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Some Important Experimental Details During Verification of Fatigue Durability of Railway Axles and Wheelsets

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Abstract. Railway wheelsets are crucial components of bogies from the viewpoint of service reliability and safety. They are compound of two subcomponents, wheels and axle, connected to each other by press fitting or shrink fitting. Wheelsets are components extremely dynamically loaded in service, by a very high number of cycles, usually more than 10^9 during the life. That is why fatigue resistance of these components have to be adequately proved during the certification process, when such proves are strictly requested Two or three characteristics are defined in the standards, which have to be proved, namely (i) fatigue resistance of the smooth part of the axle body on its free surface, so called characteristics F1 and (ii) fatigue resistance under press fit (or shrink fit) - characteristics F3.

This contribution describes a new experimental approach to verification of press fitting quality and homogeneity by measurement of mutual circumferential displacements between the axle and wheel hub during the full scale fatigue test. Though the press fit of the tested wheelset met standard requirements for the press fitting diagram in terms of minimum and maximum forces, the mutual microscopic displacements under the press fit were not homogeneous for the whole circumference, the maximum value being almost twice as much higher than the minimum one. Another effect was a dependence of these displacements on number of cycles during rotating bending fatigue tests. The results are discussed considering circumferential dynamic stresses on the axle surface.

Introduction

Railway wheelsets and axles are safety-critical components. Designing failsafe mechanisms is very difficult and the safety of the component is determined through a good understanding of the structural integrity and through effective management policies [1]. Railway wheelsets are compound of two subcomponents, wheels and axle, connected to each other by press fitting or shrink fitting. Wheelsets are components extremely dynamically loaded in service in terms of a very high number of cycles, usually more than 10^9 during the life, corresponding to several tens of service years. In spite of that axle failures occur relatively infrequently [1], consequences are usually very serious, from financial damages to heavy casualties. An example is the railway accident of the high-speed train near Eschede almost twenty years ago, where more than 100 people were killed and even more injured. The disaster was followed by a very complicated court case, in which more than 13 experts from different countries participated in the evaluation of causes of the wheel fatigue failure. It was stated in the official verdict that no unambiguous causes were found, likely just a single incident or a technological material phenomenon [2]. This is one of numerous examples, why fatigue resistance of these components have to be adequately proved during the certification process, when such proves are strictly requested. A system of European and worldwide standards [e.g. 3, 4] have been elaborated and issued and is being systematically improved according to needs of the railway transport, its increasing demands on service safety and reliability in connection with increasing train speeds, both freight and passenger, with increasing demands on payload and other aspects [5]. Furthermore, fracture mechanics starts to be used to assist in the timing of crack inspection intervals. Nevertheless a small number of failures still occur [6]. Some current pressures, particularly the need to reduce unsprung mass at high speeds, continue to challenge axle designers.

Though strict standard criteria for the press or shrink fitting methods exist like overlapping dimensions of the axle seat diameter and wheel hole, dependence of press forces during the press fitting process, press fits still remain one of the critical areas where possible cracking occur. As an example, in [7] the authors investigated the effects of rotary bending and of the press fits at the wheel and gear on the stress intensity factor, fatigue crack growth and residual lifetime so as to provide essential input information for setting up inspection intervals. It was found that the effect of rotary bending, although existent, was rather moderate whereas the press fits had a large and detrimental effect.

Another problem is that unlike fatigue resistance of most of metallic materials without defects on free smooth surface increases with increasing static material strength, in case of fretting fatigue mechanism this need not be true. A comprehensive experimental programme, which included rotating bending tests of press fitted axle models reduced to the scale 1 : 5 showed that resistance to fretting fatigue under press fit of high strength railway axle steels is comparable or even worse than the standard EA1N normalized steel with the lowest strength. Endurance limit of the models of different steels was comparable and it was indicated that retardation and arrest of initiated microcracks or short fatigue cracks in compressive residual stress field are crucial mechanisms deciding, whether the main fatigue crack will be created and final failure occur [8].

