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EVALUATION OF RESIDUAL STRESS AND TENSILE PROPERTIES OF RAILWAY AXLE USING INSTRUMENTED INDENTATION METHOD.

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Abstract
This paper deals with the characterization of residual stresses of the railway axle made of EA4T steel using the instrumented indentation technique (IIT). Additionally, tensile properties were also evaluated by using IIT. Moreover, the hole drilling method was carried out to measure the residual stress. Multiple comparison tests between conventional methods and IIT were carried out. The obtained results were also discussed against the literature data. Results of the residual stress assessed by IIT and the hole drilling follow the same trend and are in acceptable agreement. The tensile data obtained by IIT were as follows: YS ≥ 420 MPa and UTS ∈ ⟨650-800⟩MPa which is in satisfactory agreement with the results of standardized tensile tests.
Keywords: residual stress, tensile properties, instrumented indentation method, EA4T steel, railway axle, advanced indentation system

INTRODUCTION

Railway axles are one of the most crucial parts which support railway vehicles. A failure would have serious consequences and a failsafe system cannot be used as a backup; it must be designed to be reliable. To ensure a longer lifespan proper maintenance is important as well as evaluating mechanical properties and residual stress. This paper deals with evaluating the residual stress and tensile properties with the indentation method.
Since materials degrade over time and especially crack generation and propagation can lead to a component failure before its life expectancy, it is advised to test industrial facilities in service during operation as well as before use. Most conventional methods are destructive, making them unsuitable for field inspection, meaning non-destructive methods must be introduced. During the collection of specimens, damage to the machine can be caused or stress relief can be caused due to specimen extraction so the specimen can have different mechanical properties from the original site structure meaning they cannot be used as in-service tests. With the introduction of automated indentation systems quasi-non-destructive test methods were introduced [1].

The instrumented indentation technique can evaluate not only hardness but also tensile characteristics. In many components, residual stresses are the results of thermal mismatch or thermal/mechanical processing during their manufacturing and can be purposively introduced in parts to affect their mechanical properties especially to enhance resistance against crack propagation. Hence for correct estimation of the remaining lifespan of the railway axle, it is needed to estimate residual stresses and mechanical properties such as the yield stress (YS) and the ultimate tensile strength (UTS) [1,2,3].

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There are many ways to measure and evaluate the residual stress such as a hole drilling method, a ring core method, a crack compliance method, various diffraction methods, and ultrasonic or magnetic methods [4,5].

This paper deals with the measurement of tensile properties and residual stresses on the radial segment of the railway axle employing instrumented indentation testing (IIT). Furthermore, the residual stress was also evaluated using the hole-drilling method. The results of the IIT were compared to the results of conventional experimental techniques, such as tensile testing and hole drilling. The main objective of this study is to test the reliability of the IIT and validate the results of the IIT.

Nomenclature

Symbol	**Designation**	**unit**
A_c	The projected area of the contact surface between the indenter and the tested sample	mm^2
A_c^T	True contact area	mm^2
A_c^0	Actual contact area	mm^2
a_c	Contact radius	mm
a,b, c	Correlated constants	-
E_{IT}	Indentation modulus (Young's modulus)	N/mm^2
F_{max}	Maximum test force	N
h_d	Elastic deflection depth	mm
h_c	Contact depth of the indenter with the test piece at F_{max}	mm
h_{max}	Maximal indentation depth	mm
h_{pile}	Height of plastic pile up	mm
K	Strength coefficient	-
L_0	Indentation load	N
L_T	Tensile load	N
P_{max}	Maximum load	N
R	Radius of indenter	mm
S	Stiffness	N/mm
α	Proportional constant	-
γ	The half angle between the indenter and material	°
ε	Constant of the shape of the indenter	
ε_T	True strain	-
ε_u	True uniform strain	-
ε_y	Yield strain	-
n_{IT}	Indentation work hardening exponent	-
σ	Tensile strength	N/mm^2
σ_{res}	Surface residual stress	N/mm^2
σ_T	True stress	N/mm^2
σ_{uIT}	Indentation tensile strength	N/mm^2
σ_{yIT}	Indentation yield strength	N/mm^2
ψ	Plastic constraint factor	-
Note N/mm^2 = 1 MPa		

