Quench Process and Steel Chemistry Optimization to Prevent Quench Cracking during Hardening of Splined Semi – Axles

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ABSTRACT

In the paper the hardening process of splined semi-axes is discussed and physics of preventing the quench crack formation during intensive quenching (IQ) is explained. It is shown that during IQ process at the splined cylindrical surface very high compressive current band residual stresses are formed which prevent the possibility of quench crack formation on splines. It is enough to optimize the stress distribution through the section of semi-axle and perform IQ process in order to prevent quench cracks formation in splines. It is achieved via optimizing depth of surface hardened layer. In this case the depth of surface hardened layer for cylinders and for cylinders with splines are the same. There is no need to create a special thin shell on splines or perform carburization to create such shell. Due to larger martensite specific volume, it results in surface compressive residual stress formation. Absence of martensite phase at the core eliminates core swelling that could be a reason in tensile surface stresses. The idea is supported by FEM calculations and testing of real semi-axes in industrial condition. The new idea simplifies cardinally technological process and makes it less costly.

Keywords: Hardening, splined semi-axes, cracks prevention, physics of process, advanced technology.

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I. INTRODUCTION

Use of intensive quenching (IQ) process is limited by size and form of product to be hardened. If thickness of product is less than 12 mm and has complicated form, the problem can appear connected with the possible quench crack formation during IQ process. In many cases the real machine components, like semi- axles of trucks, have 5–6 mm thickness splines where probability of crack formation still exists. To prevent crack formation during quenching, products after carburizing process are slowly quenched in oil that requires additional alloying for enough thermal strengthening of material. This paper discusses the possibility of intense quenching of truck splined semi – axles in directed water flow or in spraying water induced by special sprayers.

There are two ways for preventing quench crack formation during intensive quenching. The first, the most commonly way, is interruption of intensive quench process at proper time to stop martensitic transformation when hardened layer is optimal during its penetration from surface to center. The second way is the use of an optimal hardenability steel which after complete cooling provides optimal hardened layer and maximal surface compressive residual stresses. Both issues were discussed in [1], [2]. However, sometimes steel parts are rather complicated with splines and holes on the surface which are reason for initiation of crack formation even during following the

mention rules. This paper discusses the quenching process of semi – axles with splined surfaces (see Fig. 1).

Fig. 1. A sketch of cross-section of splined semi-axle (a) and meshing for the finite-element method (b):
1 – spline bottom; 2 – spline side surface; 3 – spline tooth.

Authors [3] investigated residual stress distribution during quenching splined axles in different cooling condition. The results of FEM calculations are presented in Fig. 2 and Fig. 3. Fig. 2 provides optimal micro – structure distribution through the splined section of the axle [3]. As one can see from Fig. 2, the martensite plus bainite is equal to 1/3 D of axle, that is an optimal thickness.

Fig. 2. Microstructure distribution through the splined section of semi – axle during optimal hardened layer”: M is martensite; M+B is martensite plus bainite; P is pearlite.

Fig. 3 shows current surface hoop stresses during quenching samples (Fig. 4) in different cooling condition. The curve 1 belongs to cooling through hardened steel in oil. After complete cooling tensile hoop stresses are formed on the steel surface. The curve 2 belongs to optimal hardenability steel quenched in oil which provides microstructure shown in Fig. 2. In this case hoop surface stress is compressive and is equal to -440 MPa.

Fig. 3. Current hoop stress in spline bottom vs. time in the process of cooling in various liquid media [3]:

1 – oil cooling (alloyed steel, through hardening); 2 – optimal hardenability steel; 3 – cooling in still water (alloyed steel); 4 – optimal hardenability steel cooled in still water; 5 – alloyed steel cooled in water flow of 8 m/s; 6 – optimal hardenability steel cooled in water flow of 8 m/s.