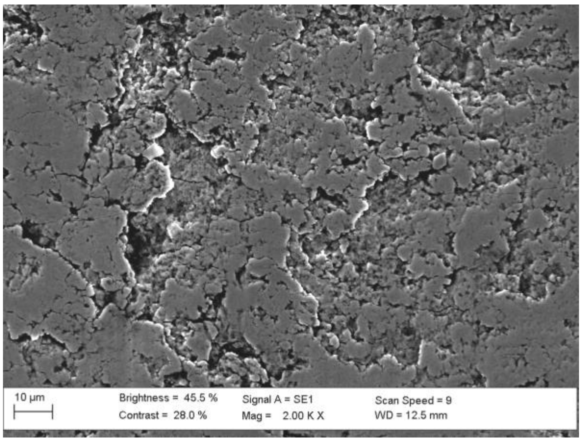

Fig. 1 Example of surface fretting fatigue damage of axle seat under press fit with microcracks and short fatigue cracks

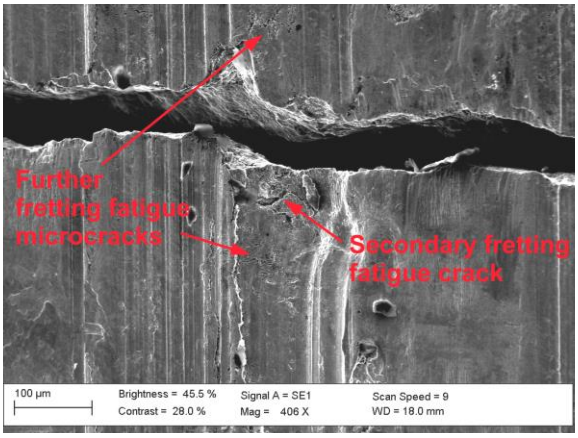

Fig. 2 Main fatigue crack under press fit with secondary crack and further fretting fatigue microcracks

Though fracture mechanics approaches to safety and reliability of railway axles start to be used particularly with the aim to specify necessary inspection intervals [9], standard requirements are still based on the safe life approach, i.e. no failure after unlimited number of cycles. Two or three characteristics are defined in the standards, which have to be proved, namely (i) fatigue resistance of the smooth part of the axle body on its free surface, so called characteristics F1 and (ii) fatigue resistance under press fit (or shrink fit) - characteristics F3.

Note that characteristics F2 does not concern solid axles, but resistance to fatigue damage of hollow axle internal surface. The fatigue resistance is usually proved by rotating bending full scale half wheelset.

Unlike the axle body, where fatigue resistance F1 is determined only by the material and surface conditions, the resistance under press fit, where different fatigue mechanisms occur, fretting fatigue being the most crucial, is affected by further factors, like quality of press fitting, which affect mutual displacements between axle seat surface and wheel hub. Too large displacements promote the fretting fatigue mechanisms and can results in premature cracking under press fit. In Figs. 1 and 2, there are characteristic examples of fretting fatigue damage, which occurred and was analysed during one of the recent full scale axle tests performed at SVUM laboratory. Fig. 1 shows system of surface fretting fatigue microcracs and pits at long initial stages of the process. The microcracks were eventually developed to the main fatigue crack fast growing to the final failure. The general conclusion in this case was that the axle seat had an insufficient value of the F3 characteristics, though it could not be said, whether the actual reason were insufficient material properties or just incorrect press fitting resulting in excessive mutual friction in the axle – hub interface.

This contribution describes a new experimental approach to verification of press fitting quality and homogeneity by measurement of mutual circumferential displacements between the axle and wheel hub during the full scale fatigue test. The results are presented and discussed considering possible effects on fretting fatigue conditions and damage.

Experiments

Fig. 3 Total view of the axle prepared for fatigue test on the Sincotec machine

Fig. 4 LVDT extensometers measuring displacement between axle and wheel

The test piece was represented by a kind of full scale half wheelset, more exactly the axle press fitted into a substitution of actual wheel – a steel disc with the same dimensions in the area of the central hole, into which the axle was press fitted. The fatigue test was performed on the very sophisticated facility Sincotec GmbH of the last generation, characteristic by very exact circumferential load distribution. The test was prepared according to standard procedure, to ensure all the requested loading conditions. These steps contained detailed static measurement of the maximum stress concentration on the axle surface, evaluation of the stress concentration factor, calibration of the machine and independent measurement of circumferential dynamic stresses during the whole test to 10^7 cycles. The total view of the test arrangement is in Fig. 3. The experimental procedure is described more in detail e.g. in [10].

Beyond the standard requirements, continuous measurement of mutual displacements between the axle and the disc simulating the wheel was performed and values recorded at three circumferential positions – for 120^o during the whole test. This measurement was performed using three LVDT extensometers Sangamo fixed to the axle using magnetic holders attached to the axle at the distance of approximately 230 mm from the hub edge – Fig. 4.

The rotating bending test frequency was approximately 25 Hz, given first of all by stiffness of the whole component and the requested load – stress amplitude 200 MPa at critical point of the maximum stress concentration. Dynamic values of the mutual displacement between the axle and hub, more exactly maximum and minimum peaks, were evaluated without interrupting the test, using separate high speed analog – digital converters Adicom PCA.

