AUBERT&DUVAL

GKH®(W - YW)

33CrMoV12-9

High-performance martensitic steel for critical mechanical components

CONTINUOUS METALLURGICAL INNOVATION

SPECIAL STEELS

DEVELOPMENT

RESEARCH

SERVICE

Enhancing your performance

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THE INDUSTRIAL ENVIRONMENT

Increasing numbers of industrial components are being subjected to high surface stresses and dynamic loads, requiring the use of special high-performance steels. Where high surface hardness and excellent fatigue strength are required and when the material is also subjected to high temperatures, nitriding technology offers the best case hardening option.

In this field, GKH offers an excellent combination of core properties to withstand structural loads and damage tolerances and surface functions in the case hardened layer. The result on components gives one of the best solutions in the market for contact pressures and fatigue performances.

GKH can also be used without nitriding and offers the triple advantage of an excellent combination of mechanical properties, high thermal fatigue and high thermal conductivity.

GKH, available under 3 melting modes (single air melted, remelted, VIM/VAR), has been successfully used for decades in the most critical mechanical components within : aerospace, motorsport, injection systems, firearms, retaining rings, etc…

SPECIFICATIONS

Brand name	Melting mode	Norms	Examples of main customers specifications
GKH	Single air melted	33CrMoV12-9 AIR: 32CDV13 UNS: K24340 EN number: 1.7765	Avio 4152 M3/M8 Airbus ASNA 3419 Safran Helicopter Engines CCT00210
GKHW	Remelted under consumable electrode	33CrMoV12-9 AIR: E32CDV13 UNS: K24340	Airbus ASNA6122/6121 Safran Transmission Systems BLFF192101 Safran Helicopter Engines CCT 00310/00237 Dassault DGQT 1300031
GKHYW	VIM/VAR	33CrMoV12-9 UNS: K24340 AMS: 6481	Avio 4158 M5/M4 Safran Transmission Systems BLFF 191101 Airbus ASNA6120/6128 Safran Aircraft Engines DMD012420 NTN-SNR LA141501 SKF CFR5213/IHA 0051/IDL10I0004 FAG FLLA22281SX

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CHEMICAL COMPOSITION (weight %)

	C	Si	Mn	S	P	Ni	Cr	Mo	V
Mini	0.29	0.10	0.40	/	/	/	2.80	0.70	0.15
Maxi	0.36	0.40	0.70	0.007	0.015	0.30	3.30	1.20	0.35

MAIN PHYSICAL PROPERTIES

Density at 20°C (68°F): 7.84 g/cm³, 0.2832 lb/in³

Mean coefficient of thermal expansion (α)

Temperature range	10^{-6}/m /m /°C	10^{-6}/ in/in/°F
20°C-100°C, 68°F-212°F	11.8	6.55
20°C-300°C, 68°F-572°F	12.7	7.05
20°C-500°C, 68°F-932°F	13.6	7.55
20°C-700°C, 68°F-1292°F	14.2	7.88

Thermal conductivity (K)

Temperature	W.m/m².°C	Btu.in/hr.ft².°F
20°C, 68°F	38	263
200°C, 392°F	35	243
500°C, 932°F	33	229
600°C, 1112°F	30	208
700°C, 1292°F	29	201

Specific heat (°C)

Temperature	J/kg/°C	Btu/lb/°F
20°C, 68°F	460	0.110
100°C, 212°F	500	0.119
200°C, 392°F	540	0.129

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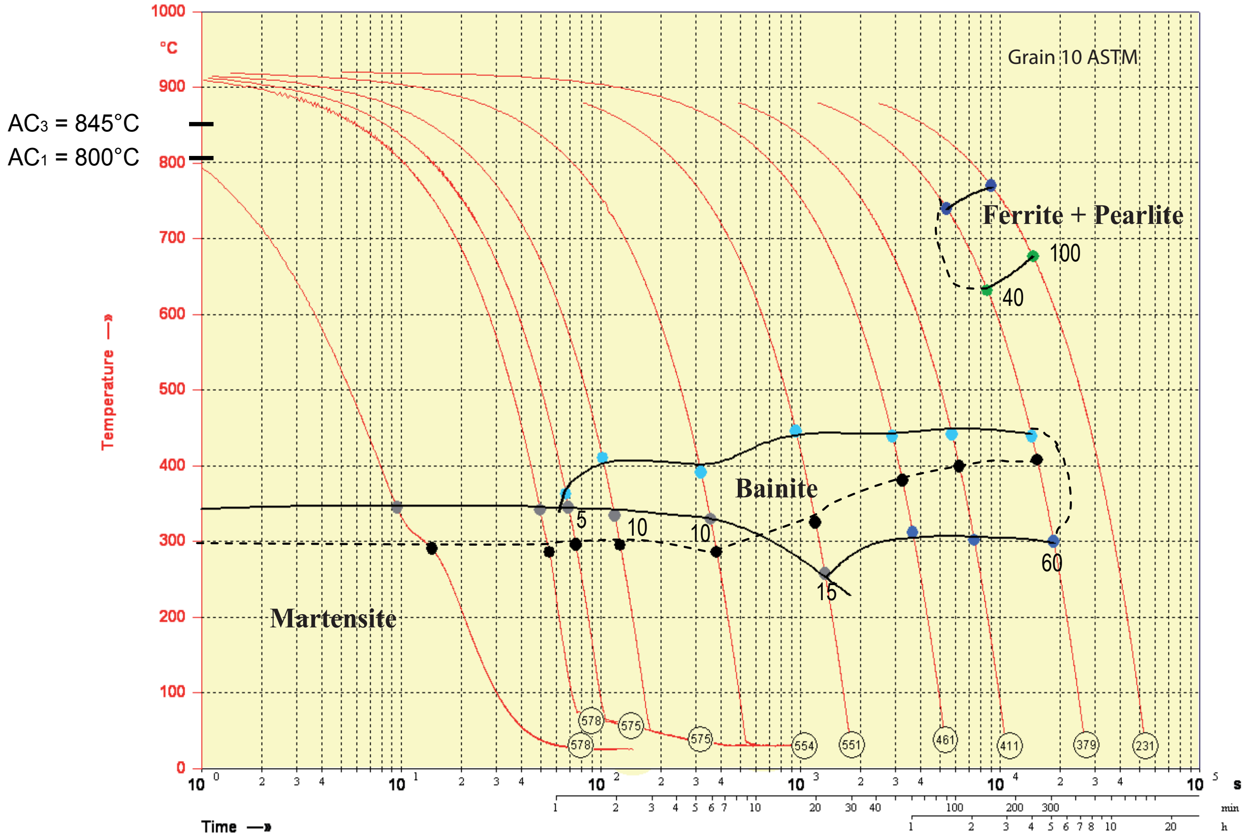
TRANSFORMATION POINTS

Ac1	800°C, 1472°F
Ac3	845°C, 1553°F
Ms	375°C, 707°F

CCT DIAGRAM



CCT Diagram _ austenitization 920°C, 1688°F

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MACROSTRUCTURE

The segregation, as measured on the ingots, complies with the tightest requirements.
Below, are examples for both single melted products and remelted grades for the aerospace industry.

