation of railway axles should fulfil two main demands: higher safety and low operation costs. A significant part of operation costs is given by frequency of regular inspection intervals which should reveal potential fatigue cracks in railway axle. Fatigue tests and tests of crack initiation and crack growth tests performed on induction hardened railway axles produced from steel quality EA4T and EA1N are compared with the results obtained from the standard heat treatment of railway axles. The comparison clearly demonstrates the benefits of new technology of surface induction hardening.

Keywords: Railway axle, induction hardening, crack initiation, crack growth, fatigue limit

1. INTRODUCTION

Fatigue damage of railway axles is one of the limiting factors in rail transport safety [1-8]. This is the main reason for development of new axle design concepts giving higher resistance to fatigue crack initiation and propagation. Because fracture failure of axles due to giga cyclic fatigue, i.e. after long periods of operation, may be initiated by much lower stress amplitude than the fatigue limit for 10^7 cycles, the consideration of fatigue strength must always be accompanied by considerations of fatigue damage tolerance in order to ensure axle safety. This approach takes into account the occurrence of short fatigue cracks, which during operation may develop into dangerous long fatigue cracks. The fatigue damage tolerance therefore takes into account not only the minimum crack size detectable using NDT methods, but also suitable intervals between NDT inspections, set depending on the location and period of operation.

In addition to these basic design concepts, studies are focused on the effects of material structure, surface treatment, methods of heat treatment and subsequent machining. One technology applied in order to increase axle fatigue strength is a surface induction hardening, which involves the relatively rapid heating of surface layers of pre-machined axles up to the hardening temperature using an inductor, followed by the rapid cooling of the axle by a water jet positioned behind the inductor and also by the transfer of heat by the axle body. This produces martensitic structure in the surface layer, increasing hardness up to 250 % compared with the axle core and producing a compressive stress state of around -800 MPa. As a consequence, the fatigue limit is significantly increased, and short fatigue cracks in surface layers are hardly able to initiate or propagate [9].

2. OPTIMIZATION OF INDUCTION HARDENING PROCESS

Applied research and coordination of technological parameters such as inductor shape, speed, power, tempering temperature and others, bring one of main advantage required by customers - a possibility to harden the all axle diameter. Obtained homogenous results of hardness profile in different sections of the axle, including transition radius axle, are shown in the **Figure 1**.

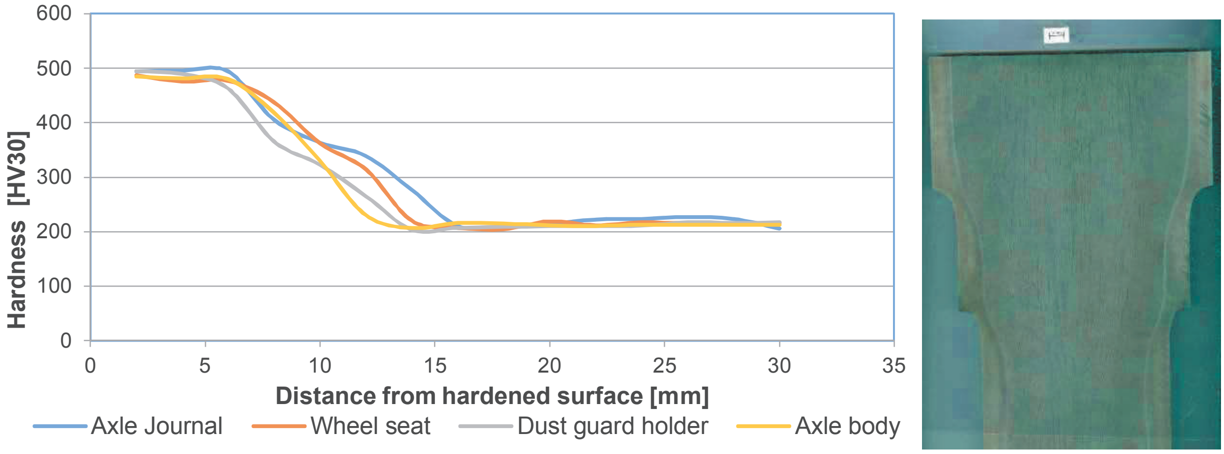

Figure 1 The hardness profile in different sections of axle diameter hardened surface from axle journal cross dust guard holder to wheel seat and macro etch with induction hardened (IH) profile

3. FATIGUE CHARACTERISTIC DETERMINED ON FULL SCALE AXLES

In case of EA4T + IH a total number of 3 drive axles were tested, with wheel seat diameter/axle body diameter ratio D / d = 207 / 180 = 1.15 and with standard R75 / R15 transition radius design. In the **Table 1** there are presented only requirements of EN 13261 standard for EA4T steel quality and results from one axle produced and tested from EA4T+IH surface. On **Table 2** you can find results from fatigue test EA1N steel quality (D / d = 205 / 173 = 1.18, with standard R75 / R15 transition radius design).