Results and Discussion

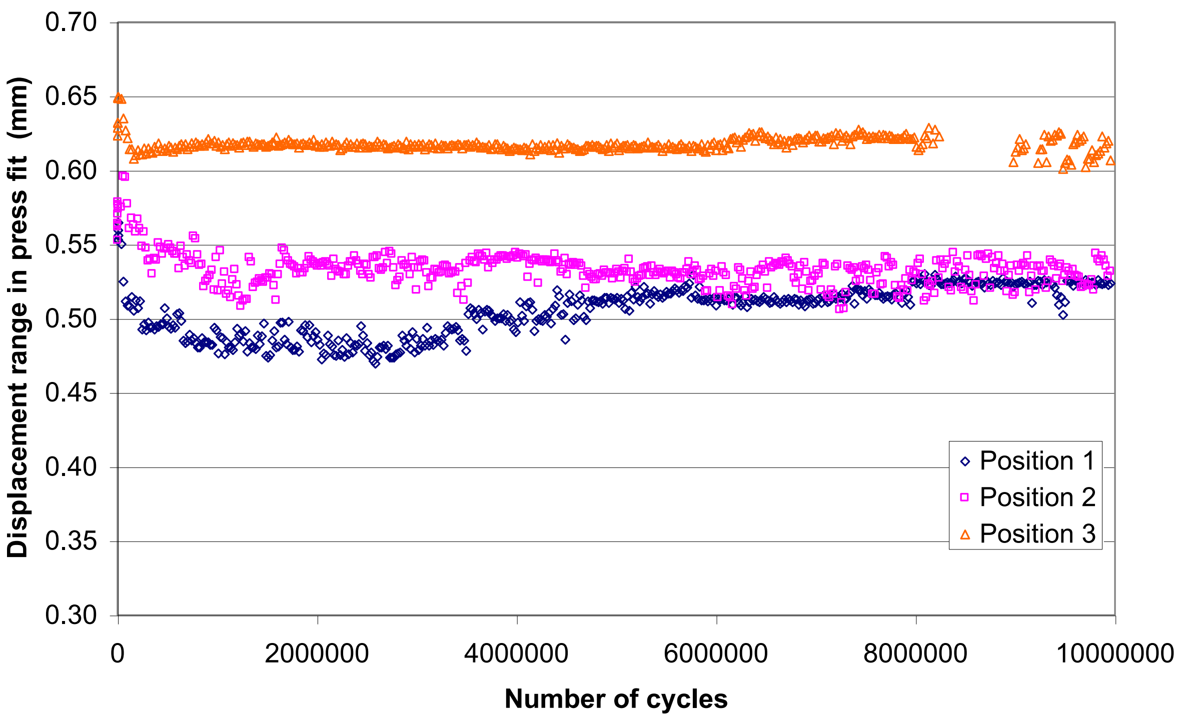

Fig. 5 Displacement range as measured by the extensometers at three circumferential points as dependence on number of fatigue load cycles

Continuous records of mutual displacement between the axle surface and the hub measured at three circumferential positions, as recorded by the LVDT extensometers, evaluated in terms of their range, difference between the maximum and minimum values as a dependence on number of load cycles is in Fig. 5.

It follows from Fig. 5 that differences between displacement values measured at different circumferential points were significant. At the beginning of the test, there were small differences between the positions 1 and 2, which, however, differed from the position 3, which was higher. The common feature of all three positions is quite significant drop of mutual displacement early after the test start. The values were saturated after 230000 cycles in case of position 3 and after more than one million cycles in case of positions 1 and 2. It indicates that some strengthening of the press fitting attachment occurs due to the repeated loading, which looks to be a common characteristic. It may be caused by an occurrence of first oxide debris by the fretting fatigue mechanism. This strengthening effect had its maximum between one and three million of cycles, then some release could be observed. Note that practically no long time strengthening effect of the mutual fixation between the axle and hub occurred at position 3 with the largest mutual displacement. It is an interesting phenomenon, because one would expect the highest oxide debris occurrence and increasing fixation particularly at points of maximum mutual displacement.

