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HIGH-STRENGTH STRUCTURAL STEELS FOR LANDING GEAR PARTS

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The materials, which are widely used for landing gear part production, should possess high static and fatigue strength, corrosion cracking resistance.

The operational reliability of these materials mainly depends on their sensitivity to stress concentration (due to geometry or part manufacturing process) and fatigue crack propagation rate, which determine part service life and frequency of inspection and overhaul.

One of the base materials, used in landing gear structures, are high-strength steels, which at relatively low cost possess such advantageous properties as good weldability, machining and hot workability compared to aluminum and titanium alloys.

High-strength medium alloy welding steels with ultimate strength from 1400 to 2000 MPa are widely used in the USSR for main part production (cylinders and damper rods; truck rockers, levels, supporting struts, wheel axes, etc.), defining landing gear weight efficiency. The steel typical mechanical properties are shown in Table 1.

Steel strength of this type mainly depends on carbon content but Cr, Mn, Ni, Mo and Si alloying ensures sufficient hardenability and toughness, including low temperatures. Si alloying of 30XGSN2A, 30XGN2MA, 40XN2SMA, BKC-9 positively effects on their technological effectiveness and reliability. Firstly, it's managed to maintain the same strength but with less carbon content and thus to increase brittle fracture and corrosion cracking resistance, to improve technological properties (weldability, hot ductility). Secondly, there is a possibility to use isothermal quenching for lower bainite and thus to get significant buckling decrease during complex-shape part quenching and as a result of that to decrease internal stresses after straightening.

Besides, isothermal quenching found use in heat treatment, in particular, of 30XGSN2A steel with ultimate strength of 1400-1600 MPa.

In this case, steel toughness and ductility are considerably higher, than after oil quenching and following tempeting at 400-450°C.

Table 1. High-Strength Medium Alloy Steel Typical Properties

Steel	Heat Treatment	$\sigma_{в}$	$\sigma_{0,2}$	δ_5		K_{IC}	σ_{-1}	Hardenability, mm
		MPa		%	%	MPa $\sqrt{m}$	MPa	
20XGSN2MFA	Oil Quenching from 900°C+ Tempering at 250°C	1350-1550	1110-1250	13	50	108-117	65	100
25X2GNTRA	Oil Quenching from 860°C+ Tempering at 200-230°C	1400-1650	1200-1250	10	45	93-108	60	50
30XGSN2A, 30XGSN2MA	Oil Quenching from 900°C+ Tempering at 210°-190°C	1600-1900	1350-1400	9	45	77-93	66	80
	Isothermal Nitre Quenching from 240-330°C	1400-1850	1000-1300	12	50	87-108	63	60
40XN2SMA	Isothermal Nitre Quenching from 900°C+Tempering at 240°-260°C	1800-2000	1400-1500	8	40	56-62	75	100
BKC-9	Oil Quenching from 950°C+Tempering at 220°-280°C	1950-2150	1600-1700	9	45	77-93	72	100

It is known, that compared to medium-strength steels, high-strength steels possess higher sensitivity to stress concentration and surface state particularly under repeated stresses, corrossive and surface - active media.

Long-term operating experience of these steels with ultimate strength of 1600-2000 MPa and fracture toughness value of 56-108 MPa $\sqrt{m}$ showed, that for the use of all high-strength steel potential possibilities it should be carried out a number of design and technological measures.

Part reliability and service life mainly depend on comprehensive working up structures and part optimum geometry selection. The revealing higher stress concentration zones at the design stage in time is the successfull operation guarantee of high-strength steels in the structures.

The working capacity of the high-strength steel parts is determined by technological discipline maintenance at all part production stages from metallurgical steel melting to the appropriate part anticorrosive protection selecting. Higher purity metal use is obligatory. Steel physical and mechanical property changing according to melting process is shown in Table 2.