	Severity for GKH
Subsurface conditions	S2
Random conditions	R1
Center segregation	C2

Macrostructure according to ASTM E381

Class	Type	Severity for GKHW and GKHYW
1	Freckles	A
2	White spots	A
3	Radial segregation	B
4	Ring pattern	B

Macrostructure according to ASTM A604

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CLEANLINESS

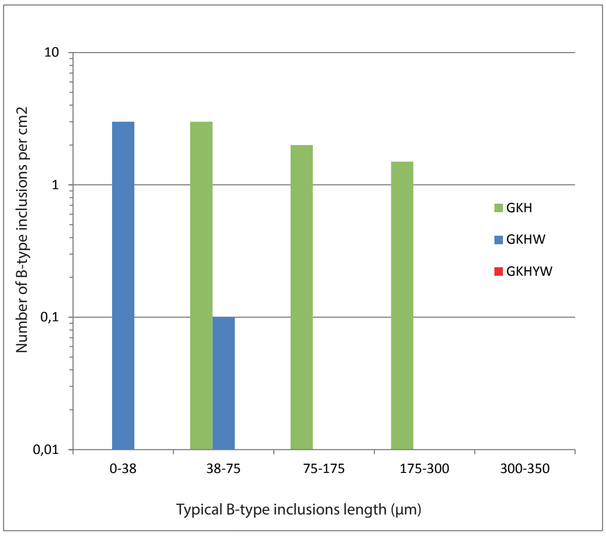
Micro-cleanliness complies with the tightest requirements.
Below, are examples of specifications met by GKH for different melting conditions.

Type	A		B		C		D	
	Thin	Heavy	Thin	Heavy	Thin	Heavy	Thin	Heavy
GKH	0.5	0.5	1.5	1.0	1.0	1.0	1.5	1.0
GKHW	0.5	0.5	1.0	0.5	1.0	0.5	1.0	1.0
GKHYW	0.5	0.5	0.5	0.5	0.5	0.5	1.0	0.5

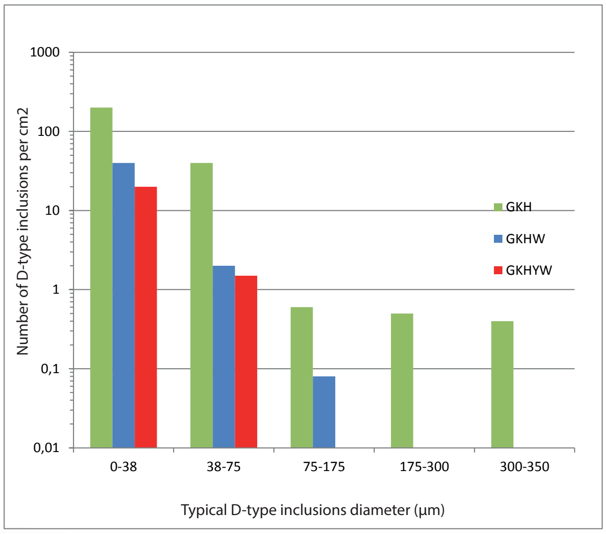
According to ASTM E 45 Method D (mean value on 160mm² surface)

Beyond the specifications, Aubert & Duval's optimized melting practices makes GKH's micro-cleanliness value far better than standard 33CrMoV12-9 and usual engineering grades using same melting processes.
Below is an illustration of the number of non-metallic inclusions depending on their sizes for B and D types, which are the most common types resulting from our melting practices.

B-type inclusions
Typical value number vs length



D-type inclusions
Typical value number vs diameter



Analysis performed on products with diameter range 40-60mm (1.57-2.36 inch)

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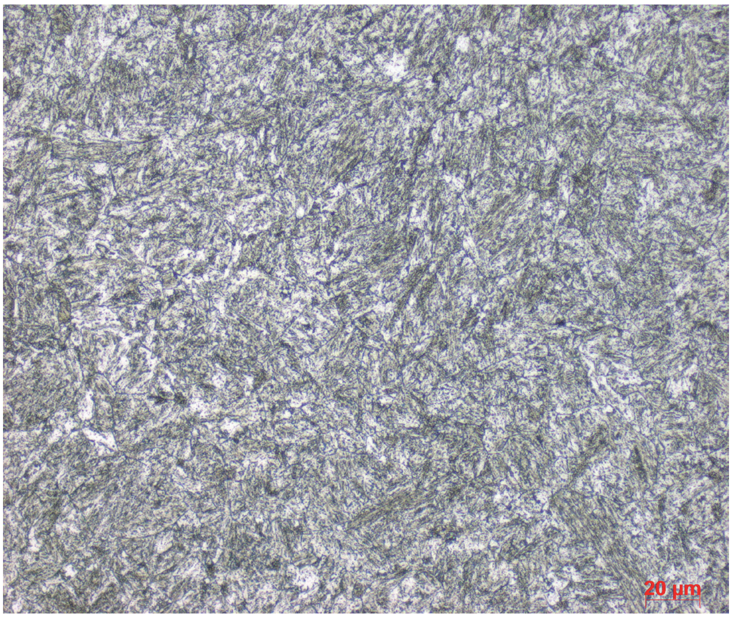
MICROGRAPHIC CHARACTERIZATION

Quenched and Tempered material:
Grade: GKHW
Austenitizing: 920°C, 1688°F
Oil quenching
Tempering: 625°C, 1157°F
Mean grain size ≥ 7 ASTM



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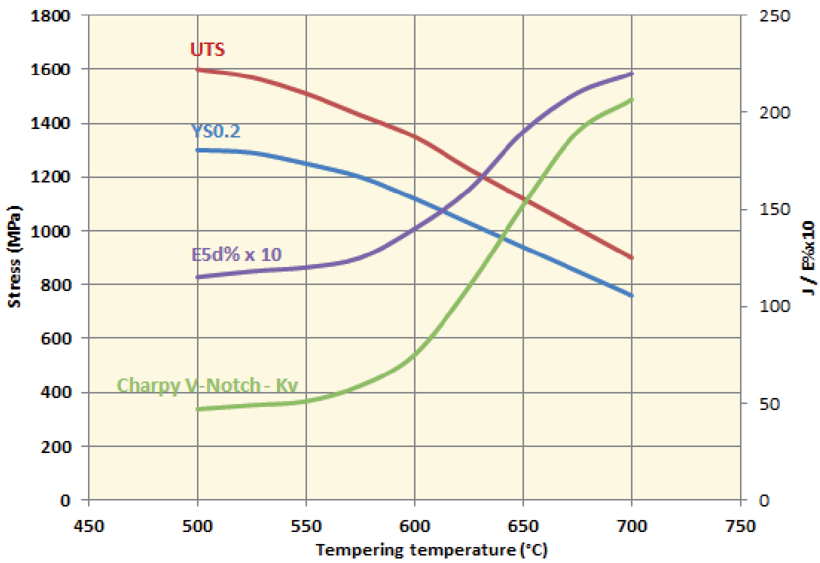
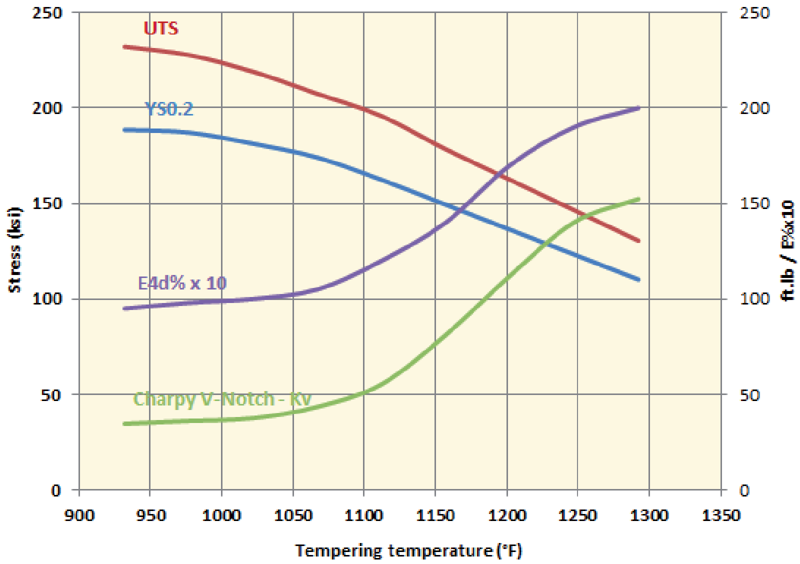
EVOLUTION OF MECHANICAL PROPERTIES WITH TEMPERING TEMPERATURE