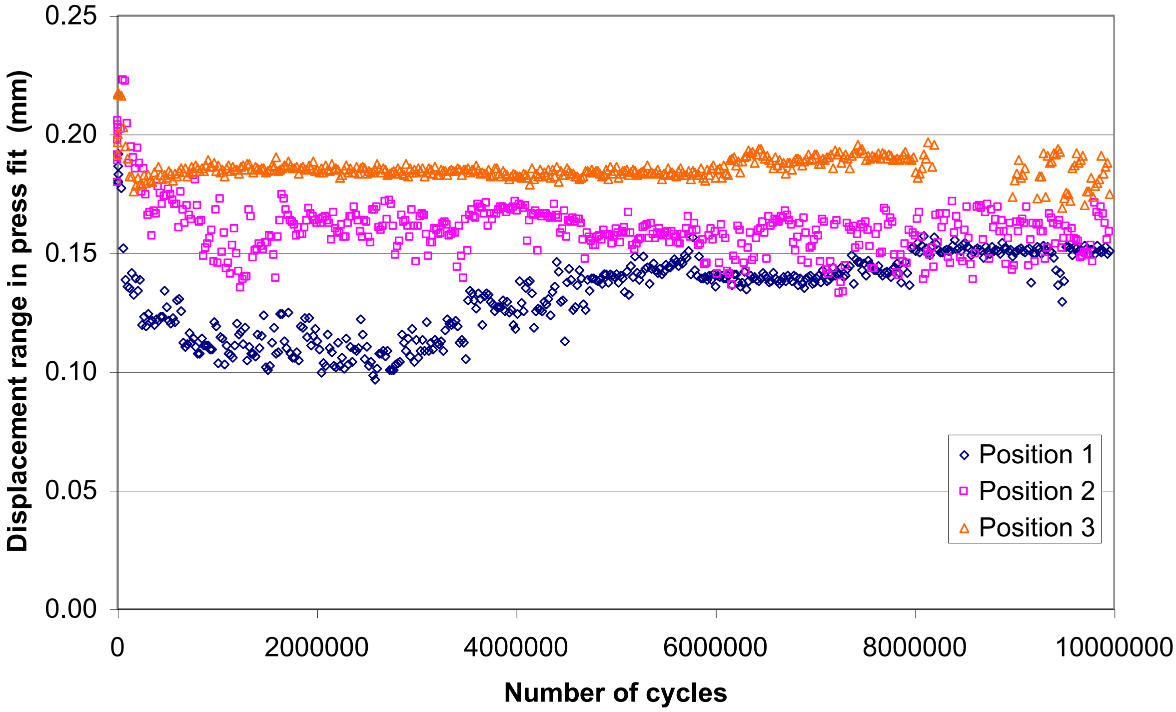

Fig. 6 Pure values of displacement between axle and hub during fatigue test after correction for elastic deformation of the part of the axle with magnetic holders

Displacement measurement shown in Fig. 5 contains, besides actual mutual displacement between the axle and hub, also the part of elastic deformation of the axle surface near the hub, at the distance of approximately 230 mm from the hub edge, where the centre of the magnetic holder was always attached. This elastic deformation was calculated and subtracted from the total displacement values shown in Fig. 5. This correction resulted in practically pure values of the mutual displacements between the axle and hub. Such corrected values are shown in Fig. 6.

Looking at Fig. 6, the features indicated already in Fig. 5 are even more distinct. The differences of displacements between positions 1 and 3 are very significant, values at position 3 being almost twice as much as those at position 1 during the first third of the test.

It should be pointed out that the differences between displacement at different measured points have nothing to do with symmetry of the component loading, which was checked by dynamic strain measurements at eight circumferential points. All the strain values were equal within the range of less than ± 1.5 %, which demonstrates that local mutual displacement was determined by local strength of the contact between the axle and hub surface, not by loading asymmetry.

The results of the displacement measurements show that even though the press fitting diagram of the axle into the wheel met the standard requirements and the pressing force was within the requested range, the homogeneity of the press fit in terms of constant dynamic displacements along the circumference during the fatigue loading was far from optimum conditions. Note that fretting fatigue mechanism and rate of the fretting fatigue damage are very sensitive on both displacement values and contact forces [11]. It would be therefore useful and interesting to investigate, whether there are some indications that the fretting fatigue damage process already started after the test interruption at 10^7 cycles and if yes, whether the intensity of this process could be correlated with the circumferential position on the axle surface, i.e. with the values of mutual displacement between the axle and hub.

Conclusions

Rotating bending fatigue test of full scale railway axle press fitted in the disc simulating actual wheel was performed according to European standards to verify sufficient fatigue durability either on the axle shank or under the press fit. Beyond the parameters monitored according to the standard requirements, shear contact displacements between the axle surface and the hub along the axle circumference were evaluated and recorded. The main results can be summarised as follows:

- In spite of that the pressure diagram – the diagram of pressure forces during pressing the axle into the hub fully satisfied the standard criteria, the mutual displacements during fatigue loading along the circumference were far from ideal homogeneity, the maximum values being almost twice as high as the minimum values. This inhomogeneity was not affected by loading itself, which was almost ideally homogeneous along the circumference.
- The inhomogeneity of the shear displacements may unfavourably affect the fretting fatigue process, which is strongly dependent on both mutual shear displacement and contact pressure forces at the axle and hub interface.

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