The effect of roll-forming onto fatigue life of railway axles

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Abstract. In the last years, roll-forming has been adopted as a technique to improve the strength against crack propagation in railway axles, but very few scientific analyses and studies of the phenomenon are available in the literature. For this reason, the Maraxil Project was started in order to give the opportunity of experimentally and theoretically investigating some aspects related to this technological process in the case of railway axles made of EA4T, a typical steel for manufacture of high speed axles.

Firstly, an experimental campaign on small-scale SE(B) specimens was carried out for determining the crack propagation behavior at stress ratios below -1, which correspond to the ones in presence of the high compressive residual stresses due to the roll-forming procedure.

At the same time, the compressive residual stress field along the radial direction and due to the roll-forming process was evaluated from axles coming from the production using both hole-drilling and x-ray diffractometry methods.

The results obtained from crack propagation tests and residual stress field measurements were used together to build up a predictive crack growth model in presence of very high compressive stresses. This model was, then, validated through dedicated experimental crack propagation tests carried out on full-scale roll-formed axles made of EA4T; good agreement was found between the model and the experiments.

Introduction

Railway axles are usually designed against fatigue limit, but, due to their very long service life they are required to perform (30 years or even more), the approach has moved to a damage tolerant one [1-2]. From the damage tolerant point of view the possibility that a crack is present in the axle is accepted; it has to be controlled periodically in order to remove axles with cracks. The inspection interval is set to H/n (with $n \geq 2$) where H is the propagation lifetime from the initial damage (or detectable crack) to the critical crack size. More refined approaches are based onto the estimation of the probability of detection of a prospective crack subjected to several inspections [3]. The problem so moves to the determination of the appropriate inspection interval from simulations of crack propagation, based on the knowledge of the crack growth rate of materials, together with the performance of the adopted non-destructive testing technique [4] and the service loads [5].

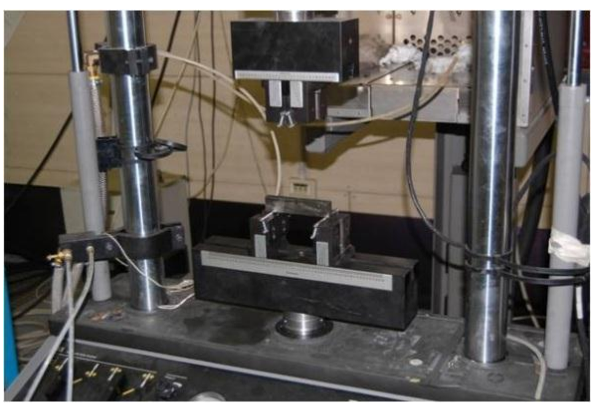
The roll-forming procedure has been more and more been adopted in the last few years as a technique to improve the residual life to crack propagation of existing railways axles, in order to increase service durability and the reliability of the high speed trains. But, while some scientific analyses were recently dedicated to the investigation of the beneficial effect of the compressive residual stresses onto fatigue life [6-9], no investigations were found in the literature regarding the effect of the cold-rolling procedure onto fatigue crack propagation onto railway axles.

For this reason, the Maraxil Project, involving PoliMi and IWM as partners, was launched in order to experimentally and theoretically investigate the effect of this technological process onto the propagation life of railway axles made of EA4T.

Firstly, the residual stress profile was measured, independently by the two partners, on two specially designed and machined full-scale railway axles, in order to measure longitudinal and circumferential residual stresses after the cold-rolling procedure; both the x-ray diffractometry and the hole drilling strain gage methods were adopted [10].
The compressive longitudinal residual stresses, in addition to the typical stress state given to the axle by the rotating bending loading spectrum in exercise, modify the stress ratio from R=-1 (rotating bending) to the very negative region (R=-10 or even below). The second topic is so dedicated to the characterization of the material behaviour to crack propagation in the unexplored region of the very negative stress ratios, typically acting on a crack inserted in a cold-rolled railway axle.
Then, a crack propagation algorithm able to take care of the residual stresses given by the cold-rolling procedure was prepared, based on the Shiratori weight functions [11] for the calculation of the stress intensity factors. Finally, the developed algorithm was tested and compared to the results obtained from a full-scale test on a specifically machined railway axle. Experimental test results are very close to simulations. In particular results have shown a significant increase in fatigue life even in presence of a 2mm defect considering the stress spectrum of a high speed train.