THEORETICAL BACKGROUND

Tensile properties evaluation

To be able to measure with indentation methods it is needed to convert indentation load to tensile properties and stress with the corresponding contact area. While in light microscopy area is calculated by observation under the microscope in instrumented indentation testing (IIT) area is calculated from shape of the indenter and the depth of the indent. When testing even if the material is considered not to be elastic material the response always includes elastic deflection and plastic response such as pile-up and sink-in of material. Those factors result in a difference in indentation depth and real contact depth. In the past Oliver-Pharr equation was widely used for contact mechanics (Hertz law) (1).

$$h_d = \varepsilon \frac{P_{max}}{S} \tag{1}$$

Where P_{max} is the maximum load, S is contact stiffness, and ε is the constant of the shape of the indenter (0.75 for spherical indenter). Later the equation was changed [6] to (2)

$$\frac{h_{pile}}{h_c} = f\left(n_{IT}, \frac{h_{max}}{R}\right) \tag{2}$$

Where h_c is contact depth, h_{max} is maximal indentation depth and h_{pile} is the height of plastic pile up, R is the radius of the indenter and n is strain hardening exponent. Afterward using Tabor's relations, the indentation load can be expressed by representative stress σ and mean pressure p_m [7]. Solving multiple equations derived by Kwon, Lee, Kim, Kim, and Choi in 2005 [8] and later followed by Kwon, Kim, Kim, Kim, and Song in 2011 [9] we get to the Eq. (3).

$$\varepsilon_T = \left(\frac{\alpha}{\sqrt{1-(\frac{a_c}{R})^2}}\right)\left(\frac{a_c}{R}\right) = \alpha \tan\gamma \tag{3}$$

Where ε_T and α are representative strain and proportional constant. Stress is then defined by the following equation

$$\sigma_T = \frac{1}{\psi}\frac{F_{max}}{A_c} \tag{4}$$

F_{max} is the maximum test force, A_c is the projected area of the contact of the indenter at distance h_c correlated to h_{pile} and h_c from the tip, and A_c is calculated from (5) [10]:

$$A_C = \pi(2Rh_c - h_c^2) \tag{5}$$

For steels, it is then sufficient to use the constitutive Eq. (6) for power-law hardening materials and (7) for linear hardening materials to fit the stress-strain dependence. σ_T is true stress and a, and b are correlated constants. K is Strength coefficient and ε_T is true strain [10]:

$$\sigma_T = K\varepsilon_T^n \tag{6}$$

$$\sigma_T = a + b\varepsilon_T \tag{7}$$

Afterward, it is needed to determine yield strength as the intercept point of the elastic line and plastic curve (8) where E_{IT} is the indentation modulus (Young's modulus), and K is the strength coefficient. E_{IT} is determined from the unloading part of the indentation curve.

$$K\varepsilon_{T}^{n_{IT}}{}_{y} = E_{IT}(\varepsilon_y - 0{,}002) \tag{8}$$

The tensile strength is determined by the instability in tension:

$$\frac{d\sigma}{d\varepsilon} = \sigma \tag{9}$$

When combining the Eqs. (6) and (9) we get $\varepsilon_u = c \cdot n_{IT}$, c is the correlated constant, and n is the strain hardening exponent. With Eqs. (2-9) we can calculate tensile properties $\sigma_{y,IT}$, $\sigma_{u,IT}$, n_{IT}, E_{IT} [8,11].

Residual stress evaluation

The fundamentals of evaluating residual stress with the IIT are based on the comparison of the reference place which is stress-free with the target point of interest with measured residual stress. The residual stress shifts the indentation load-depth curve depending on the state of the material. If the material is under tensile residual stress the indenter penetrates deeper into the material than in a stress-free state and likewise, material under compressive residual stress is penetrated less by the indenter. This is shown in Fig. 1.