Curve 3 belongs to alloy steel cooled in still cold water. As seen from Fig. 3, the surface hoop stress reaches maximum approximately in 40 seconds and then decreases to -150 MPa. Reason for such huge decrease is swelling of core caused by formation of martensite with the larger specific volume. Curve 4 presents surface hoop stress forming versus time on the bottom of spline during quenching optimal hardenability steel in still water. Due to absence of martensite at the core of splined sample, core did not swell, and residual stress was fixed at the highest its value. Curve 5 belongs to alloy through hardened steel quenched in water flow 8 m/s. Curve 6 presents hoop stress distribution at the bottom of spline during quenching optimal hardenability steel in water flow 8 m/s. From the made FEM calculations, it follows the important conclusion that optimal hardenability steel is the most suitable for manufacturing of splined semi – axles. Along with high hoop stress forming, IQ process results in super strengthening material in surface layers [4].

Fig. 4. Residual hoop stresses at the surface of a cylindrical specimen versus the generalized Biot number Bi_v , which is directly related to the cooling rate.

Note that the hoop stress changes from tensile to compressive when Bi_v is equal to 4.3 (see Fig. 4) [4].

II. SPRAY AND WATER FLOW COOLING

Samples shown in Fig. 5 were spray quenched while samples shown in Fig. 6 were quenched in water flow at 8–9 m/s.

Fig. 5. Sketch of splined testing samples 62 mm diameter made of different steel grades: 1, cracks on splines; 2, crack on edge of test sample.

Fig. 6. Sketch of tested semi – axle 50 mm diameter, made of AISI 4340 steel.

Heat transfer coefficient (HTC) during spray quenching is evaluated from the dimensionless correlation which is published in well-known literature [5]:

$$\bar{Nu} = K_1 K_2 \text{Re}^{2/3} \text{Pr}^{0.42} \quad (1)$$

Here

$$K_1 = \left[1 + \left(\frac{H/D}{0.6} \sqrt{f} \right)^6 \right]^{-0.05}$$

$$K_2 = \frac{\sqrt{f}(1 - 2.2\sqrt{f})}{1 + 0.2(H/D - 6)\sqrt{f}}$$

$$f = \frac{(\pi/4)D^2}{A_{\text{square(hexagon)}}$$

Maximal HTC during spray quenching of splined samples (Fig. 5) was equal to $48,000 \text{ W/m}^2 \text{ K}$.

For the semi-axes shown in Fig. 6, HTCs were evaluated from the dimensionless correlation (2) [6]:

$$\bar{Nu} = 0.021 \text{Re}^{0.8} \text{Pr}^{0.43} (\text{Pr}_m / \text{Pr}_{sf})^{0.25} \varepsilon_l \quad (2)$$

If $\frac{L}{D} = 10$, $\varepsilon_l \approx 1$ and the water temperature in the quench chamber is 20°C , the wall temperature is approximately 100°C , then (2) can be rewritten as [6]:

$$\bar{Nu} = 0.03 \text{Re}^{0.8} \text{Pr}^{0.43} \quad (3)$$

Maximal HTC during water flow quenching of splined semi-axes (Fig. 6) was equal to $42,000 \text{ W/m}^2 \text{ K}$.

The mentioned above values of HTCs allowed to perform so called direct convective quench process when transient nucleate boiling process is absent from the very beginning of cooling and convection mode exists during all process of cooling [6]. According to US patent [7], direct convection is established during quenching if criterion Biot number Bi (4) is satisfied:

$$Bi = \frac{2(\mathcal{G}_o - \mathcal{G}_l)}{\mathcal{G}_l + \mathcal{G}_{uh}} \quad (4)$$

Here

$$\mathcal{G}_l = 0.293 \cdot \left[\frac{2\lambda(\mathcal{G}_o - \mathcal{G}_l)}{R} \right]^{0.3} \quad (5)$$

λ is thermal conductivity of steel in $\text{W/m} \cdot \text{K}$;

$\mathcal{G}_o = T_o - T_s$; T_o is initial austenitizing temperature;

T_s is saturation temperature;

$\mathcal{G}_l = T_l - T_s$;

T_l is initial nucleate boiling temperature;

$\mathcal{G}_{uh} = T_s - T_m$ is underheat temperature;

T_m is bath temperature;

R is radius of semi-axle.