1. Characterization of the material to crack propagation

An experimental campaign was needed in order to characterize the material behavior to crack propagation, especially in the non-explored region of the very low stress ratios; since the life of a typical railway axle is spent mostly in the near-threshold region, particular attention was given to the thresholds stress intensity factors.
Since it is known from literature that the traditional ΔK-decreasing test indicated in the ASTM E647 standard [12] generates threshold stress intensity factors higher than the expected values and in the non-conservative direction [13-16], all the used specimens, in the form of 12x24mm SE(B) specimens, were tested using the newer compression pre-cracking approach [16-19]. The difference between the generated thresholds was shown to increase more and more with decreasing the stress ratio [16], showing differences up to 25% for the A1N tested material; since the stress ratios of interest in the presence of cold-rolling residual stresses are exactly in the very negative range, a higher accuracy and safety is expected using the compression pre-cracking approach.



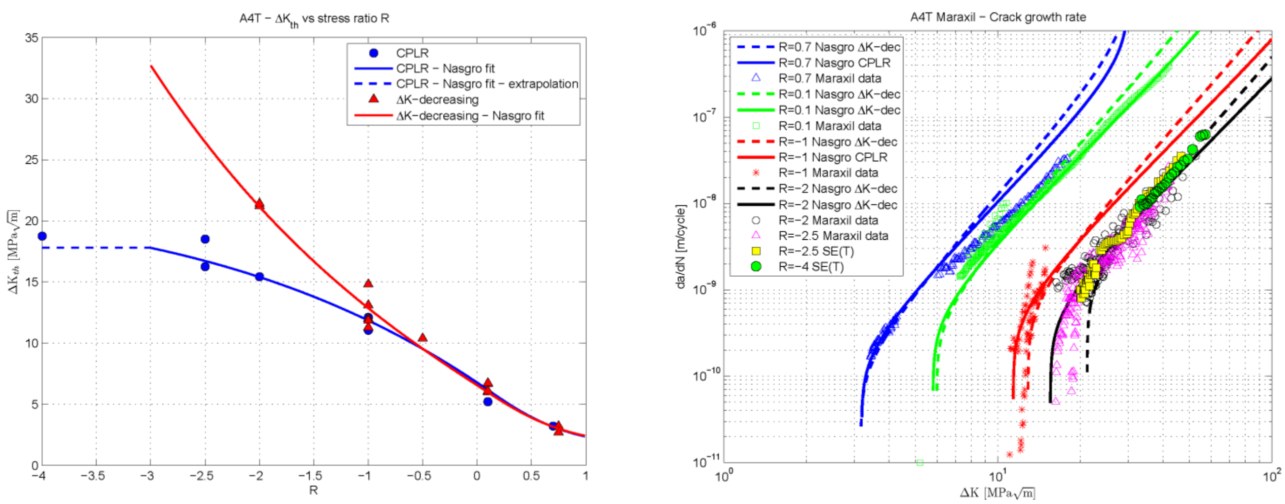
(a) Compression pre-cracking setup

(b) Crack propagation setup

Figure 1: Experimental setup for crack propagation characterization

Compression pre-cracking was applied to specimens by a four point bending configuration using a servo-hydraulic uniaxial facility with a 100kN load cell and a dedicated device, in Figure 1(a). The applied load was chosen in order to generate a 130Nm bending moment at stress ratio R=10 and at a