Table 1 Results from fatigue tests performed on full scale axle produced from steel quality EA4T+IH

EN 13261	**Local stress [MPa]**	**Nominal stress [MPa]**	**Stress in press fit area [MPa]**	**No. of cycles [ ]**
Request EN 13261	-	240	145	10 000 000
BON*AXLE*®	450	419	274	10 000 000
	500	465	305	-

Table 2 Results from fatigue tests performed on full scale axle produced from steel quality EA1N+IH

EN 13261	**Local stress [MPa]**	**Nominal stress [MPa]**	**Stress in press fit area [MPa]**	**No. of cycles [ ]**
Request EN 13261	-	200	120	10 000 000
BONAXLE®	352	285	174	10 000 000
	370	300	183	3 300 000

As it is obvious from the **Table 1** and **Table 2,** the fatigue strength increased minimally about 75 % compared to the EN 13261 standard in case of EA4T and minimally about 41 % in case of EA1N steel. It should be noted that such improvement cannot be achieved by any other technologies.

4. CRACK INITIATION AND PROPAGATION TESTS

For verification of benefits IH technology applied on axle was performed crack initiation and propagation tests with a spark-eroded notch in the transition radius on one standard EA4T axle and the same on one axle EA4T with induction hardened surface were organized in cooperation with DB Systemtechnik Prüfstelle in Minden.

The tested objects were “half-wheelsets” with diameter of axle body 185 mm and diameter on wheel seat press-fit area 215 mm. The artificial elliptical defect with typical width (surface length) 3.75 mm, and depth 1.5 mm was positioned in the transition radius R75 / R15 at a distance 34 mm from wheel seats. The exact position of the artificial defect was determined by FEM analysis.

The test of standard EA4T axles started under normal conditions specified by the FEM analysis with crack initiation on testing amplitude of nominal stress 112 MPa which corresponded to 134 MPa of local stress. At this level a starting crack occurred. The surface crack length of 5.7 mm was measured after $8*10^5$ load cycles. After verification of omission level of low-amplitude load cycles the regular fatigue growth testing started with the defined test load spectrum. After a distance covering of 1.200 000 km, the surface crack length determined on the crack measurement strain gauges had grown from 5.7 mm to 6.6 mm**.**

As a second step a test on the same axle type made of EA4T steel including induction hardening of the axle surface was performed. Totally different behaviour occurred during testing of induction hardened EA4T steel quality axle. The test started with increased load amplitude at nominal stress 200 MPa for crack initiation. This stress level was applied at 5.10^6 load cycles with no crack initiation. Then the testing amplitudes increased at 240 MPa for 5.10^6 load cycles, 280 MPa for 10^7 load cycles and 300 MPa for 10^7 load cycles. After application of 340 MPa the test was stopped due to currently limited capacity of the test bench without any crack initiation.

Table 3 Comparison of crack initiation and growth test for EA4T steel quality

	Standard EA4T axle		**EA4T axle + induction hardening**	
	Testing amplitude / No. of cycles	Crack length [mm]	Testing amplitude/ No. of cycles	Crack length [mm]
Crack initiation	112 MPa / 0.8 mil. cycles	3.75 -> 5.7	200 MPa / 5 mil cycles	3.75
			280 MPa / 10 mil cycles	3.75
			300 MPa / 10 mil cycles	3.75
			340 MPa / 1.1 mil cycles	3.75
Crack growth	Load spectra represented 1.2 mil. km	5.7 -> 6.6	-	-

If these results published in **Table 3** from induction hardened EA4T axle were compared with results of standard EA4T axle it can be concluded that induction hardened axle sustained 2.6 multiplied of nominal stresses, which caused crack initiation on standard steel quality EA4T axle from an artificial notch. Even more it can be stated that it was not possible to initiate start of the crack growth on the IH axle with a standardized notch. On the other hand EA4T steel quality has to fulfil 10^7 cycles during fatigue testing of the real scale 1:1 axle according to standard EN 13261 on nominal testing stress 240 MPa. It needs to be remembered that this standard axle for the EN 13261 fatigue test is performed on axle without any crack. On induction hardened axle nominal stress 300 MPa was applied without any crack initiation from the artificial notch. It needs to be noted that this axle contained initial crack. In future testing of crack initiation on test level of 340 MPa, eventually higher will continue. After crack initiation crack growth for determination of service intervals on induction hardened axles made from EA4T steel will be tested.