Typical value obtained on heat treated blanks (heated at 900-925°C,1652-1697°F and oil quenched)

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EVOLUTION OF MECHANICAL PROPERTIES WITH OPERATING TEMPERATURE

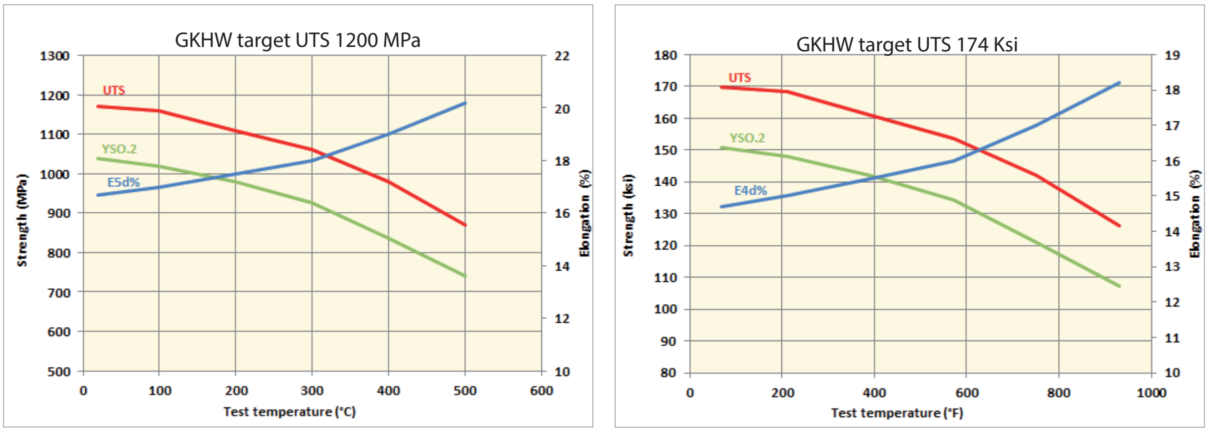
Shown below is the evolution of mechanical properties when measured from room temperature up to 500°C (932°F).

Grade: GKHW

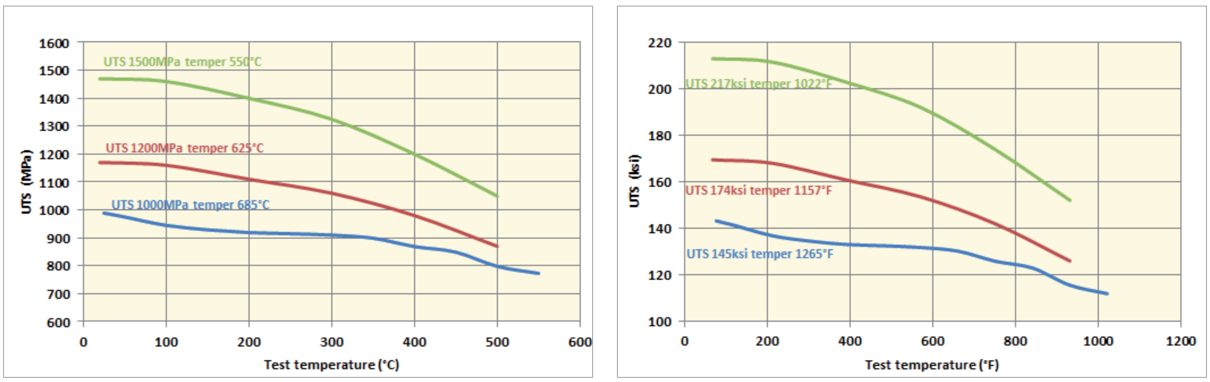
Austenitizing: 920°C, 1688°F

Oil quenching

Tempering: 625°C, 1157°F



Evolution of mechanical properties with operating temperature



Evolution of hot properties of GKHW for different tempering treatments

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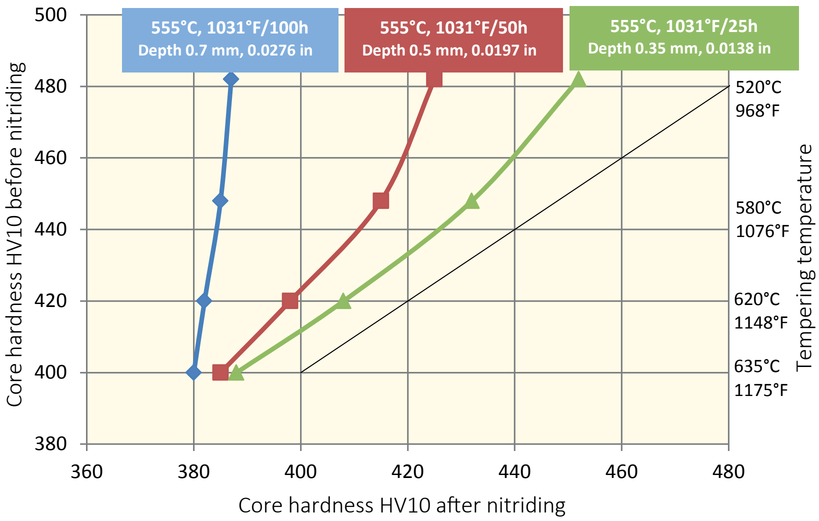
NITRIDING ABILITY

The nitriding process is performed on parts, after a complete heat treatment, in the most advanced stage of machining. Nitriding being a low temperature process (380-600°C, 842-1112°F), distortions are far smaller than for carburized and quenched parts. One major cause of part distortion during nitriding is the softening of the base metal, due to complementary tempering effects.

The effect of different nitriding treatments (from 25 h to 100 h at 555°C, 1031°F) on the softening of the base metal for different initial hardness values (from 400 to 480 HV10) is given below for gas nitriding technology.



Evolution of core properties with different gas nitriding treatments done at 555°C, 1031°F

The nitriding time at 555°C (1031°F) required on GKH to produce a case depth below 0.5mm does not have a significant effect on base metal softening. In this case, we can afford to Quench and Temper GKH to the highest tensile strength (up to 1500MPa or 217ksi / 450HV) without any major softening and risks of distortions.

For the longest nitriding treatment (duration > 100 h needed to obtain the deepest case hardened layer), the initial hardness should be close to 380 - 420 HV in order to limit softening and consequently distortions. This corresponds to a tempering temperature in the range 620 - 650°C (1148 - 1202°F). The typical mechanical properties obtained after Q&T heat treatment compared to AMS 6481 is given in the table next page :