frequency of 30Hz. This bending value was set in order to generate, in 10^6 cycles, the naturally arrested pre-crack of about 0.3mm length at the two free surfaces.
After compression pre-cracking, every specimen was instrumented gluing two krak-gages RMF-A10, one for each side, with a measuring base equal to 10mm; these krak-gages are used, associated with the dedicated RUMUL Fractomat control unit, for the real-time monitoring of the crack length advancing during the test, by the meaning of the potential drop technique.
Crack propagation tests were carried on a Rumul Cracktronic resonant facility generating plane bending and vibrating at about 130Hz, in Figure 1(b). A total of 12 SE(B) specimens was tested, at different stress ratios ranging from R = 0.7, corresponding to the effective curve, till the value R=−2.5. A special attention was given to the very negative stress ratios, lower than -1, which are the expected stress ratios at the surface of the crack in a cold-rolled axle; for every stress ratio considered both the crack growth rate ('CPCA' test [18]: Compression pre-cracking Constant Amplitude) and the thresholds ('CPLR' test [13]: Compression Pre-cracking Load Reduction) were determined.
In order to move to the more negative stress ratios, two SE(T) 50x20mm specimens were pre-cracked in compression and tested to crack propagation on a mono-axial servo-hydraulic Schenck facility of 250kN maximum load; the setup permitted to test specimens till R=-4.



(a) ΔK_{th} dependency on the stress ratio R (b) Crack growth rate data

Figure 2: EA4T characterization for crack propagation

Figure 2 resume all the experiments done on the EA4T material. In Figure 12(a) is shown the threshold dependency upon the stress ratio R for the actual experimental campaign in comparison with the previous available data from literature [20]; it is evident that the compression-pre-cracking approach results in lower thresholds, with differences from the standard approach increasing for the very negative stress ratios and up to 25%. No significant difference between testing methods was found on the linear region of the Paris diagram, in Figure 1(b); the most interesting thing to be noted in this picture is that the curve tends to overlap for the very low stress ratios, so being indistinguishable; the test carried on at R=-4 coincide perfectly with the R=-2 curve.

2. Residual stresses profile

In Figure 3 is shown the approximation of the measurements performed by Polimi and IWM using both the XRD and the strain gage methods [10], regarding just the longitudinal stresses, directly acting on the crack opening; the residual stresses are confined in the first 2mm in the radial direction, starting from values higher than three times the σ_{lim} in compression at the surface and tending to zero at about 2mm in depth.

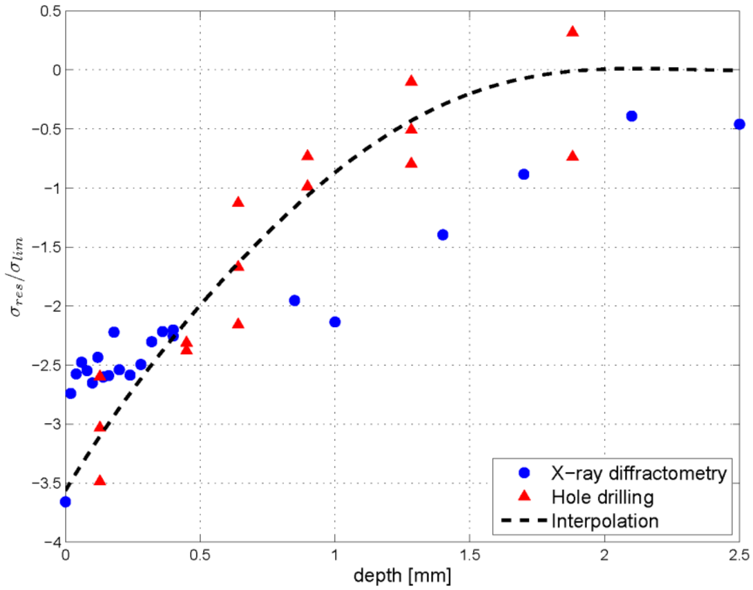


Figure 3: Longitudinal residual stresses behaviour in depth due to the cold-rolling procedure

Data from experiments is available just for the first 2.5mm in depth; it is reasonable to suppose that below this depth the residual stresses are no more acting.

