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THE INFLUENCE OF FORGING TEMPERATURE, DEFORMATION DEGREE AND HEAT TREATMENT ON THE MECHANICAL PROPERTIES OF SHIP AXLES

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ABSTRACT
Forgings of ship axles are the group of middle and large forgings. They are produced by free forging on hydraulic presses, and production technology alone is very complex, careful lasting long time, and very expensive. In aiming observation and innovation of forging and heat treatment technology in this paper are presented performed mechanical testing and structural characteristics examination of forgings made from carbon steel (internal mark LRK). These forgings are one or two times normalisation annealed under the industrial scale conditions.
Keywords: ship axles, temperature, deformation degree, normalisation annealing, mechanical properties

1. INTRODUCTION
For manufacturing ship axles are used carbon, carbon-manganese and alloyed steels. Theirs chemical analysis and production process is ordered by manufacturers, while manufacturing, grade and manner of quality control are defined by contract or regulations of specialized register of companies* as: LR, BV, DNV, ABS, HRB, RIN, etc. Ship axles represent very responsible parts, which fail can provoke wide repercussion connected with safety of ships and men.
In this paper researches are directed to examination influence of finishing forging temperatures, deformation degree and heat treatment on mechanical properties of carbon steel for ship axles.

2. MANUFACTURING OF SHIP AXLES
Total technological manufacturing process of steel for ships axles forgings is regulated by contract and regulation one of mentioned register Limited. Regulations of that register Limited between other facts content limited values of chemical analysis, mechanical properties and delivery conditions.

2.1. Chemical analysis
Maximal values of each element of carbon and carbon-manganese steels (mass. %) for forgings prescribed by HRB and LR regulations, is obtained at Table 1.

Table 1. Chemical analysis of steels in accordance with HRB and LR [1,2]

Regu-lations	Elements content (mass %)								
	C max.	Si max.	Mn	P max.	S max.	Cu max.	Cr max.	Ni max.	Mo max.
HRB	0.50	0.50	0.3/1.7	0.035	0.035	0.30	0.035	0.035	0.08
LR*	0.65	0.65	0.8/1.5	0.035	0.035	0.30	0.035	0.035	0.15

* Content of Cu+Cr+Ni+Mo = 0.85 % max.

Chemical analysis of elements is ordered by manufacturer in dependance of wanted properties. Manufacturer can, in dependance of situation use also elements for grain rafination as Al, Nb or V.

2.2. Deformation degree and heat treatment

During axles forging from ingots, degree of section reduction must not be smaller than ratio 3:1 for parts with forgings length L>3, in regard to 1,5:1 for parts with forgings length L≤ D, where is D diameter of forgings. Heat treatment is prescribed by the manufacturer. All register companies prescribed that tempering temperature must be over 550 ^oC.

2.3. Mechanical and technological properties

Mechanical properties of ships axles forgings in normalising conditions have to be in accordance with HRB and LR regulations, presented at Table 2.

Table 2. Mechanical properties of steels in accordance with HRB and LR [1,2]

Regu-lations	Diameter (mm)	R_m (MPa)	R_{eH} (MPa)	A (%) min			Z (%) min			KV (J) min			KU5 (J)			HB
				U	T	P	U	T	P	U	T	P	U	T	P	
HRB	<250≤500	400	200	26	23	19	50	42	35	32	25	18	30	25	20	110-150
	<500≤1000									32	25	18	27	22	17	
	<250≤500	520	260	21	18	15	45	38	30	25	20	15	25	20	17	150-185
	<500≤1000									24	18	13	20	15	11	
LR*		400	200	26	-	19	50	-	35	-	-	-	-	-	-	-
		520	260	21	-	15	45	-	30	-	-	-	-	-	-	-

*In accordance with these regulations it is planed testing for bending with angle, $\alpha = 180^o$

Remark: marks U, T, P are marks for position of testing pieces into forgings
(U – longitudinal, T – tangential, P - transversal)

3. EXPERIMENTS

In accordance with aim of examination of influence of forging temperature, deformation degree and heat treatment on mechanical properties of ship axles, it has been 2 step forgings from steel internal marks LRK* under the industrial scale of Iron and Steel Works "Zenica" Zenica (today Mittal Steel).

