UDK 669.14.018:621.73:621.438
Professional article/Strokovni članek

ISSN 1580-2949
MTAEC9, 42(3)135(2008)

AN EVALUATION OF THE PROPERTIES OF ROTOR FORGINGS MADE FROM 26NiCrMoV115 STEEL

OCENA LASTNOSTI IZKOVKOV ZA ROTORJE IZ JEKLA 26NiCrMoV115

Martin Balcar[1], Václav Turecký[1], Libor Sochor[1], Pavel Fila[1], Ludvík Martínek[1], Jiří Bažan[2], Stanislav Němeček[3], Dušan Kešner[3]

[1]ŽĎAS, a. s., Strojirerska 6, 59171 Žďár nad Sázavou, Czech Republic
[2]VŠB TU – Ostrava, Czech Republic
[3]COMTES FHT, s .r. o. Plzeň, Czech Republic
martin.balcar@zdas.cz

Prejem rokopisa – received: 2007-09-26; sprejem za objavo – accepted for publication: 2007-10-15

The development and verification of production technology for the rotor forgings of compressors and generators demonstrate the significant effect of the forming of the input ingot on the final properties of the forgings.

The measured yield strength and the strength limit show a trend of dependence on the sample's position in the rotor. Significant differences in the longitudinal as well as in the transversal directions over the cross-section of a forging have been found, especially for the transition temperature FATT T_{50}. The mechanical properties of experimental rotor forgings made of 26NiCrMoV115 steel indicate that the forming and heat-treatment processes can be optimized.

Keywords: gas turbine, rotor shaft, forging, mechanical properties, FATT T_{50}

Razvoj tehnologije za preverjanje izdelave rotorskih izkovkov za kompresorje in generatorje kaže na zelo pomemben vpliv preoblikovanja izhodnega ingota na dosežene lastnosti izkovka. Meja plastičnosti in trdnost sta odvisni od položaja vzorca v rotorju. Ugotavljene so bile pomembne razlike med podolžno in prečno smerjo na prerezu rotorja, posebno pri prehodni temperaturi FATT T_{50}. Mehanske lastnosti eksperimentalnih izkovkov za rotorje iz jekla 26NiCrV 115 kažejo, da bi bilo mogoče optimizirati procesa kovanja in toplotne obdelave.

Ključne besede. plinska turbina, rotorska gred, kovanje, mehanske lastnosti, FATT T_{50}

The investigations were performed within the EUREKA program of the E!3192 ENSTEEL project, identification number 1P04EO169. The project was funded partially with the financial support of the Ministry of Education, Youth and Sport of the Czech Republic.

1 INTRODUCTION

The manufacturing of rotors for gas-turbine compressors and generators, applying the technology in the company ŽĎAS, a. s., Czech Republic, was verified from the viewpoint of the obtained in-service properties of the product.

Three experimental heats were produced (EU1, EU2 and EU3) from the steel grade 26NiCrMoV115. The 8K10.0 ingots were cast and the rotor forgings were forged to the shape shown in **Figure 1**. After the basic heat treatment of the forgings, consisting of water quenching from 850 °C, tempering at 615 °C and a cooling rate of 25 °C/h down to 250 °C, followed by air cooling, the mechanical properties on the forging's cross-section were determined.

The following places were chosen for determining the mechanical properties of the final forging: (B) – bottom, (C) – centre, (H) – head. These correspond to the same positions in the original ingot.

The properties were determined with tensile tests (THZ 723), toughness tests (PSW 300 and AMSLER TV 742) and Brinell hardness measurements (KPE 3000).