3. **Propagation lifetime of full-scale cold-rolled axles**

A simple first calculation of the effect of the high compressive residual stresses due to the cold-rolling procedure, acting in the longitudinal direction, so closing the crack faces, leads to the graph of Figure 4. This graph shows, in dependence of the depth of an hypothetical crack inserted in the T-transition of the considered axle, the minimum stress amplitude required in order to overhaul the threshold SIF so letting the crack propagate. For cracks smaller than 2mm the load to be applied in order to propagate the defect are very high; for example, even in the worst case, considering the CPLR threshold, the value of the required stress for propagating a crack of 1mm depth is twice than the typical in-line stress; in other words, the residual stresses play a significant role in reducing the event of a crack initiation and propagation.
The beneficial effect, considering the deepest point of the crack, is acting just for the first two mm in depth, while the residual stresses remain negative; for cracks bigger than 2mm no beneficial effect is expected since the residual stresses tend to zero. This is valid for the deepest point of the crack, while the two surface points remain always compressed by the cold-rolling residual stresses, so limiting the opening of the crack itself during a loading cycle.

The second step for better understanding the effect of the residual stresses onto crack propagation was to made some comparative simulations of the process considering or not the presence of the cold-rolling residual stresses onto the axle. Since the purpose is just a comparison of results, simulations have been carried on using the same geometry of the axle used for the residual stress measurements.

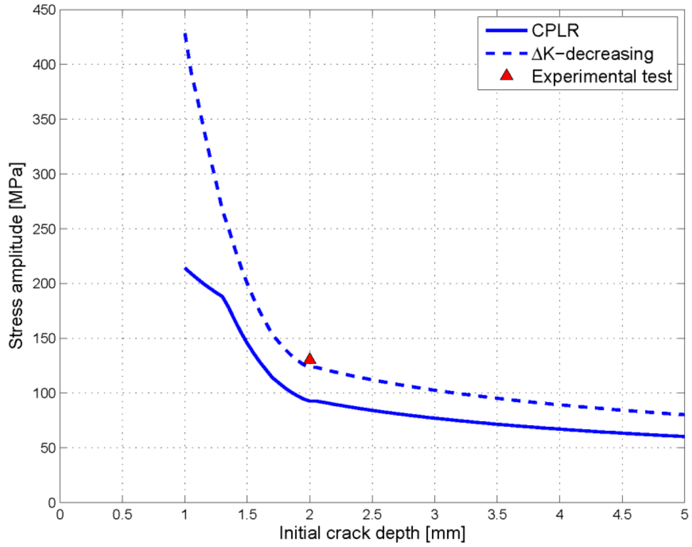


Figure 4: Minimum stress amplitude of the loading step required for overtaking the threshold SIF

The fictitious crack was placed in the T-transition of the axle, at the point affected by the maximum principle stress in bending; the load spectrum is the same derived from the service of the Kiruna axle (about 500km) [21], reported in detail in Figure 5(a) and (b).

The crack propagation algorithm was developed at PoliMi and it is based on the Shiratori weight functions [11] for the stress intensity factors calculation. These SIF solutions were developed considering the case of a semi-elliptical crack inserted in a thick plate subjected to a known stress distribution, which can be approximated in a polynomial form till the cubic degree.

The two contributions to the stress state, given by the superposition of the rotating bending and the residual stresses due to the cold-rolling procedure, were evaluated separately in terms of SIF acting on the crack; furthermore, this weight functions approach allowed the definition of the SIF independently for the two extreme points of the crack, at the bottom and at the free surfaces.

The value of the adimensional SIF is given in a tabular form for the two points *A* (bottom of the crack) and *C* (surface point), for every approximating polynomial degree; in particular, four crack dimensions *a/t* (0.2−0.4−0.6−0.8) with *t* thickness of the plate and four crack shapes *a/c* (0.2−0.4−0.6−1.0) are covered; the right adimensional SIF *M* in eq.(1) is evaluated during the simulation by extrapolation, considering the two stress shapes, given by the rotating bending and the residual stresses, which corresponds to given parameters K_0-K_3 in eq.(2).