3.1. Chemical analysis

Gradual forgings have been produced from ingots with mark K 30S (mass 30 t). Ingot was poured from melt with chemical analysis presented at Table 3.

Table 3. Chemical analysis of steels (melt number 034917V)

Content of element (mass %)								
C	Si	Mn	P	S	Cu	Cr	Ni	$Al_{top.}$
0,34	0,23	0,76	0,013	0,022	0,11	0,04	0,02	0,008

Chemical analysis of elements is between limits ordered by regulations for steel LRK [3]. Melt was vacuum treated before pouring.

3.2. Plastic deformation – forging

After heating of ingots K 30S (mass 30 t) on 1250 ^oC and forging onto dimension Ø 625x260 mm from upper part of ingot - head part it was cut part (mass about 6 t). From that part were forged two pieces as step forging (figure 1).

Forging process of manufacturing of gradual forging was performed on hydraulic 4-column support press with power of pressing with 51 MN with preheated fitted into tool with width of 250 mm and with notch angle of 135 ^{o}. One of forgings was forged after heating up to 1020 ^oC and another up to 900 ^oC. After forging step forgings have been cooled on the air, and then they have been undertaken to dimensional and ultrasonic waves control. By ultrasonic waves control testing there was not detected any internal defects. From cooled forgings have been taken samples for mechanical and structural testing and examination.

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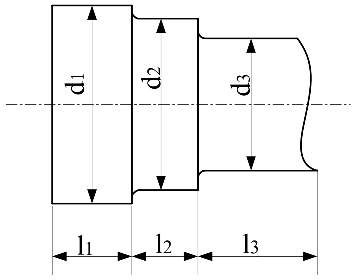
* Steel with internal mark LRK is carbon steel with 0.20 – 0.26 % C and with 0.65 - 0.90 % Mn, which poses good combination of tensile and ductile properties.



Forging Temperature (°C)	Dimensions (mm) and deformation degree ϵ (%)								
	d_1	l_1	ϵ_1	d_2	l_2	ϵ_2	d_3	l_3	ϵ_3
900	570	280	15	510	230	32	390	330	60
1020	575	230	14	522	210	29	410	375	56

Figure 1. Shape and dimensions of step forgings

3.3. Heat treatment

Both gradual forging are double normalised, after that treatment from them are taken samples for mechanical and structural testing and generally after each normalisation. Place and position of sampling on the forgings are presented on Figure 2.

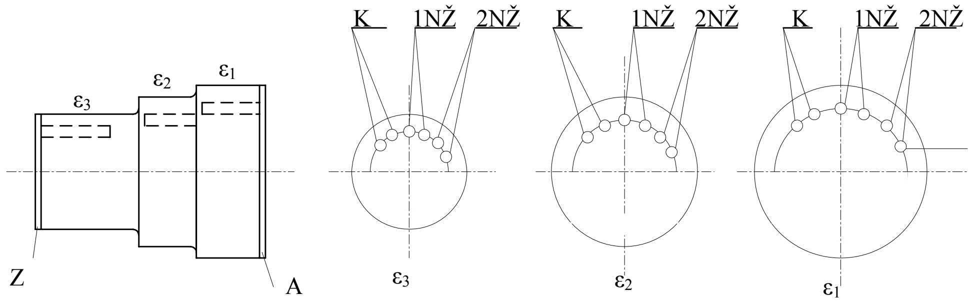


Figure 2. Place and position of sampling on gradual forgings

In accordance with Figure 2, has been taken twice 2 samples (rods ∅ 22x180 mm) from each grade from both forgings and also after forging (F) after first (1NA) and after second (2NA) normalisation, i.d. together 36 samples. Position of the samples was along the length of the forgings, and on the distance of two thirth of forgings radius (R) form longitudinal length. Mechanical testing are included examination of tensile strength and examination of impact test. Reminders of samples from impact testing, as well as plates A and Z (figure 2), are used for metallographic examination.

3.4. Results of examination

3.4.1. Results of mechanical testing

Results of mechanical testing are presented in Table 4.