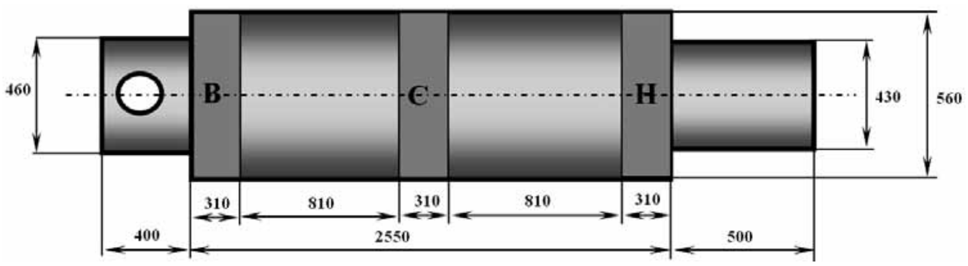

Figure 1: Layout of the experimental piece of the forging and the places from where the samples were taken
Slika 1: Položaj izrezov iz izkovka in mesta odvzema vzorcev

In **Table 1** the requirements for the mechanical properties of the rotors for the compressor and generator are given according to the customer's specification.

The heat-treatment conditions for the compressor rotors were chosen for the experimental tests. It was assumed that it would be possible to obtain the required yield strength and tensile strength for the mechanical properties of the generator's rotor by increasing the tempering temperature.

It is also worth noting that the forging dimensions at the place where the sample is taken for a determination of the mechanical properties do not exceed a diameter of 250 mm or a wall thickness of 200 mm. The test forgings were semi-products designated for the determination of the impact of forming and the heat treatment on the obtained service properties of the material during the fabrication of forgings with a large cross-section.

2 TENSILE TEST AT ROOM TEMPERATURE

Table 2 summarises the tensile properties determined in the longitudinal direction at room temperature (20 °C). The values obtained with the specimen cut at the forging surface that are not highlighted do not fulfil the required values for the mechanical properties of the compressor rotor.

It is clear from **Table 2** that the required yield point was not achieved in the heat EU1 at the surface of the

Table 1: Requirements of the mechanical properties of forgings for the 26NiCrMoV115 steel
Table 1: Zahtevane mehanske lastnosti izkovkov iz jekla 26CrNiMoV115

26NiCrMoV115	Position of test		Mechanical properties (20°C)						
			$Rp_{0.2}$	Rm	Elongation	Reduction of area	Charpy KV	Ductile fracture	FATT T_{50}
			($N.mm^{-2}$)	($N.mm^{-2}$)	(%)	(%)	(J)	(%)	(°C)
Compressor rotor	longitudinal	surface	800 to 900	≤ 1080	≥ 14	≥ 45	≥ 90	100	-
Generator rotor	longitudinal	axis	700 to 800	≤ 960	≥ 16	≥ 50	≥ 80	100	-
	longitudinal	surface	700 to 800	≤ 960	≥ 17	≥ 55	≥ 100	100	-
	transversal	surface	700 to 800	≤ 960	≥ 16	≥ 50	≥ 90	100	-40

Table 2: Mechanical properties at room temperature – longitudinal direction
Table 2: Mehanske lastnosti pri sobni temperatruri – vzdolžna smer

Longitudinal direction		$Rp_{0.2}$ MPa			Rm MPa			Elongation %			Reduction of area %		
		surface	1/2R	axis	surface	1/2R	axis	surface	1/2R	axis	surface	1/2R	axis
EU1	H	795	781	829	955	928	927	17.4	17.4	14.8	65.2	59.0	43.8
EU2		877	811	836	1005	939	939	15.8	16.0	14.6	65.2	52.4	51.0
EU3		848	809	830	968	928	941	17.4	16.2	16.8	66.4	56.4	53.8
EU1	C	793	826	796	966	931	943	16.8	16.4	15.0	65.2	53.8	53.8
EU2		817	786	780	934	899	917	17.2	14.0	15.8	65.2	31.1	55.1
EU3		812	791	788	934	915	921	17.2	18.0	16.2	64.0	56.4	56.4
EU1	B	867	806	823	992	926	933	17.2	15.4	13.4	67.5	52.4	53.8
EU2		810	778	789	912	881	868	17.8	15.4	14.8	67.5	52.4	45.2
EU3		822	783	811	927	895	903	17.0	17.0	15.0	66.4	56.4	55.1

Table 3: Mechanical properties at room temperature – transversal direction
Table 3: Mehanske lastnosti pri sobni temperaruri – prečna smer