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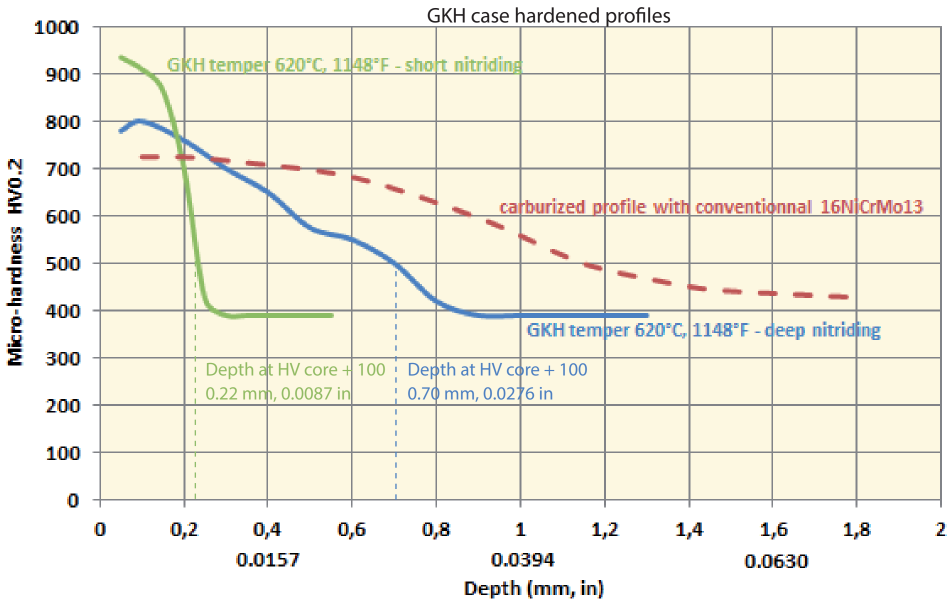
GKHYW conditions		YS0.2 (MPa, ksi)	UTS (MPa, ksi)	E4d %	Charpy V-notch (J, ft-lb)
Quench & Temper Temper >600°C, 1112°F	AMS6481 minimum criteria	951, 138	1137, 165	13	68, 50
Quench &Temper Temper 620-650°C, 1148-1202°F	Typical value	1050, 152	1245, 180	15.5	140, 103
Quench & Temper & Nitride Temper 620-650°C, 1148-1202°F Ageing to simulate nitriding operation (555°C, 1031°F / 100hrs)	Typical value	995, 144	1200, 174	15.5	125, 92

Below are described results of different gas nitriding conditions on case hardened profiles :

- Reference heat treatment :
- Austenitization 920°C, 1688°F
- Oil quenching
- Tempering 620°C, 1148°F
- Gas nitriding for 25h and 120h



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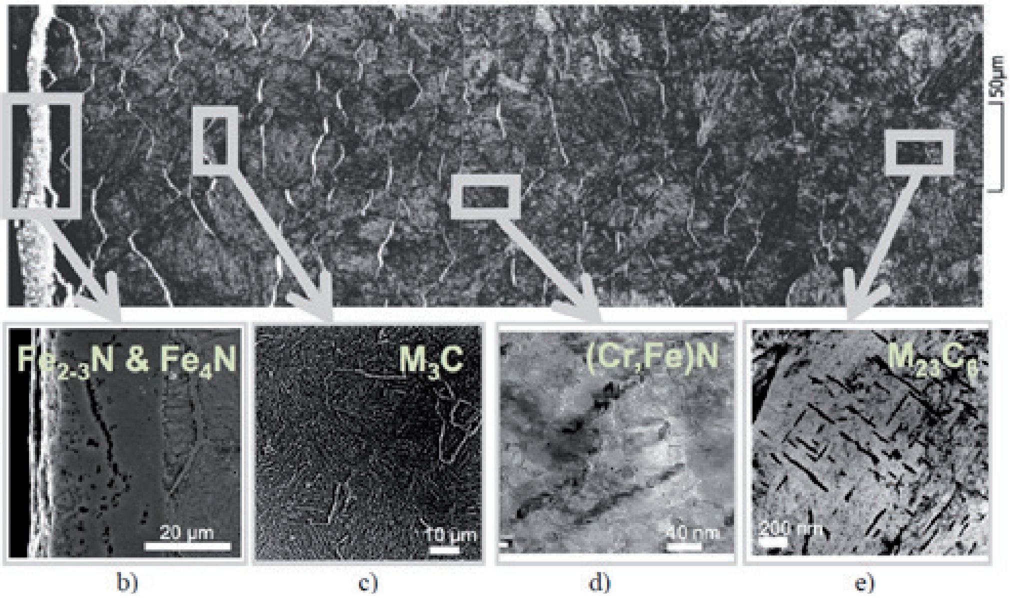
Using a gas nitriding process with a controlled atmosphere, GKH develops, in deep nitrided conditions, a compound layer around 30µm (0.00118 in) thick. 50µm (0.00197 in) material stock should be removed by grinding operation.
Other alternatives can be used with ion (or plasma) nitriding technology where people claim process conditions results in a surface with a very limited compound layer.



Typical microstructure of deep nitrided layer on GKH (gas nitriding)
b) compound layer with Fe2-3N (porous) and Fe4N (sub surface)
c) Alloyed cementite at grain boundaries in diffusion layer (IGN intergranular nitrides)
d) (Fe,Cr)N nitride precipitate in place of prior M23C6 carbides
e) Alloyed M23C6 intra and inter martensite lathes carbides in base metal

Components are generally nitrided in order to increase surface properties (wear, friction) and/or fatigue life. Gas nitriding technology is the most developed treatment for improving fatigue properties of highly loaded mechanical parts in Aeronautic or Motorsport markets.

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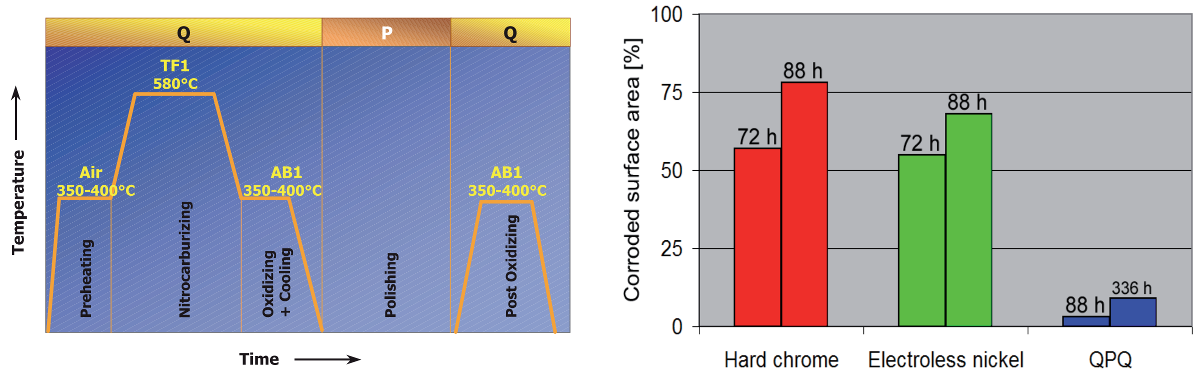
For some specific applications (Defense, mechanical engineering parts), Ferritic Nitro-carburizing is also a well-used process. This is a specific case hardening process that diffuses nitrogen and carbon into ferrous metals at sub-critical temperatures. Four main classes of ferritic nitro-carburizing exists : gaseous, salt bath, ion or plasma, and fluidized-bed. When associated with a polishing and oxidizing passivation treatment, this process gives a remaining compound layer particularly resistant to wear, seizure, corrosion, hot cracks (with black coloration). With GKH, it produces surface micro hardness values around 64HRC with very good wear and corrosion resistance.



Example of a salt bath ferritic nitrocarburizing process and salt spray results (ASTM B117) - Tenifer® QPQ

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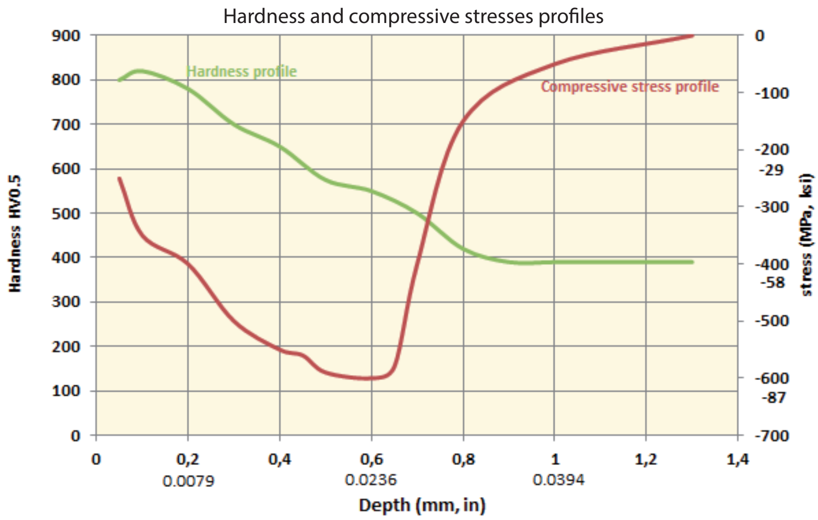
FATIGUE PERFORMANCES OF QUENCHED & TEMPERED AND CASE NITRIDED PRODUCTS

Fatigue improvement of case nitrided components is related to the compressive residual stresses in the layer, generated by deformation and volume changes occurred during processing.