From Table 4 it is possible concluded:

- mechanical properties both gradual forgings into once or twice normalised state are over values given into regulations of register of limited as HRB, LR etc.;
- values from Table 4 indicate that is questionable perform double normalisation, because of that, that values are insignificantly higher comparing to once performed normalisation;
- values of mechanical properties for forgings forged at 1020 °C and at 900 °C are insignificantly differ, so it would be more justified to (saving of energy) performed final forging at about 900 °C;
- deformations degree (from 14 % to 60 %) at both mentioned temperatures there is no essential influence on mechanical properties.

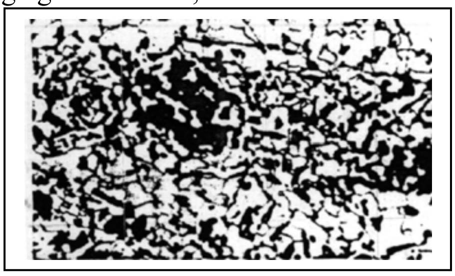
Table 4. Results of mechanical testing

Forging Temperature	Status	Deformation degree ε (%)	R_{eH} (MPa)	R_m (MPa)	A (%)	Z (%)	Impact work values* KU (J) Particular value 1	2	3	Aver. value
900 °C	Forged	15	260	484	32,9	60,5	46	40	41	42
		32	266	490	31,6	58,7	41	40	43	41
		60	276	497	30,6	56,8	38	49	46	44
	Normalised once	15	273	484	32,3	61,4	42	40	42	41
		32	273	490	32,7	61,4	46	41	44	44
		60	291	490	34,3	59,9	43	47	43	44
	Normalised twice	15	266	481	32,9	60,5	44	50	50	48
		32	266	487	32,1	61,4	50	48	52	50
		60	277	488	28,6	59,9	52	58	56	50
1020 °C	Forged	14	260	497	30,3	54,0	42	41	43	42
		29	260	487	30,9	53,0	42	42	46	43
		56	266	500	27,1	54,9	48	46	56	50
	Normalised once	14	292	484	31,4	63,1	50	52	50	51
		29	292	484	32,9	64,9	56	56	60	57
		56	318	474	34,1	61,4	58	54	52	55
	Normalised twice	14	240	471	30,9	63,1	56	46	44	49
		29	244	477	33,3	62,0	52	56	57	55
		56	244	477	31,7	62,3	52	52	58	54

* Notch is 5 mm (KU 300/5)

3.4.2. Results of metalography examination

Metalography examinations are preformed on macro and micro level. On the plates A and Z are performed macro examinations (Baumann print and deep etching). On the plate A is discovered tolerated presence of segregations onto central cone and rough structure, while onto plate Z there is no defects. Microstructure is observed and estimated on the specimens into forged state as well as after normalisation or after double normalisation. There is no difference of structure after normalisation or after double normalisation. Structure is ferrite-bainite (figure 3) while there is on forgings after forging from 1020 °C without normalisation with 14 % of deformation discovered unpleasant Widmanstätten structure, which was removed by performing double normalisation annealing. Widmanstätten structure is not discovered after forging onto 900 °C, or after ones ore double normalisation annealing.



a) 1% HNO3 magnification 100x

b) 1% HNO3 magnification 100x

Figure 3. Microstructure: a) Ferrite-bainite; b) Widmanstätten structure

4. CONCLUSIONS

Mechanical properties of graduated forgings made from steel with internal marks LRK on forging temperatures 1020 °C and 900 °C and with deformation degree between 14 % and 60 %, as well as after once or double normalisation at all satisfy regulations HRB [1] and LR.

Mechanical property values, except for impact work, for once normalised graduated forgings are double higher than at double normalised forgings. If final forging operations are performed at temperature 900 °C and if there is minimal degree of deformation 15 %, it is possible to apply one normalisation annealing, what is large saving of energy and in men power.

5. REFERENCES

[1] *** Regulations for technical inspection of maritime ships (Part 25., Section 1.), 1996,
[2] *** Rules for the manufacture, Testing and certification of materials, July 2004,
[3] *** Regulations for chemical analysis of steel, RMK-Zenica, May 1989.