Transversal direction		$Rp_{0.2}$ MPa			Rm MPa			Elongation %			Reduction of area %		
		surface	1/2R	axis	surface	1/2R	axis	surface	1/2R	axis	surface	1/2R	axis
EU1	H	863	797	820	963	923	926	14.6	15.6	14.8	66.4	60.3	60.3
EU2		818	803	796	927	920	927	15.6	16.8	16.6	64.0	62.8	60.3
EU3		821	787	833	982	933	939	17.8	16.2	17.0	69.8	61.6	61.6
EU1	C	810	803	816	920	913	940	14.6	15.2	15.4	66.4	59.0	59.0
EU2		790	772	784	905	894	903	16.6	15.2	13.8	64.0	57.8	56.4
EU3		814	794	791	925	912	920	18.6	17.2	16.4	69.8	61.6	60.3
EU1	B	828	818	820	936	938	945	17.2	15.6	16.6	61.8	60.3	59.0
EU2		765	754	779	889	894	892	16.6	16.4	13.8	60.3	56.4	51.0
EU3		803	779	795	918	909	917	17.2	17.4	16.4	68.6	59.0	61.6

Table 4: Mechanical properties at room temperature – average of heats EU1 – 3
Table 4: Mehanske lastnosti pri sobni temperaturi – povprečje talin EU1 – 3

Direction of testing	Rp0.2 MPa			Rm MPa			Elongation %			Reduction of area %		
	surface	1/2R	axis	surface	1/2R	axis	surface	1/2R	axis	surface	1/2R	axis
Longitudinal	827	797	809	955	916	921	17.1	16.2	15.2	65.8	52.3	52.0
Transversal	812	790	804	929	915	923	16.5	16.2	15.6	65.7	59.9	58.8

Table 5: *KV* (J) and share of ductile fracture – DF (%) at room temperature
Table 5: *KV* (J) in delež duktilnega preloma – *DF* (%) pri sobni temperaturi

Transversal direction		Surface KV	Surface *DF*	1/2 R KV	1/2 R *DF*	Axis KV	Axis *DF*
		J	%	J	%	J	%
EU1	H	118	100	48	47	91	83
EU2	H	130	100	45	43	68	63
EU3	H	144	99	39	33	59	57
EU1	C	120	100	48	45	51	53
EU2	C	106	90	40	42	50	48
EU3	C	147	100	34	28	56	50
EU1	B	113	100	36	38	68	62
EU2	B	143	100	55	50	68	57
EU3	B	151	100	43	28	70	55

Longitudinal direction		Surface KV	Surface *DF*	1/2 R KV	1/2 R *DF*	Axis KV	Axis *DF*
		J	%	J	%	J	%
EU1	H	92	98	32	35	45	51
EU2	H	80	83	33	32	42	45
EU3	H	136	98	33	22	44	35
EU1	C	103	98	28	28	32	35
EU2	C	97	88	36	28	36	40
EU3	C	99	83	34	22	37	33
EU1	B	90	97	36	35	31	31
EU2	B	85	90	35	38	37	38
EU3	B	99	83	39	30	39	28

forging from the part of the body under the head and in the central part of the original ingot. Other mechanical properties satisfy the requirements for the compressor rotor in accordance with **Table 1**.

Table 3 shows the values of the mechanical properties determined by a tensile test in the transversal direction with the highlighted values of $R_{p0.2} < 800$ MPa.

Table 4 shows the average values of the mechanical properties determined by tensile tests of the forgings from ingots cast from the heats EU1, EU2 and EU3.

It is clear from the average values in **Table 4** that the mechanical properties in the longitudinal and transversal directions are comparable. However, the tensile strength is higher in the longitudinal direction.

3 THE NOTCH TOUGHNESS AND TRANSITION TEMPERATURE

The results of the measurement of notch toughness at room temperature in the longitudinal direction given by the change of the peak load *KV* (J) and the share of the ductile fracture (%) in terms of the position of taking the sample from the forging are given in **Table 5**.

The average values of three measurements on samples cut out at the forging surface in the longitudinal direction that do not satisfy the requirement *KV* = 90 J or share a portion of 100% ductile fracture (DF) are highlighted.