Example of hardness and residual compressive stresses profiles (X rays analysis) on nitrided GKH

In case of high cycles fatigue, when stress concentrations increase, bending fatigue is highly improved by a nitriding treatment. Under low cycles fatigue condition and under axial loading, the benefit of case hardening is less obvious, the material core being more loaded than the case hardened layer (ratio between nitrided surface and non- nitrided surface defining the distribution of residual stress field).

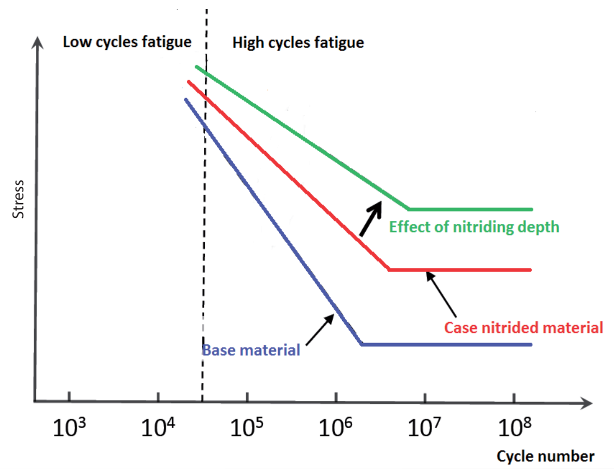


Illustration of benefits of case nitriding on Fatigue limits (S-N curves)

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Results on quenched and tempered material

Austenitizing: 920°C, 1688°F

Oil quenching

Tempering: 620°C, 1148°F

Mechanical properties

	YS0.2 (MPa, ksi)	UTS (MPa, ksi)	Fatigue limit for 20 Millions cycles (MPa, ksi)
GKH	1114, 161	1303, 189	631, 91
GKHW	1060, 153	1253, 182	697, 101
GKHYW	1085, 157	1276, 185	718, 104

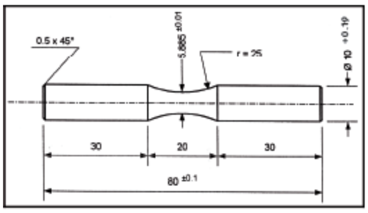
Fatigue method

Rotative bending mode R=-1

Unnotched specimens Kt=1.035

Specimens prepared with turning and finish grinding/polishing in longitudinal direction

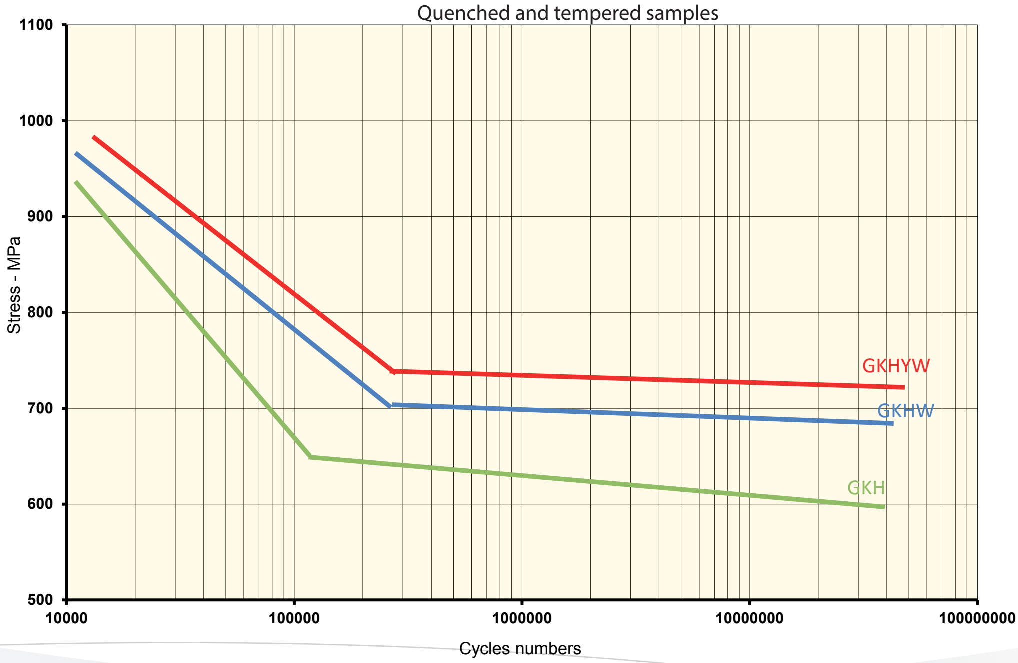
Endurance limit measured by stair case method for 20 Millions cycles (P0.5)



S-N curve - rotative bending mode

Target UTS 1250MPa, 181ksi / temper 620°C, 1148°F

Quenched and tempered samples



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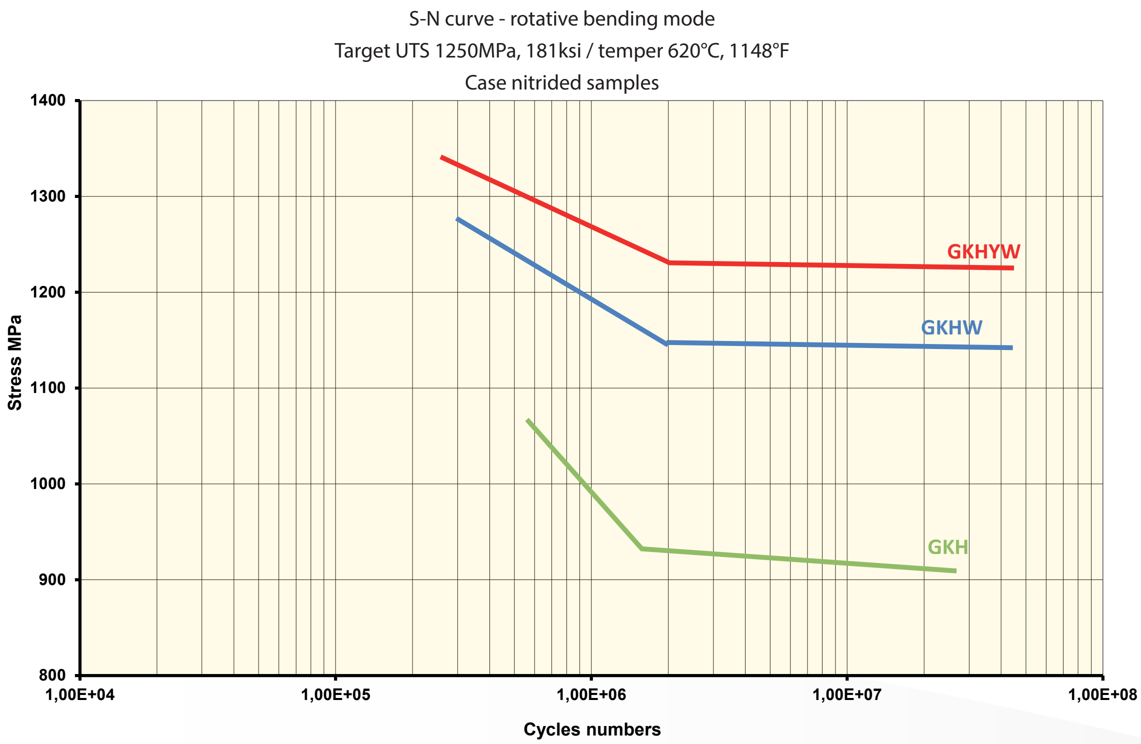
Results on quenched & tempered and nitrided material