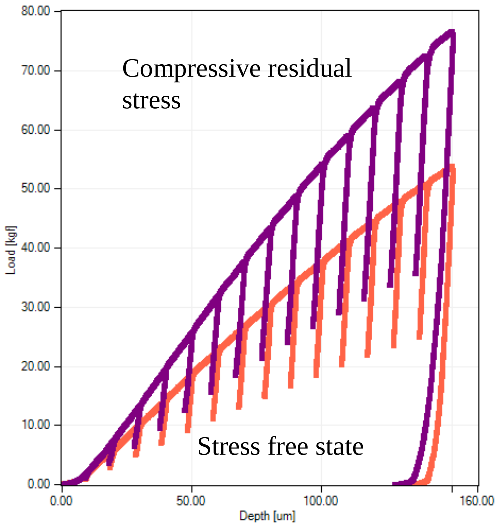

Fig. 1. Comparison of indentation curves in a stress-free state and with residual stress

Since in practice depth is used as constant, to reach the same depth load will be greater/lesser than in a stress-free state depending on residual stress. Assuming the surface residual stress is in equibiaxial tensile state ($\sigma_{res,x}$=$\sigma_{res,y}$=σ_{res}, $\sigma_{res,z}$=0) and by removing hydrostatic stress we get to Eq. 10 [6] where A_C^T is contact area and L_0-L_T is the load shift due to tensile stress:

$$\sigma_{res} = \frac{3(L_0 - L_T)}{2A_C^T} \tag{10}$$

In case that the stress is not completely equibiaxial influence of biaxial stress has to be taken into consideration and ratio p =($\sigma_{res,x}$/$\sigma_{res,y}$) has to be introduced (11):

$$\sigma_{res} = \frac{3(L_0 - L_T)}{(1+p)A_C^T} \qquad (11)$$

However, presented theoretical models deal only with the magnitude of the average stress meaning we do not get any data about the direction or magnitudes of individual components of the stress [5,6,11].

EXPERIMENTAL

Material

The material under study is a radial segment of the railway axle. The dimensions are as follows, the diameter is 18 cm and the segment thickness is 3cm. The surface had been ground up to 2400 grit sandpaper. Chemical analysis of the railway axle has been performed and it was confirmed that the tested material was steel EA4T (25CrMo4). The chemical composition is shown in Tab. 1.[12].

Tab. 1. Chemical composition of the EA4T steel

C [wt %]	Mn [wt %]	Si [wt %]	P [wt %]	S [wt %]	Cr [wt %]	Ni [wt %]	Mo [wt %]
0.0038	0.00489	0.00077	2E-04	3E-04	0.00887	0.00081	0.00145
Cu [%]	Ti [wt %]	Co [wt %]	Pb [wt %]	V [wt %]	W [wt %]	Al [wt %]	Nb [wt %]
0,00006	<0.001	<0.001	<0.001	4E-04	0.0005	0.00011	<0.001

Tensile properties tests

IIT was performed by AIS 3000HD made by Frontics Co., Ltd. The AIS3000HD attached to the railway axle segment via the sample holder is shown in Fig. 2. Every test consists of 15 loading and unloading cycles to a max depth of 150 μm as is shown in

Fig. 3. Tests are performed by spherical indenter from tungsten carbide with a radius of 500μm. The unload ratio is 50%. Multiple tests were performed from the center to the outer surface of the tested axle. However, due to the loading limit of the AIS 3000HD, it was not possible to get precise data in the outer induction hardened layer.