It is apparent from **Table 5** that the values satisfying the peak load in the transversal direction at the surface part of the forging were achieved, and only in two cases were areas of brittle fracture found on the ductile fracture surface. Comparatively low levels of peak load were achieved in the longitudinal direction, and in all cases the share of brittle fracture on the fracture surface was less than 20 %.

It can be concluded from these experimental results, especially from the share of the ductile fracture, that the required peak load values can be obtained with the existing technology of heat treatment only for small cross-sections.

Table 6: *KV* (J) and share of ductile fracture *DF* (%) for a determination of the FATT T_{50}
Table 6: *KV* (J) in delež duktilnega preloma *DF* (%) pri sobni temperaturi za določitev FATT T_{50}

transversal direction	T	Surface KV	Surface *DF*	1/2 R KV	1/2 R *DF*	axis KV	axis *DF*
	°C	J	%	J	%	J	%
H	80			114	100	127	100
H	60			102	88	121	99
H	40			77	67	85	78
H	20	130	100	44	41	73	68
H	0	110	83	29	23	49	48
H	-20	75	62	26	13	35	18
H	-40	85	67				
H	-60	60	49				
C	80			94	88	103	93
C	60			91	83	101	91
C	40			76	68	72	66
C	20	124	97	41	38	52	51
C	0	119	88	29	20	42	36
C	-20	99	78	27	11	27	15
C	-40	68	57				
C	-60	48	38				
B	80			106	93	119	98
B	60			113	97	111	93
B	40			74	63	92	75
B	20	135	100	45	39	69	58
B	0	130	100	36	30	42	34
B	-20	100	77	30	12	31	20
B	-40	107	83				
B	-60	53	37				

longitudinal direction	T	Surface KV	Surface *DF*	1/2 R KV	1/2 R *DF*	Axis KV	Axis *DF*
	°C	J	%	J	%	J	%
H	80			57	68	77	88
H	60			50	55	66	74
H	40	107	92	45	48	53	60
H	20	103	93	33	29	44	44
H	0	97	85	31	17	32	24
H	-20	47	43				
H	-40	75	70				
H	-60	37	22	17	0	21	4
C	80			67	77	73	83
C	60			50	53	54	66
C	40	113	100	41	43	51	54
C	20	100	90	32	26	35	36
C	0	86	74	20	9	31	23
C	-20	72	69				
C	-40	50	45				
C	-60	37	23	16	0	14	0
B	80			69	88	57	70
B	60			53	63	78	72
B	40	106	98	47	48	58	52
B	20	91	90	37	34	36	32
B	0	76	76	21	10	36	24
B	-20	85	81				
B	-40	54	52				
B	-60	62	53	13	0	15	1

Table 7: Material hardness on the cross-section of the forgings – the average from the heats EU1, EU2 and EU3
Table 7: Trdota materiala na prečnem prerezu izkovkov – povprečje talin EU 1, EU 2 in EU 3

$HBW_{5/750}$	surface	◄direction surface		1/2 R	direction axis ►		axis
sample range distance from the surface of the forging (mm)	0 to 40	41 to 80	81 to 120	121 to 160	161 to 200	201 to 240	240 to 280
H	301	290	290	292	294	292	297
C	300	283	282	286	285	286	288
B	309	295	285	282	283	283	282

A second method for the evaluation of the mechanical properties of the rotor forgings was the determination of the FATT T_{50}, i.e., the Fracture Appearance Transition Temperature, defined by the ratio 50 % of brittle and 50 % of ductile fracture.

The results obtained for these tests in the longitudinal and transversal directions are given in **Table 6** with the transition from ductile fracture to brittle fracture being highlighted.

These results confirm that a satisfactory FATT T_{50} transition temperature at the surface part of the rotor forging was obtained.

The values of the transition temperature are lower for the interior parts of the forging, with a higher toughness in the axial part than in the zone 1/2*R*, at half the distance between the forging surface and the centre. The transition temperature of the FATT T_{50} can be obtained by an approximation in the diagram *KV* – *DF*.

4 HARDNESS

The hardness *HB* was determined on the cross-section of the forgings from the heats EU1, EU2 a EU3, and the results are given in **Table 7**.