If $\lambda = 23 \text{ W/mK}$, $T_o = 870^\circ \text{C}$, $T_s = 100^\circ \text{C}$, $T_m = 20^\circ \text{C}$, $R = 0.025 \text{ m}$, then

$$\mathcal{G}_l = 0.293 \cdot \left[\frac{2 \times 23 \times (770 - 20)}{0.025} \right]^{0.3} \approx 20^\circ \text{C}$$

And according to (4), the Biot number

$$Bi = \frac{2(\mathcal{G}_o - \mathcal{G}_l)}{\mathcal{G}_l + \mathcal{G}_{uh}} = \frac{1500^\circ \text{C}}{100^\circ \text{C}} = 15$$

or

$$\alpha_{\min} = \frac{15\lambda}{R} = 13270 \text{ W/m}^2 \text{ K}$$

For spline of average thickness 8 mm the value $\mathcal{G}_l = T_l - T_s$ is:

$$\mathcal{G}_l = 0.293 \cdot \left[\frac{2 \times 23 \times (770 - 35)}{0.004} \right]^{0.3} \approx 35^\circ \text{C}$$

And according to (4), the Biot number Bi is:

$$Bi = \frac{2(\mathcal{G}_o - \mathcal{G}_l)}{\mathcal{G}_l + \mathcal{G}_{uh}} = \frac{1470^\circ \text{C}}{115^\circ \text{C}} = 12.8$$

or

$$\alpha_{\min} = \frac{12.8 \times 23}{0.004} = 73,500 \text{ W/m}^2 \text{ K}$$

It means that on cylindrical surface of sample takes place direct convection while on the surface of splines the nucleate boiling continues that results in self – tempering and formation tensile residual stresses. Both these factors decrease surface hardness of splines and create some cracks. The hardness measurements support such idea (see Table I).

TABLE I: HARDNESS AND NUMBER OF QUENCH CRACKS ON SPLINES AFTER SPRAY QUENCHING CYLINDRICAL SAMPLES IN CONDITION
HTC = $42,000 \text{ W/m}^2 \text{ K}$ [1]

Steel	Cooling time, s	Number of splines with cracks, %	HRC on top of spline	HRC on cylinder
47GT	10	5	49	42.
	15	6	50	47.
	20	10	57	50
4340	10	0	49	47
	15	0	52	49
	25	0	57	57
	40	0	61	65

Table I shows that steel 47GT creates crack on splines during intensive quenching while AISI 4340 steel does not make quench cracks. It is not understandable why less hardenability 47GT steel creates quench cracks on splines while through hardened steel 4340 does not make cracks.

III. QUENCHING IN WATER FLOW OF SPLINED SEMI – AXLES

To be sure that semi – axles with splines and made of alloy steel can be quenched intensively with no risk of quench cracks, they were quenched in water flow 8–9 m/s. The semi – axles were made of steel containing in wt.% 0.40 C; 0.65 Mn; 0.25 Si; 1.8 Cr; 0.4 Ni; 0.2 V. After quenching from 870°C in water flow 8 m/s and tempering at 420°C for two hours was measured hardness HRC through cylindrical and splined sections (see Fig. 5 and Fig. 7).

Fig. 7 Three sections of semi-axle where hardness was measured (see Fig. 6).

Results of hardness measurements are presented by Fig. 8, Fig. 9, and Fig. 10.

Fig. 8. Hardness HRC distribution through cylindrical section of semi-axle after quenching in oil and tempering in industrial condition.

Fig. 9. Hardness HRC distribution through splined cylindrical section of semi-axle after quenching in oil and tempering in industrial condition.

Fig. 10. Measured hardness in the splined cylindrical section of a semi-axle after its intensive quenching and tempering at 420 °C.

As seen from performed measurements, hardness was almost the same after oil and intensive quenching and

corrected by tempering. It was varying within 35–45 HRC when proceeding from center to surface. To be sure that it was no cracks inside of semi- axles, the last went for twist test to failure (see Fig. 11).

a)

b)

Fig. 11. View of surface sections after semi – axle failures: a) quenching in oil; b), intensive quenching.

Table II below presents ultimate torsion strength in kG.m which was applied to semi – axle to destroy it. M_{pr} is torsion yield strength; M_{fl} is ultimate torsion strength.