$$M = \frac{K_I}{(1/\Phi)\sigma_0\sqrt{\pi a}} \qquad (1)$$

$$K_I = AK_3 + BK_2 + CK_1 + DK_0 \qquad (2)$$

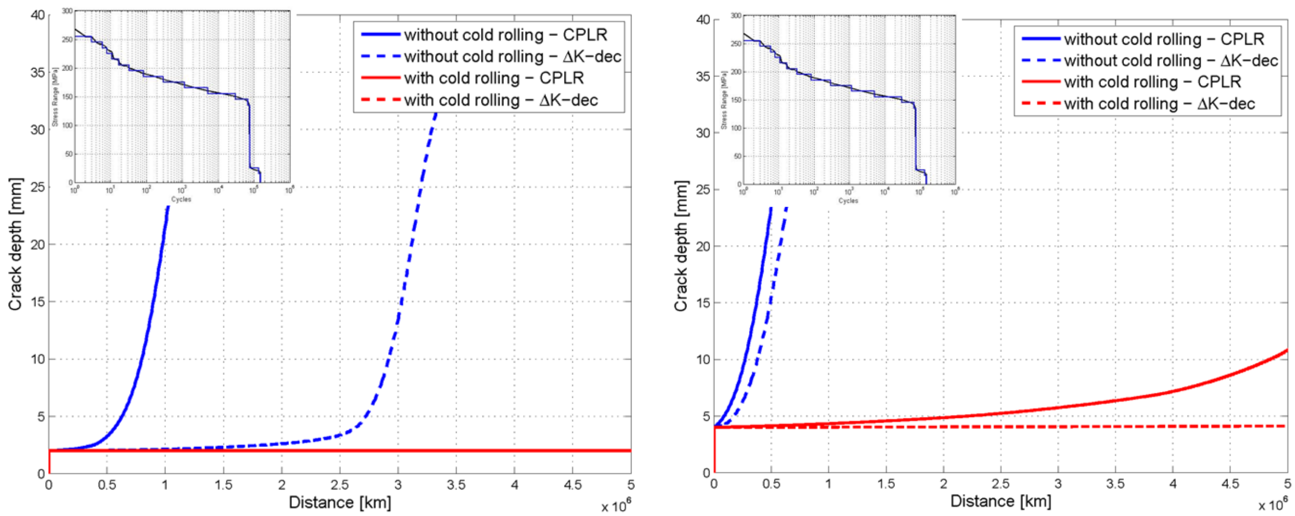
The solution developed by Shiratori gives good results not only for the thick plate, but also when applied to a full-scale axle with a typical semi-circular crack inserted [22]; the crack dimension is, in fact, small compared to the axle diameter, being well approximated by the Shiratori hypothesis.

The crack propagation algorithm is defined for every step of the load spectrum as follows:

1. definition of the initial crack depth and shape; a semi-circular crack was chosen;
2. calculation, given the load spectrum step, of the stress ratio acting at the depth and at the surface of the crack, given by the superposition of the rotating bending and the residual stresses field;

3. evaluation of the crack growth rate given the stress intensity factor and the stress ratio for both the extremes of the crack independently;
4. calculation of the actual crack depth and shape, which act as input for the following step of the load spectrum; the load spectrum sequence is repeated till failure.

In Figure 5 the results of the calculations are shown; two cases were considered, starting from semi-circular initial crack of 2mm and 4mm. Every plot contains the crack propagation curves evaluated for the two conditions of presence or not of the cold-rolling procedure.



(a) From an initial defect a_0=2mm (b) From an initial defect a_0=4mm

Figure 5: Crack growth predictions

The cold rolling procedure has a big impact onto life propagation; what is evident from the two graphs in Figure 5 in that a crack of initial depth a_0=2mm, the typical size of the defect usually considered from the definition of the inspection interval, is not able to propagate at all in presence of compressive residual stresses due to the cold-rolling procedure, while the same crack size can propagate till rupture in about 1 million km.

The simulations made on the axle, in presence of cold-rolling, carry to an estimated residual life of more than 1 million km even with a crack of initial depth a_0=4mm, extending considerably the residual life and the possibility of increase the distance between subsequent inspections, making it a "one million miles axle", in other words an axle that can be inspected every one million cycles.

4. Full scale test

In order to validate the theoretical model, a full-scale test was carried on a specially designed roll-formed railway axle, in Figure 6. The specimen was subjected to the same roll-forming treatment of the high speed axle. For the sake of simulating the presence of cracks, two artificial semicircular defects of 2mm depth were introduced in the roll-formed section by EDM.

The axle was tested at PoliMi under a full scale test bench which applies a three point bending on the rotating full-scale specimen (capacity 250kNm).