Figure 2 shows graphically the average values of the hardness on the cross-section of the forgings. The highest hardness was achieved for all three forgings at the surface.

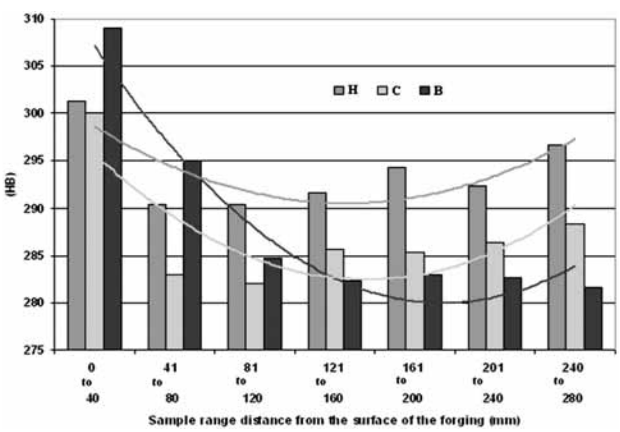

Figure 2: Average hardness on the cross-section of the forgings from the heats EU1, EU2 and EU3
Slika 2: Povprečna trdota na preseku izkovkov

5 CONCLUSIONS

The mechanical properties were determined on the cross-sections of the test forgings from the experimental heats. These properties show certain trends with respect to the position on the forging in the cross-section.

In longitudinally oriented samples, in comparison with transversally oriented samples, higher values of the mechanical properties were determined from a tensile test at room temperature; in the longitudinal direction from an average of three forgings the following satisfactory properties were achieved on the surface of the forgings: $R_{p0,2}$ = 827 MPa, R_m = 955 MPa, A_5 = 17.1 %, *Z* = 65.8 %. The other values in the direction towards the forging axis show, from the viewpoint of the yield point and the strength, a lower material strength and also lower plastic properties, defined by the ductility and the contraction.

The notch toughness of the steel, defined as the peak load during the impact test at room temperature, was in the range of *KV* = 80 J to 136 J in the longitudinal direction and of *KV* = 106 J to 151 J in the transversal direction. The share of ductile fracture *DF* = 83 % to 98 % in the longitudinal direction and *DF* = 90 % to 100 % in the transversal direction confirms that the notch toughness at the surface of the forging was better in the transversal direction. The values of the peak load decrease sharply from the surface towards the axis of the forging. At a distance of ½ the shaft radius the following values were obtained in the transversal direction: *KV* = 34 J to 55 J at *DF* = 28 % to 50 %, and in the forging axis: *KV* = 50 J to 91 J at *DF* = 48 % to 83 %. The steel has a better notch toughness in the axial part of the forging than in the middle radius.

The values of the yield point and the tensile strength of the experimental forgings document mutually comparable properties with a low dependence on the place from where the sample was taken. Greater differences in the longitudinal and transversal directions were found, particularly for the values of the transition temperature FATT T_{50}.

The obtained mechanical properties of the experimental rotor forgings made of the 26NiCrMoV115 steel indicate the necessity for a further improvement in the forming process and the heat treatment.

The transition temperatures of the FATT T_{50} determined by considering the peak load *KV* (J) and the share of ductile fracture on the fracture surface *DF* (%) show a change in the steel's plastic properties. The lowest transition temperature was always found for the surface of the forging. In all cases a lower transition temperature was achieved in the axial part in comparison with the part at the middle radius of the rotor forging. No important differences related to the position of the sample in the original ingot were found.

The hardness on the forging cross-section is in agreement with the changes of the mechanical properties. A significant drop of hardness was found at a distance of 40 mm below the forging surface, while the changes related to the axis direction are insignificant. The highest average hardness of *HB* 294 was achieved at the place corresponding to the part under the ingot end, a lower average hardness of *HB* 288 was found in the footing part, and a comparable average of *HB* 287 was achieved in the central part of the forging, i.e., of the original ingot.

The comparison of the scatter of the mechanical properties indicates an acceptable anisotropy of the mechanical properties.

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