Results published in **Table 4** for the axle produced from EA1N steel quality bring in case crack initiation min. about 95 % better results in comparison with axles produced from standard EA1N steel quality. After crack initiation on testing level 260 MPa the test continued on the same testing level from reason determined how fast will crack growth. After application additional 45 mil cycles the crack growth extremely slowly grows, only about 0.3 mm in comparison with test of standard axles EA1N where crack growth on testing level 123 MPa about 2.25 mm after application only 8 mil cycles. This number of cycles included necessary time for crack initiation.

Table 4 Comparison of crack initiation and growth test for EA1N steel quality

	Standard EA4T axle		**EA4T axle + induction hardening**	
	Testing amplitude/ No. of cycles	Crack length [mm]	Testing amplitude/ No. of cycles	Crack length [mm]
Crack initiation	123 MPa/8 mil cycles	3.75 -> 6	200 MPa / 5 mil cycles	3.75
			220 MPa / 5 mil cycles	3.75
			240 MPa / 5 mil cycles	3.75
			260 MPa /5 mil cycles	3.75-> 4.1
Crack growth	Load spectra represented 1.2 mil. km	5.7 -> 6.6	260 MPa /45 mil cycles	4.1-> 4.4

5. CONCLUSION

The verification of the technology of surface induction hardening of EA4T and EA1N axles confirmed benefits of this technology for increase of fatigue resistance and lifetime of railway axles. Main conclusions are the following.

High internal compressive residual stress on the axle surface (-800 MPa) cause that it is impossible a short fatigue crack could be initiated in surface layers. This significantly increases lifetime of the axle.

Verification of this result was performed using tests of crack initiation in the induction hardened railway axles made of EA4T and EA1N steel. It was practically impossible to create on the axle surface initiation defect from which the fatigue crack could propagate under real load spectra measured in the service.

Significant increase of the fatigue limit was recorded (minimally about 41 % in case of EA1N steel and 75 % in case of EA4T steel). Because of impossibility to test railway axle on higher test level (500 MPa for EA4T), the real fatigue limit of axles protected by presented technology is still unknown.

The technology of surface hardening allows reducing in the future the number of ultrasonic service inspections. This saves considerable amounts of money incurred in regular rolling stock side-tracking and inspections.

ACKNOWLEDGEMENTS

This article has been elaborated in the framework of the project EPSILON, reg. no. TH02020634, supported by Technology Agency of the Czech Republic.

REFERENCES

[1] SAKAMOTO H., ISHIDUKA H., AKAMA M., TANAKA K. Fatigue crack extension under large cyclic compressive stress in medium frequency induction hardened axles. In *16th International Wheelset Congress*, Cape Town, March 2010.

[2] HIRAKAWA K., TOYAMA K., KUBOTA M. The analysis and prevention of failure in railway axles. *International Journal of Fatigue*, 2011, vol. 20, no.2, pp. 135-144.

[3] KLINGER C, BETTGE D. Axle fracture of an ICE3 high speed train. *Eng. Fail. Anal. , 2013,* http://dx.doi.org/10.1016/j.engfailanal.2012.11.008

[4] AKAMA MAKOTO. Bayesian analysis for the results of fatigue test using full-scale models to obtain the accurate failure probabilities of the Shinkansen vehicle axle. *Reliability Engineering and System safety,* 2002, *vol.* 75, pp. 321-332.

[5] ZERBST U et al. Safe life and damage tolerance aspect of railway axles-A review. *Eng. Fract. Mech.,* 2012, http://dx.doi.org/10.1016/j.engfracmech.2012.09.029.

[6] VARFOLOMEEV I., LUKE M., BURDACK M. Effect of specimen geometry on fatigue crack growth rates for the railway axle material EA4T. *Eng. Fract. Mech., 2011, vol.* 78, pp. 742-753.

[7] VARFOLOMEEV I., LUKE M. Assessment of crack initiation and propagation in press fits of railway axles. In 16th *International Wheelset Congress*, Cape Town, March 2010.

[8] LUKE M., VARFOLOMEEV I., LÜTKEPOHL K., ESDERS A. Fatigue crack growth in railway axles: Assessment concept and validation tests. *Eng. Fract. Mech., 2011, vol.* 78, pp. 714-730.

[9] KRISTOFFERSEN H., VOMACKA P. Influence of parameters for induction hardening on residual stress. *Materials and Design. 2001, vol.* 22, pp. 637-644.

[10] GRUM J. A view of the influence of grinding conditions on resulting residual stress after induction surface hardening and grinding. *Journal of Materials Processing Technology* , 2001, vol. 114, pp. 212-226.

[11] SHAFFER S.J., GLAESER W.A. Fretting Fatigue. *ASTM Handbook*, vol. 19, fatigue and fracture.

[12] EN 13261: Railway applications - Wheelsets and bogies - Axles - Product requirements