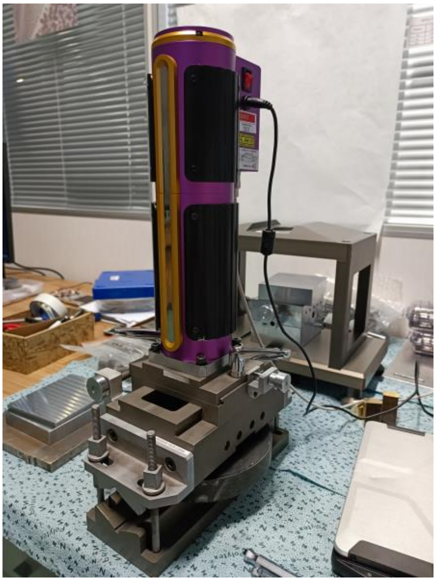

Fig. 2. AIS3000HD with railway axle segment

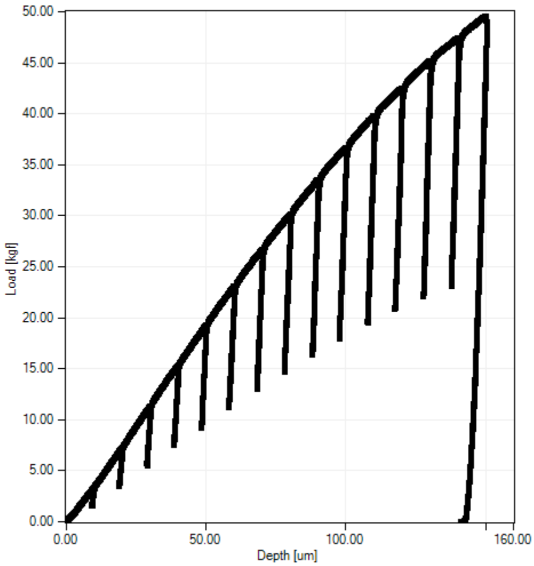

Fig. 3. Load-displacement curve of the tensile test by IIT

Residual stress measurement

IIT was performed with AIS 3000HD. Two sets of tests must be performed for each series. One set is with a spherical indenter and the second set is with a Vickers indenter. Both tests have reference indents in the material without any residual stress and then target spots of interest. The spherical indenter is visible in Fig. 4. Both reference tests consist of 15 loading and unloading cycles with partial unloading with an unloading ratio of 50%. The same goes for target tests with spherical indenter. Unlike the rest of the tests, Vickers target has a single loading cycle to max depth with consequent unloading. With Vickers indenter, the controlling parameter is max load. Using Eqs. (10-11) residual stress is then calculated.

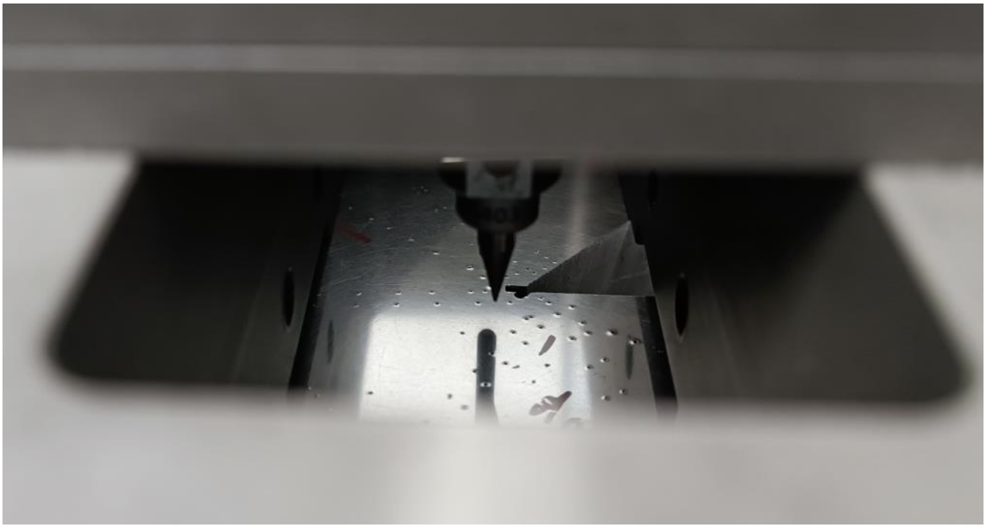

Fig. 4. Spherical indentor of AIS3000HD and visible indents of tests

Hole drilling

Residual stress evaluation by hole drilling method was performed using MTS3000 – RESTAN by SINT technology. First, the surface of the tested specimen was ground. Points of measurement were in distances of 35 mm and 47 mm from the center of the axle. Then strain rosettes were soldered to the tested place and the measuring apparatus was fixed to the axle. The high-speed drill moved down to 2 mm with 0,05 mm increments. For each drilling step, strains created by relaxation were acquired and used to calculate residual stress.

RESULTS AND DISCUSSION

Tensile properties

The reason for the partial unloading is twofold. Firstly, using each unloading cycle is intended to estimate contact radius, F_{max}, h_{max}, and S, and secondly, by partially unloading during the test we relieve elastic deformation, so we get more accurate results of tensile properties. Each test gives us a stress-strain curve depicted in Fig. 5.