Austenitizing: 920°C, 1688°F
Oil quenching
Tempering: 620°C, 1148°F
Nitriding for 0.7mm (0.0276in) case depth

Mechanical properties

	Core properties before nitriding on Q&T material		Properties on case hardened material
	YS0.2 (MPa, ksi)	UTS (MPa, ksi)	Fatigue limit for 20 Millions cycles (MPa, ksi)
GKH	1114, 161	1303, 189	910, 132
GKHW	1060, 153	1253, 182	1140, 165
GKHYW	1085, 157	1276, 185	1230, 178



Effect of melting mode on GKH fatigue limits (for core UTS 1250MPa, 181ksi and case depth 0.7mm, 0.0276in)

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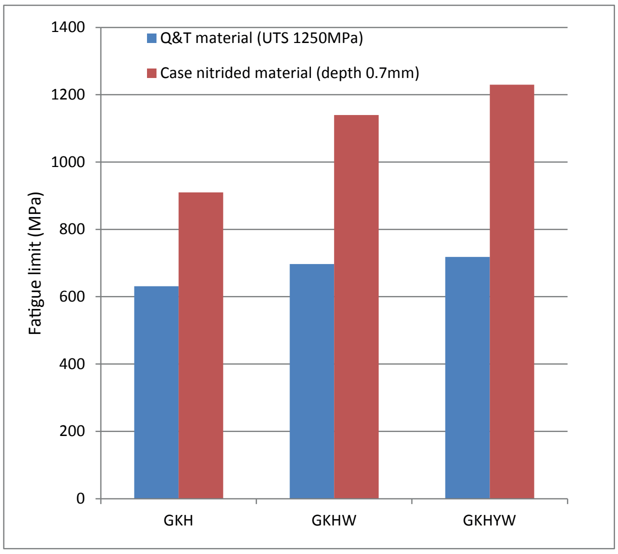
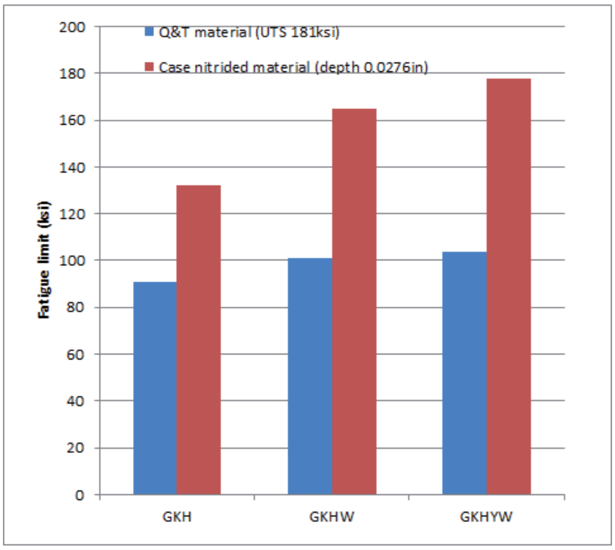
Below, is a summary of the fatigue limit measured in rotative bending mode at 20Millions cycles for Q&T and case nitrided material, depending on melting modes (single air melted, remelted, VIM/VAR).





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APPLICATION IN DEFENSE / FIREARMS
GKH FOR GUN BARRELS

Functions for gun barrels

Gun barrels are designed to withstand the high pressures and temperatures generated during firing. Basically, high yield strength levels (both at room and elevated temperature) combined with good ductility and toughness are required.

Problems on barrels	Barrels degradation modes	Material properties
Permanent bore expansion	Maximum pressure developed in combustion chamber	0.2% Proof strength at room and elevated temperature
Barrel rupture under extreme testing	Extreme gas pressure	No brittleness but plastic ductility at RT and low temperature High Charpy-V energy and low transition temperature
	Obstruction tests	
	Torture tests at low temperatures	
Unacceptable loss of material resulting in bore ovalization, lack of muzzle velocity, lack of accuracy	After thousands firing cycles, growth and coalescence of micro-cracks	Good resistance to Thermal fatigue
	Action of hot gases at high velocity	Resistance to Erosion wear due to gas (combination of thermal, mechanical and chemical causes)
	Interaction of projectile with barrels wall when moving through the bore	Resistance to abrasive Wear (mechanical degradation) - High surface hardness

For this application, air melted GKH offers the best high strength / toughness compromise on the market. The specification we usually deliver for a cold hammering / cold swaging process is given below. Other Ultimate Tensile Strength levels can be achieved and released depending on customer need and forming capacity (cold hammering or rifling).

	GKH
Type	Martensitic CrMoV
Symbol	33CrMoV12-9
UTS (MPa, ksi)	930-1080, 139-156
YS0.2 (MPa, ksi)	≥ 750, 108
E5d (%)	≥ 15
Charpy V-notch (RT) J, ft-lb	≥ 140, 103
Charpy V-notch (-40°C, -40°F) J, ft-lb	≥ 130, 99

Specification on heat treated material (Q&T) for UTS level 930MPa, 139ksi - delivery state (longitudinal direction)

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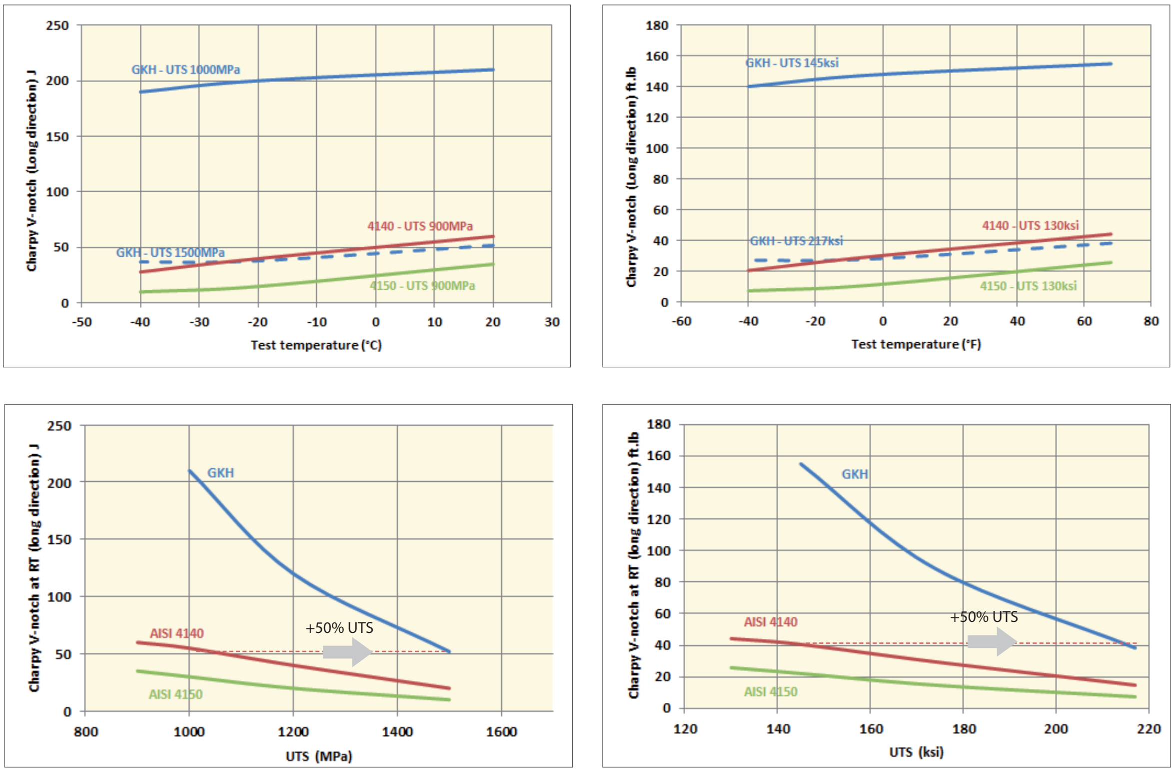
GKH PERFORMANCE COMPARED WITH AISI 4140 AND AISI 4150