Table 2

Melting Technique Effect on High-Strength Steel Properties ($\sigma_{\text{в}}$ = 1950 MPa)

Melting	ψ %	K_{IC} MPa $\sqrt{m}$	$\sigma_{\text{кр}}$ MPa *)
OAS+VAR	50	67-81	730
VIS+VAR	57	78-112	100
OAS+VAR+EBR	57	101-105	120

OAS - open arc melting
VIS - vacuum-induction melting
VAR - vacuum-arc remelting
EBR - electron-beam remelting

*) - critical stress, at which the corrosion cracking of smooth ground samples during 20% H_2SO_4+30 g/l. NaCl solution test for 24 hours doesn't take place.

The requirements for the purity are enhanced with steel strength increase. High cracking resistance values can be obtained only on the metal of high purity according to S,P non-ferrous and low non-metallic impurity content.

In steels with ultimate strength to 1700 MPa, both S and P impurity content should not be exceeded 0,015% for providing high physical, mechanical and low anysotropic properties; S and P impurity content is ~ 0,010% with ultimate strength increase upto 1800-2000 MPa, and with the further strength increase, this impurity content should be decreased down to $\leq$0,005%.

The deleterious impurity content decrease is achieved through such melting method use as duplex and triplex of processes (VIS+VAR; OAS+VAR+EBR).

The change-over from OAS+VAR melting to VIS+VAR and VAR+EBR is followed by gaseous and non-metallic impurity content decrease, that, in turn, results in ductility and toughness increase, mechanical property anisotropy decrease and, respectively, corrosion cracking resistance and fracture toughness increase.

The requirements of reliability and service life increase make to search for ways of high-strength steel improvement. During the last years the new economically alloyed welding BKC-9-type steel has been developed on the base of chemical composition optimization and metallurgical production methods. This is heat-treated steel with ultimate strength of 1950-2150 MPa and reliability, significantly exceeding that of 40XN2SMA steel; it can be compared practically with 30XGSN2A steel ($\sigma_{\text{в}}$ = 1700-1800 MPa) and in some cases it has the superiority over the last one (see Table 1). Compared to 30XGSN2A steel, BKC-9 steel possesses higher strength and corrosion cracking resistance. Fractographic analysis shows higher microductility in BKC-9 steel fracture sample, compared to 30XGSN2A steel after test in the corrosive medium. BKC-9 steel shows higher low-cycle fatigue resistance; it possesses less fatigue crack propagation rate in the fine crack zones (250-300 μ m), higher static cracking resistance at low temperature (Table 3).

Table 3

Comparison of High-Strength Steel Properties

Steel	BKC-9	30XGSN2A
Ultimate Strength $\sigma_{\text{в}}$, MPa	1950-2150	1700-1800
Yield Strength, $\sigma_{0,2}$ MPa	1600	1350
Elongation, ψ %	40	45
Fracture Toughness, K_{IC}, MPa $\sqrt{m}$ at +20°C	78-95	78-90
Fracture Toughness in 3,5% NaCl, K_{ISCC}, MPa $\sqrt{m}$	22-24	16-17,5
Fatigue Crack Propagation Resistance, mm/1000 cycles		
at ΔK=31 MPa $\sqrt{m}$	0,20	0,38
ΔK=46,5 MPa $\sqrt{m}$	0,50	0,80
(R_{max} =0,1; f =5 hz)		
*) σ_{brutto} =250 MPa Tensile Low-Cycle Fatigue, $N \times 10^{-3}$ cycles		

Steel	BKC-9	30XGSN2A
at σ_{max}=500 MPa	100	28
at σ_{max}=450 MPa	200	50

*) ear-like plane sample, K_t=2,8 R=0,1

In landing gear structures, used in the USSR, a number of parts are produced with the help of welding. In this case high-strength 30XGSN2A, 30XGSN2MA, BKC-9, 40XSN2MA steels can be welded both between themselves and with other low-alloy steels. In this case steels are alloyed in such a way, that their martensitic point is rather high (300°C), thus formed martensit during welding is tempered in the process of cooling down to the room temperature and the danger of weld crack formation is decreased.