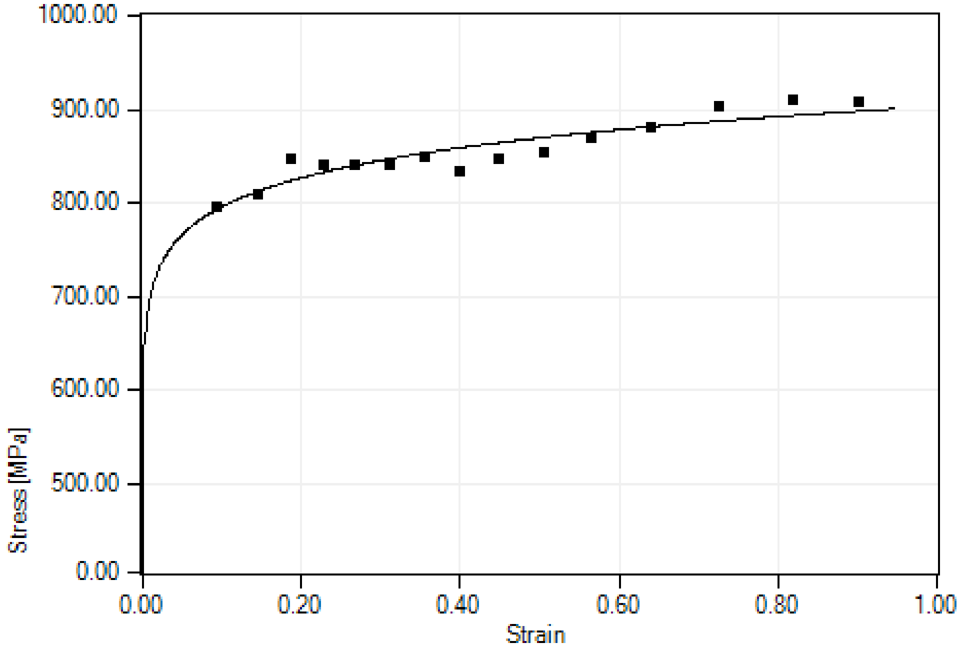

Fig. 5. True stress-strain curve of indentation test performed on AIS 3000HD used for calculations of YS and UTS

Every point in the diagram is one cycle of the tensile test and it gives us values of coefficients, load, and depth by which using Eqs. (5-8) yield strength (YS) and ultimate tensile strength (UTS) are calculated. The measured values are engineering values. 24 tests were performed in 3 rows of 8 and the results are summarized in Tab. 2.

Tab. 2. Results of the tensile tests

No. Of test	1	2	3	4	5	6	7	8
YS [MPa]	597	623	648	591	619	589	665	635
UTS [MPa]	711	782	733	693	748	724	759	733
No. Of test	9	10	11	12	13	14	15	16
YS [MPa]	607	635	614	595	618	650	626	630
UTS [MPa]	707	803	701	698	734	728	710	722
No. Of test	17	18	19	20	21	22	23	24
YS [MPa]	653	615	642	647	620	626	645	389
UTS [MPa]	751	699	727	731	729	764	751	756

The results of tests were discussed against the literature data. The standard EN 13261 [12] sets properties of the EA4T steel in the following way: $YS \geq 420\ MPa$ and $UTS \in \langle 650 - 800 \rangle$. As is visible in Tab. 2. YS as well as UTS are in satisfactory agreement with the standard values. The values of YS and UTS are plotted in Fig. 6 as functions of the distance from the axle center. The values are independent of the radial distance.