The test consisted on the repetition of 10 million cycles at 125MPa of nominal stress on the cracked section; this stress corresponds to a ΔK higher than the SIF threshold at the bottom of the crack, as in Figure 4; at the surface point all the cycle remains in compression. During the test, no crack growth was measured during inspections using both visual (by optical microscope) and ultrasonic testing (single crystal and phased array probes).

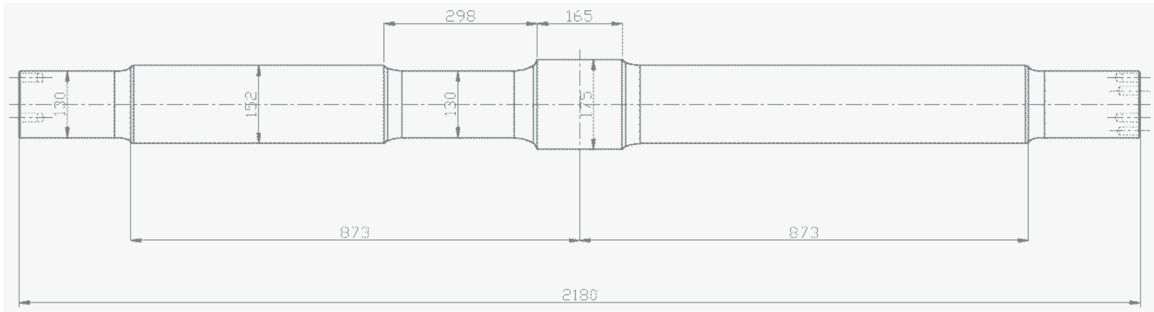


Figure 6: Full scale cold-rolled specimen specially designed for the crack propagation test

After the test at constant amplitude, the axle was tested using the same loading spectrum from the typical high-speed service [21] already used for the calculations; the following tests were performed:

- original load spectrum till reaching a distance of approx. $4x10^6$ km;
- load spectrum increased by 125% till reaching a distance of approx. $3.5x10^6$ km.

Also during the variable amplitude loading test, the crack didn't propagate, even with an increasing of the loading steps of 125% in amplitude.

Concluding remarks

In this research we have examined the effect of cold rolling upon the propagation lifetime of railway axles. The research has dealt with the following phases: i) characterization of propagation of axles steel with R<-1; ii) measurements of the residual stresses onto cold rolled axles; iii) estimation of propagation lifetime; iv) verification onto full-scale rolled specimens; v) estimation of inspection intervals in rolled axles.
A big effort was made for the characterization of the EA4T steel grade in the region of the very low stress ratios (below -1) in order to understand the material behavior in presence of the very high compressive residual stresses acting on the surface of the axles when cold-rolled; considerable discrepancies were found in the threshold region between experimental techniques, leading to non conservatism using the traditional ΔK-decreasing procedure; the threshold behavior below the stress ratio -2.5 was found to be nearly constant.
The effect of the roll forming procedure was found to be highly beneficial for the railway axle; the simulations of the crack propagation showed a big increasing of the residual lifetime considering crack of initial depth 2 and 4mm, which are not able to propagate for several million cycles, making the axle a "one million miles axle".
The experiments carried on a full scale specimen, cold rolled with the same procedure as the high speed axles, confirmed the results from simulations; an artificial defect of 2mm depth was not able to propagate for more than 7 millions km even increasing the load spectrum, from the high speed service, by a factor 125%.

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References

[1] A. F. Jr.Grandt, *Fundamentals of Structural Integrity*, JohnWiley & Sons, Hoboken, NJ, 2004.

[2] U. Zerbst, R. Lunden, K.-O. Edel, RA. Smith, *Introduction to the damage tolerance behaviour of railway rails – a review*. Eng Fracture Mech 2009;76:2563–601.

[3] M. Carboni, S. Beretta, *Effect of probability of detection upon the definition of inspection intervals of railway axles*. J Rail Rapid Transit, 221 (2007), pp. 409–417.

[4] S. Cantini, S. Beretta, M. Carboni, *POD and Inspection Intervals of High Speed Railway Axles*, 15th International Wheelset Congress, Prague, Czech Republic, 2007.