TABLE II: COMPARISON TORSION FORCES IN KG.M TO DESTROY SEMI – AXLES AFTER OIL AND INTENSIVE QUENCHING

Coolant	M_{pr}	M_{fl}
Oil	1334	2576
IQ _I	2024	2530
IQ _{II}	1932	2438

As seen from Table II, the limit of proportionality is larger for 33% for intensively quenched semi – axles.

IV. OPTIMAL HARDENABILITY STEEL

The correlation for optimizing chemical composition of steel, depending on size and form of steel part, is evaluated from correlation which is discussed in detail in [8], [9].

$$\frac{DI_a}{D_{opt}} Kn^{0.5} = 0.35 \pm 0.095 \quad (6)$$

Here DI_a is the critical thickness of a small model which is equal to form of a real steel part; D_{opt} is thickness of steel part to be quenched; Kn is Kondrat'ev number. For cylindrical form like semi-axle, that is quenched in condition $Bi \rightarrow \infty$, the correlation (6) became simpler and is written as:

$$\frac{DI}{D_{opt}} = 0.35 \pm 0.095 \quad (7)$$

According to Grossmann (Grossmann, 1964) critical diameter DI for cylinder depends on chemical composition of steel, Eq. (8), and it can be calculated as [10]:

$$DI = 25.4 \times f_{Fe} \times f_{Mn} \times f_{Si} \times f_{Cr} \times f_{Ni} \times \dots \quad (8)$$

where f_x is the multiplicative factor for the particular alloying element. The available set of alloy factors is presented in the handbook of authors [11]. These multiplicative factors are used for optimizing chemical composition of steel depending on size and form of steel part [12]. More information on an optimal hardenability steels and chemical composition optimization one can find in the book [8].

Optimal hardenability steel provides optimal stress distribution through section of hardened steel part (see Fig. 12) while low hardenability steel provides not safe stress distribution when its thickness is slighter of the optimal thickness. Such non safe stress distribution results in quench crack formation that was supported by accurate experiments (see Table I).

More information on contemporary methods of residual stress calculations, one can find in the published literature [13]–[16].

Fig. 12. The most common stress distribution after intensive quenching of optimal hardenability steel.

Fig. 13. Possible stress distribution after quenching of low hardenability steel when its thickness is slighter of the optimal thickness.

V. DISCUSSION

To prevent quench cracking during intensive quenching there are three ways already carefully tested by heat treating industry. The first way is IQ process interruption to fix maximal surface compression stresses and providing self – tempering of quenched steel. The second way is usage of an optimal hardenability steel that creates surface compression residual stresses and keeps viscose core of hardened steel part. The third way is the creation condition of direct convection for smallest thickness of quenched steel part to reduce tensile stresses through section of steel part to minimum. The low hardenability steel makes more quench cracks when it is used for large objects of complicated forms because high tensile residual stresses as formed in the transition boundary from martensite to pearlite. Martensitic surface layer in this case thin and transition gradient from martensite to pearlite is very short. In this situation stress distribution looks like stress distribution shown in Fig. 13.

Optimal hardenability steel and alloy steel after quench interruption process has more safe stress distribution (see Fig. 12).

Proceeding from the laws of physics, the safe quenching of semi-axes can be performed if in the surface layers (see Fig. 14, gray area) high compression residual stresses are formed, and core (orange area) is viscose where smaller tensile stresses cannot generate micro cracks. Simultaneously, splines should be quenched as faster as possible to create at least small tensile stresses at top of splines.

Experiments discussed in the current paper showed that splined semi – axes made of alloy steel can be intensively quenched with no risk of quench crack formation. Authors of experimental investigations [17] came to conclusion that absence of quench cracks on splines is explained by uniform and very intensive quenching of their surface.

Fig. 14. The scheme of optimal stress distribution with splined cylindrical surface during intensive quenching that prevents quench crack formation.

VI. CONCLUSIONS

Optimizing of quench process can be done by use the criterion responsible for direct convection while optimizing the steel chemistry is governed by the ratio of similarity (critical diameter to real semi- axles thickness) which should be equal to 0.35.