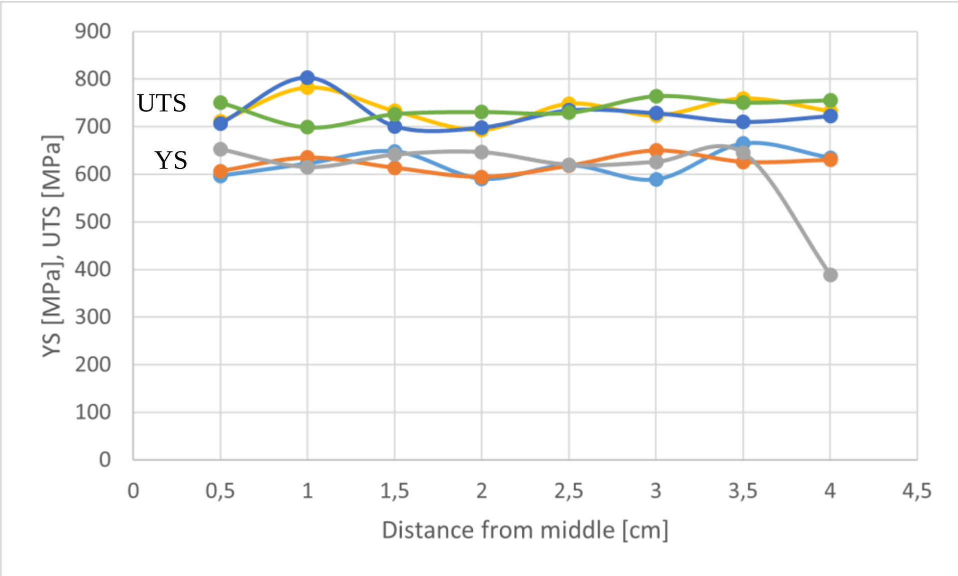

Fig. 6. YS and UTS measured by IIT measured from the middle to the outer surface of the axle

Residual stress

Multiple tests by indentation methods were performed and two tests by drilling method were carried out for comparison. Sets of tests by IIT were performed from the center of an axle to the outer surface. In the inner part of the axle, it was possible to get accurate results, however, in the outer induction hardened layer the results were incorrect due to the loading limit of indentation equipment.

Two tests by drilling method were performed in 35 mm and 47 mm from the middle of the railway axle. The acquired values are presented in Fig. 7 and compared to the results of IIT tests positioned at the same distance from the center of the axle segment. The results are in very good agreement at point 35mm from the middle. The results of the second test by drilling method differ a lot from the first drilling test and tests done by the IIT. The mean values differ considerably. A mean value of 274 MPa was assessed by IIT and a mean value of 115 MPa was determined by the hole drilling.

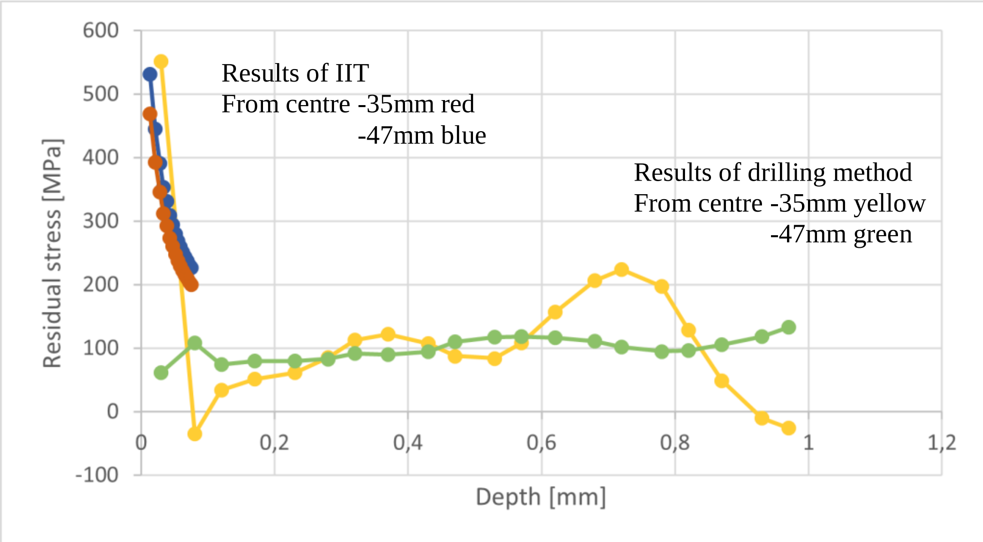

Fig. 7. Residual stress measured by IIT and the drilling method as a function of the depth of measurement.

SUMMARY AND CONCLUSIONS

The possibility of measuring tensile properties and residual stress on the radial segment of the railway axle with instrumented indentation testing was studied.

Multiple tests of tensile properties were performed and as the results were in satisfactory agreement with the standard values, it was shown that IIT is a viable technology for measuring tensile properties.

Series tests of residual stress measurement by IIT were performed and compared to the results of the conventional drilling method. The mean value of the results differs a lot. The hole drilling method results are from a higher depth which influences the mean value by a high margin. However, in the same depth, the results of IIT and hole drilling follow the same trend and are in satisfactory agreement. The results further suggest that surface residual stress can differ by a high margin. IIT has a higher limit in the maximum depth compared to hole drilling. That is why the results may differ substantially.

The results of IIT could not be evaluated in the induction hardened layer of the axle, because the hardness of the material was too high in that area, and consequently, the limit load of AIS3000HD was reached. Further testing by IIT needs to be carried out in this region to find the right parameters.

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