In this bar diameter range (bar diameter ≤ 55mm, 2.165in on firearms gun barrels), GKH achieves a 100% martensitic microstructure after quenching. After tempering at high temperature, it exhibits an exceptional ductility and toughness for a given Ultimate Tensile Strength level (UTS).
This gives the opportunity to manufacture barrels with the highest strength to withstand pressure, fatigue and erosion combined with the highest toughness to enhance performances in torture tests.



Exceptional combination of Kv and UTS for GKH, compared with AIS I4140 and AISI 4150

The toughness of GKH is so high that the customer can afford to heat treat and temper the material (after rifling or cold hammering) in order to achieve Ultimate Tensile Strength up to 1500MPa, 217ksi. For an Ultimate Tensile Strength 50% higher, the fracture toughness will remain equivalent to AISI 4140 and better than AISI 4150. This opens some huge opportunities for weight savings and strong lifetime improvement by upgrading tensile and fatigue strength for the most loaded areas.

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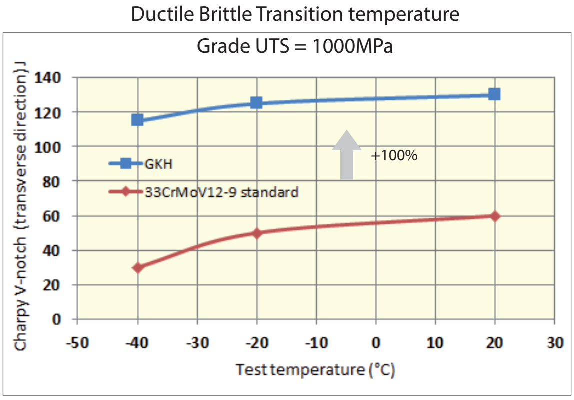
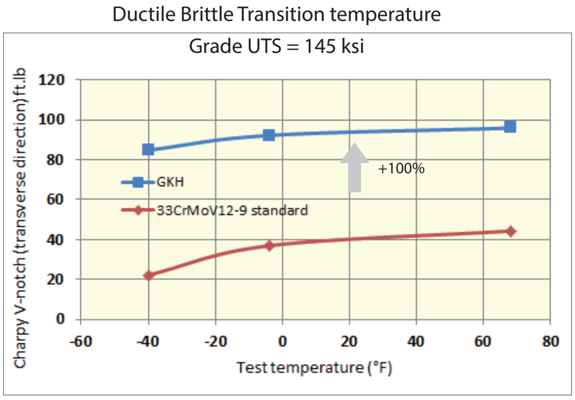
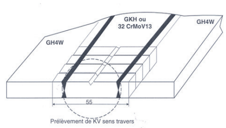
GKH PERFORMANCE COMPARED WITH STANDARD 33CrMoV12-9

Barrels being submitted to a transverse load during firing, specific attention must be paid to the transverse properties of the bars. GKH presents a highly isotropic structure, given to the material stable properties when longitudinal and transverse directions are compared.





Reconstitution of Charpy V specimens in transverse direction from small diameter bars by excising coupons from bars and welding extemities of Kv specimens



Charpy V-notch measured in transverse direction – comparison of GKH with a standard 33CrMoV12-9 (+100% increase)

GUN BARREL MANUFACTURING ABILITY WITH GKH

GKH is manufactured using an ultra-clean melting process associated with a conversion leading to the most isotropic and finest structure possible. This provides consistency, high quality and the following characteristics:

- Good machinability for gun drilling and reaming, with excellent polish ability for uniform lapping; necessary for bore accuracy
- High level of accuracy during cut, broached or button rifling (precise groove dimensions)
- Exceptional cold hammering / swaging ability

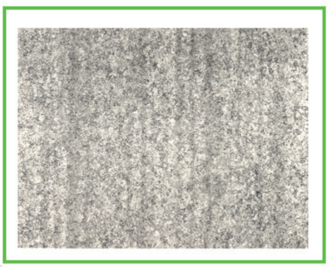


Illustration (x100) of fine and isotropic micro-structure on GKH

Basic CrMoV Grade

GKH® (W - YW)

33CrMoV12-9

It has been especially demonstrated over many years that GKH brings additional value compared with standard CrMoV grades:

Benefits for firearm producer/designer:

- Use higher rates of cold hammering and preserve more material compared with other grades
- Integrate functions like a combustion chamber in the gun barrel design during cold hammering, this saving production and assembly costs
- Use fatigue/strength upgrading opportunities of GKH to design lighter barrels with thinner wall sections
- Ensure stable process and limit troubles during manufacturing
- Ensure perfect straightness during the cold hammering / swaging operation

Benefits for firearm user:

- Keep perfect straightness during intensive firing and keep accuracy
- Have longer fatigue lifetime, limiting bore ovalization and lack of accuracy
- Use a lighter weapon

Gun barrels forming process

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APPLICATION IN INJECTION SYSTEMS
GKH / GKHW FOR NOZZLES AND BODY PUMPS

Technical challenges in Diesel and Heavy Fuel Oil injections systems

Stringent existing and future regulations request drastic reduction of particulate matter emissions for Diesel, Heavy Fuel Oil & Gasoline. This trend is true regardless of the applications (on-road and off-road) and locations (USA, EU, Asia). The driver for injection systems is to improve the spray properties. Higher pressures increase penetration into the combustion chamber and produce smaller fuel droplets, resulting in a drastic reduction of particles and smoke emissions.

The consequences to nozzle design concepts is the necessity to upgrade existing material solutions with improved fatigue and high operating temperatures (up to 450°C, 842°F). Nitrided GKH offers an excellent and quite unique solution in this field, covering all requirements.

	Nozzles requirements	Material properties
Part concept	Withstand high pressure for same casing	Core strength, fatigue
	Particle load effect	Wear
	Thermal load effect	Tempering resistance
	Transverse stress in pressure vessel	Material isotropy
	High reliability	High cleanliness material
Manufacturing	Cost	Simple hardening process
	Cost	Low distortions

GKH properties compared with existing nitrided and carburized solutions

Compared with legacy nitrided grades used for these kinds of applications, GKH brings significant additional value: H13 tool steel gives the worst combination of core properties (with very low toughness). 41CrAlMo7-10 is not suitable for applications requiring case layer ductility (risk of brittle case nitrided layer). 31CrMoV9 gives the lowest hardness profile. Existing solutions present major drawbacks regarding core properties and fatigue limits. Compared with these solutions, GKH offers the best compromise with exceptional core properties (very high toughness) and the highest fatigue performances on case hardened specimens.