It is recommended to use electron-beam welding, though in some cases automatic argon-arc or flux welding use is admitted. Welding is applied to as annealed parts; part heating upto temperature not lower than 200°C is used to avoid weld crack initiation. Weldments are designed on the basis of the weldment strength properties (Table 4).

Table 4

BKC-9 Steel Weldment Properties (Welding + Complete Heat Treatment)

Welding	Test Temperature,0°C	$\sigma_{в}$, MPa	KCU MJ/m^2	K_{IC} MPa $\sqrt{m}$
Electron-beam	+20	1900	0,4-0,6	52-65
	-70	1950	0,2-0,3	52-59
Argon-arc	+20	1570	0,5-0,8	78-100
	-70	1700	0,4	-
	+20	1700	0,4-0,7	78-93
	-70	1750	0,35	-

To achieve equal strength with base material weldments have thickening with smooth passage to the base. Weldment position in stress concentration zones isn't admitted.

Weldments both outside and melting-thru are mechanically treated for fatigue strength increase.

It is advantageous to use Fe-Ni-Co-Mo-Ti high-strength maraging steel for manufacturing parts, in which, high yield strength and proportionality limit values along with high ultimate strength are necessary. They also possess good technological effectiveness and make it possible to produce parts without allowances for heat treatment, to perform cold upset of bolts and thread rolling; besides they are good weldable.

Vacuum induction melting with the following vacuum arc remelting and special deoxidation allows to provide low deleterious impurity content (C,N,etc), to refine grain boundaries and also to secure high technological effectiveness during ingot hot deformation. Applied melting technology gives a possibility to obtain necessary material properties for large-size parts as well.

The application of above - mentioned melting and heat treatment technology, forming phase cold hardened fine structure and microstructure practically without carbon and nitride impurity content along grain boundaries (30-40 μm) provides high properties, including large cross-section semiproducts. Phase cold hardening with a particular strength property increase allows to improve such reliability properties as K_{1C}, K_{1SCC} (See Table 5).

The maraging steel properties with $\sigma_{в}$ = 1600-2200 MPa compared to widely used 30XGSN2A steel are presented in Table 6. It is evident, that the maraging steels have the significant advantage in fracture toughness K_{1C}, particularly at the negative temperatures, and also K_{1SCC} in the corrosive medium of 3% NaCl for 1000 hours. These types of steels, produced by the optimum technology are not prone to slow brittle fracture under moisture film on the notched samples (d_{ext}= 7 mm, d_{int}= 5,6 mm, r = 0,1 mm, at 60°) at stress to $\sigma = 0{,}8\sigma_{в}^{n}$.

Table 5. Phase Cold Hardening Effect on BKC-210 Steel Properties

Condition	MPa	ψ %		σ_{-1} MPa	K_{IC} MPa$\sqrt{m}$	K_{ISCC} MPa$\sqrt{m}$	Time to Notched Sample Fracture under Moisture Film at $K_t=4$ and $\sigma=1500$ MPa
		Longitudinal Direction	Transverse Direction				
Without Phase Cold Hardening	2000	52	45	660	68	11,8	48 hours
With Phase Cold Hardening	2100	48	40	720	78	24,5	960 hours without fracture

Table 6.

Steel	σ_B	$\sigma_{0,2}$	K_{IC} MPa$\sqrt{m}$ at			Fatigue Crack Propagation Rate 2dl/dN mm/ 1000 cycles ber at $\Delta K=54$ MPa$\sqrt{m}$	K_{ISCC} MPa m in 3% NaCl for 1000 h.	Time to Notched Sample Fracture under Moisture Film at $K_t=4$ and $\sigma=1500$ MPa
	MPa		+20		-70			
			Longitudinal	Transverse				
BKC-210 02N18K9M5T	1950-2200	1850-2100	78	70	70	1,00	24,5	960 hours without fracture
BKC-170 0ZN18K8M5T	1600-1850	1500-1750	130	-	120	1,05	66,0	960 hours without fracture
30XGSN2A	1600-1850	1250-1450	80	-	48	1,54	11,0	48-240 hours