In the paper experiments with through hardened semi – axles were performed to see whether quench optimizing can prevent spline crack formation. There were no cracks at all when providing direct convection both for cylindrical and splined surfaces.

Optimizing quench process and chemical composition of steel result in significant improvement of service life of semi – axles [1], [8].

REFERENCES

- [1] Kobasko, N. I., Steel Quenching in Liquid Media Under Pressure, Naukova Dumka, Kyiv, 1980, 206 p.
- [2] Kobasko, N. I., W. S. Morhuniuk, and B.K. Ushakov, Designing of Steel Intensive Quench Processes, Handbook of Metallurgical Process Design, G. Totten, K. Funatani, and Lin Xie, Eds., Marcel Dekker, New York, 2004, pp. 733–764.
- [3] Kobasko, N. I., W. S. Morhuniuk, and A. P. Morganyuk, Hardening of Complex Configuration Bodies by Intensive Cooling, Proceedings of the 7th International Congress on Heat Treatment of Materials, December 11–14, 1990, Moscow, Vol. 2, 1990, pp. 232–239.
- [4] N.I. Kobasko, Aronov M. A., Powell J. A., Totten G. E., “Intensive Quenching Systems: Engineering and Design”. ASTM International, USA, 2010. 234 p. doi: 10.1520/mnl64-eb
- [5] Martin, H., Impinging Jets, Hemisphere Handbook of Heat Exchanger Design, G. F. Hewitt, Coordinating Ed., Hemisphere, New York, 1990, pp. 2.5. 6–1.
- [6] Mikheev, M. A., and I. M. Mikheeva, Osnovy teploperedachi (Basics of heat transfer), Energy, Moscow, 1977.
- [7] Kobasko, N. I., Quenching Apparatus and Method for Hardening Steel Parts, U.S. Patent No. 6,364,974 B1, April 2, 2002.
- [8] Kobasko, N. Optimal hardenability steel and method for its composing, Lambert Academic Publishing, Germany, 2018, 120 p.
- [9] Ukrainian Patent UA 114174, C2, (2017). Alloyed Low Hardenability Steel and Method of its Designing, Filed on Sep.23, 2013, File number: a 2013 11311, Published on June 25, 2016 in Bulletin No. 12, Legal day is May 10, 2017.
- [10] Grossmann, M. A., 1964. Principles of Heat Treatment. Ohio: American Society for Metals, 302 pages.
- [11] Totten, G.E., Bates, C.E., and Clinton, N.A., *Handbook of Quenchants and Quenching Technology*, ASM International, Materials Park, OH, 1993, 507 p.

- [12] Kobasko, N.I., (2017). A method for optimizing chemical composition of steels to reduce radically their alloy elements and increase service life of machine components. EUREKA: Physics and Engineering, 1, 2017, pp. 3–12. doi: 10.21303/2461-4262.2017.00253.
- [13] Ferguson, B. L., Z. Li, and A. M. Freborg, Modeling Heat Treatment of Steel Parts, Computational Materials Science, Vol. 34, No. 3, 2005, pp. 274–281.
- [14] Ferguson, B. L., A. M. Freborg, and Z. Li, Improving Gear Performance by Intensive Quenching, Proceedings of the 24th ASM Heat Treating Conference, 2007, pp. 156–162.
- [15] Ferguson, B. L., and A. M. Freborg, A Design Tool for Tuning and Optimizing Carburizing and Heat Treat Process, SAE International Off-Highway Congress, Las Vegas, Nevada, March 19– 21, 2002, SAE Technical Paper Series 2002-01-1475.
- [16] Inoue, T., and K. Arimoto, Development and Implementation of CAE System “Hearts” for Heat Treatment Simulation Based on tallothermo-mechanics, Journal of Materials Engineering and Performance, Vol. 16, No. 1, 1997, pp. 51–60.
- [17] Bogatyrev, Ju.M., Shepelyakovskii, K.Z., Sklyarov, I.N., Cooling rate effect on crack formation at steel quenching, MitOM, No. 11, 1967, pp. 15–22.