[5] S. Beretta, M. Carboni, *Inspection Intervals of Railway Axles: Influence of Stress Spectrum*, Eighth International Conference on Engineering Structural Integrity Assessment (ESIA8), Manchester, United Kingdom, 2006.

[6] M.A. Moshier, B.M. Hillberry, *The inclusion of compressive residual stress effects in crack growth modeling*, Fatigue Fract Eng Mater Struct, 22 (1999), pp. 519–526.

[7] F.P. Brennan, S.S. Ngiam, C.W. Lee, *An experimental and analytical study of fatigue crack shape control by cold working*, Engineering Fracture Mechanics 75 (2008) pp. 355–363.

[8] C. Gardin et al., *Numerical simulation of fatigue crack propagation in compressive residual stress fields of notched round bars*, 2007 Fatigue Fract Engng Mater Struct 30, 231–242.

[9] C. Gardin et al., *The influence of roller burnishing on the fatigue crack propagation in notched round bars - Experimental observations under three-point bending*, 2007 Blackwell Publishing Ltd. Fatigue Fract Engng Mater Struct 30, 342–350.

[10] S. M. H. Gangaraj, M. Guagliano, M. Carboni, *On the residual stress generation during deep rolling of cylindrical parts: experimental and numerical analysis*, submitted to ICRS9, October 2012, Germany.

[11] M. Shiratori, T. Miyoshi, K. Tanikawa, *Analysis of Stress Intensity Factors for surface cracks subjected to arbitrarily distributed surface stresses*, Trans. Japan. Soc. Mech. Engrs., Vol.52 (1986), pp.409-417.

[12] ASTM E647-05, *Standard Test Method for Measurement of Fatigue Crack Growth Rates*, Annual Book of ASTM Standards, Vol. 3(1), ASTM International.

[13] S. C. Forth, J. Jr. Newman, and R. G. Forman, *On Generating Fatigue Crack Growth Thresholds*, Int. J. Fatigue, Vol. 25, 2003, pp. 9–15.

[14] S. C. Forth, J. Jr. Newman, and R. G. Forman *Evaluation of Fatigue Crack Thresholds Using Various Experimental Methods*, J. ASTM Int., Vol. 2, 2005, Paper ID JAI12847.

[15] J. Jr. Newman, J. Schneider, A. Daniel, and D. McKnight, *Compression Pre-Cracking to Generate Near Threshold Fatigue-Crack-Growth Rates in Two Aluminum Alloys*, Int. J. Fatigue, Vol. 27, 2005, pp. 1432–1440.

[16] M. Carboni, L. Patriarca, D. Regazzi, *Determination of ΔKth by compression pre-cracking in a structural steel*, Journal of ASTM International, 6(9):1-13, 2009.

[17] R. Pippan, *The Growth of Short Cracks Under Cyclic Compression*, Fatigue Fract. Eng. Mater.Struct., Vol. 9, 1987, pp. 319–328.

[18] J. Jr. Newman, Y. Yamada, *Compression Pre-Cracking Methods to Generate Near-Threshold Fatigue-Crack-Growth-Rate Data*, 17th European Conference on Fracture (ECF17), Brno, Czech Republic, 2008.

[19] R. Pippan, H. P. Stüwe, K. Golos, *A Comparison of Different Methods to Determine the Threshold of Fatigue Crack Propagation*, Fatigue, Vol. 16, 1994, pp. 579–582.

[20] M. Carboni, D. Regazzi, *Effect of the experimental technique onto R dependence of ΔK_{th}*, 11th International Conference on the Mechanical Behavior of Materials, June 5-9, 2011, Como (Italy); pp. 2937-2942.

[21] S. Beretta, M. Carboni, S. Cervello, Design review of a freight railway axle: fatigue damage versus damage tolerance, Mat.-wiss. U. Werkstofftech. 2011, 42, No. 12.

[22] M. Madia, S. Beretta, M. Schödel, U. Zerbst, M. Luke, I. Varfolomeev, *Stress intensity factor solutions for railway axles*. Engng Fract Mech, 78 (2011), pp. 764–792.