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33CrMoV12-9

Designations	Case hardening technology	Max operating temperature (°C, °F)	YS0.2 (MPa, ksi)	UTS (MPa, ksi)	Charpy V Notch - Kv (J, ft-lb) - Core	Hardness surface HV10	Case depth (mm, inch)	Fatigue limit (MPa, ksi) on case hardened pdt *
18CrNi8 1.5920	Carburizing	150, 302	900, 130	1260, 182	40, 29	700	0.80, 0.0315	550, 80
X40CrMoV5-1 H13 – 1.2344	Nitriding	450, 842	1070, 155	1300, 188	15, 11	1100	0.25, 0.0098	720, 104
41CrAlMo7-10 1.8509		450, 842	1000, 145	1150, 167	40, 29	1150	0.25, 0.0098	660, 96
31CrMoV9 1.8519		450, 842	900, 130	1050, 152	90, 66	850	0.25, 0.0098	650, 94
33CrMoV12-9 GKH		450, 842	1060, 153	1250, 181	130, 96	900	0.25, 0.0098	810, 117

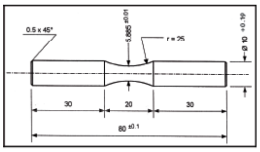
Single melted grades comparison for injection – typical value

* Fatigue Testing Conditions

Rotative Bending mode R=-1 – frequency 100Hz

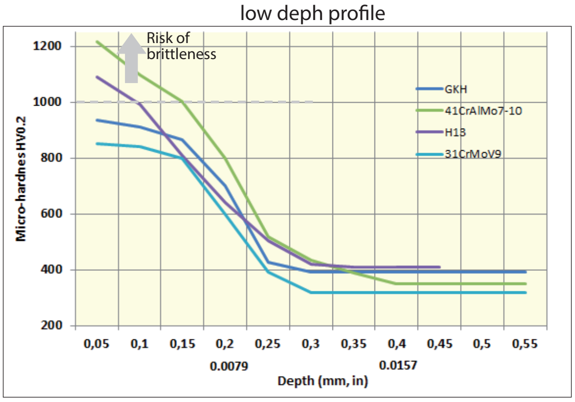
Kt = 1.035 sample polished in the longitudinal direction

Fatigue limit at for 20.10^{6} cycles with stair case method

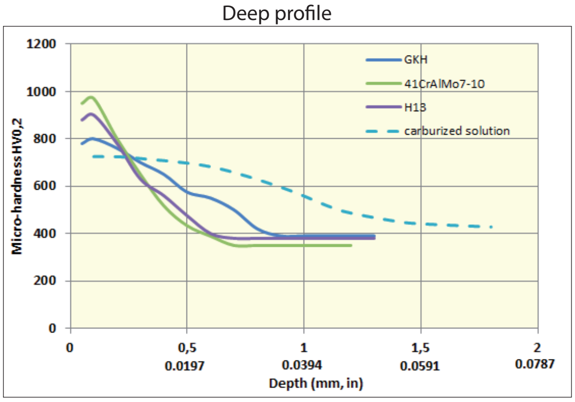


Compared with existing case carburized solutions, nitrided solutions offer high operating temperatures, low distortions process and very high wear performances due to higher surface hardness.
If a deep case layer is required (typical disadvantage of nitriding compared with carburizing), GKH closes the gap by being suitable for the deepest nitrided layers (0.7mm, 0.0276in), achieved with a realistic cycle time (<120hrs).

Case nitrided layer
low deph profile



Case nitrided layer
Deep profile



Typical case hardened profiles after gas nitriding : low depth profile 0.25mm, 0.0098in and deep profile 0.7mm, 0.0276in for GKH

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Delivery conditions

In order to cope with highly precise machining processes, the usual delivery conditions for GKH/GKHW in injection systems can be either normalized and tempered or quenched and tempered (using a very high tempering temperature and giving a very low hardness, ready to be machined). Passing all transformations points before final heat treatment prevents the major distortions during processing.

GKH is already running successfully, both in single air melted and remelted versions, for Diesel injection. Part performance is reported as exceptional with long lifetime and high reliability.

Marine common rail injector

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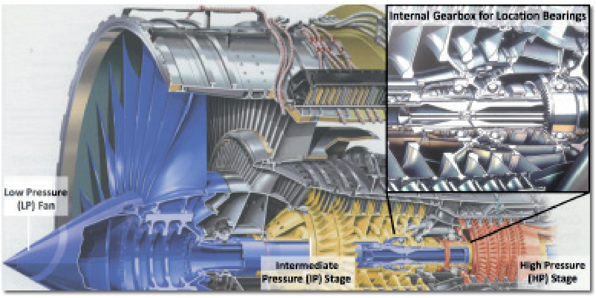
APPLICATION IN AEROSPACE BEARINGS
GKHYW FOR MAINSHAFT BEARINGS IN JET ENGINES

Technical challenges on mainshaft bearings

Bearings for aerospace applications need to be extremely reliable in order to reduce the In Flight Shut Down (IFSD) ratio and reduce the frequency of maintenance operations. In addition to that, bearings must contribute to weight savings and CO_2 emissions reduction by a drastic downsizing, withstanding higher loads with a reduced casing.

These functional and economic issues require the implementation of appropriate and reliable material. GKHYW associated with deep nitriding technology overcomes the limits of legacy grades, such as resistance to surface damage and toughness. Deep nitrided GKHYW provides a case deeper than 0.65mm (0.0256inch), a high surface hardness in the diffusion zone and generates compressive residual stresses, while maintaining an extremely tough core. All these properties offer major benefits in extending both the surface resistance to contamination and the ability to design bearings with an integrated design and thin sections that consequently reduce the weight of components. This GKHYW solution has been running for years in mainshaft bearings in the most reliable jet engines.



Front section of jet engine (RR TRENT 900) illustrating the locations of bearings

GKHYW properties compared with conventional VIM/VAR bearing grades

Usual name	A&D name	Technology	Core properties					Fatigue limit on hardened material (MPa, ksi) *
			Surface hardness	UTS (MPa, ksi)	YS0.2 (MPa, ksi)	Charpy V-notch (J,ft-lb)	K1c (MPa.Vm, ksi.Vinch)	
M50 80MoCrV42-16	RA50YW	Through hardening	61HRC, 720HV			3, 2	20, 18	950, 138
50NIL 13MoCrNiV42-46-14	50NILYW	Carburizing	700HV	1420, 206	1230, 178	12, 9	55, 50	1075, 156
33CrMoV12-9 AMS6481	GKHYW	Deep nitriding	820HV	1250, 181	1060, 154	140, 103	180, 163	1230, 178

Typical properties of VIM/VAR engines bearings grades for high operating temperatures (<450°C, 842°F)

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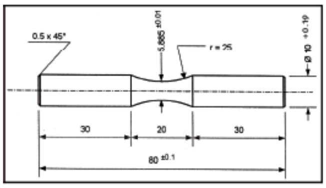
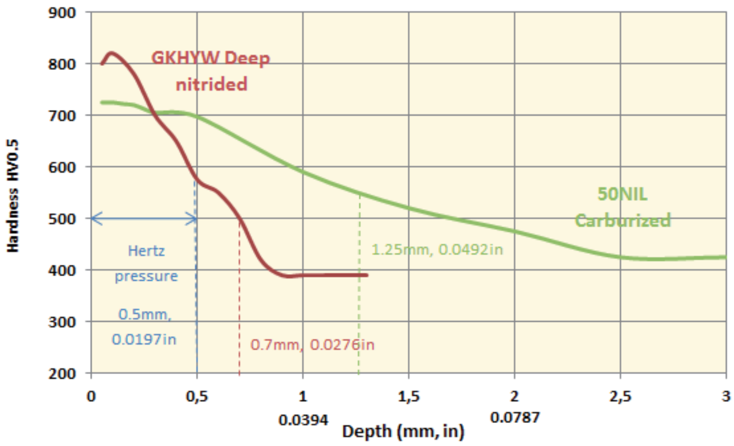
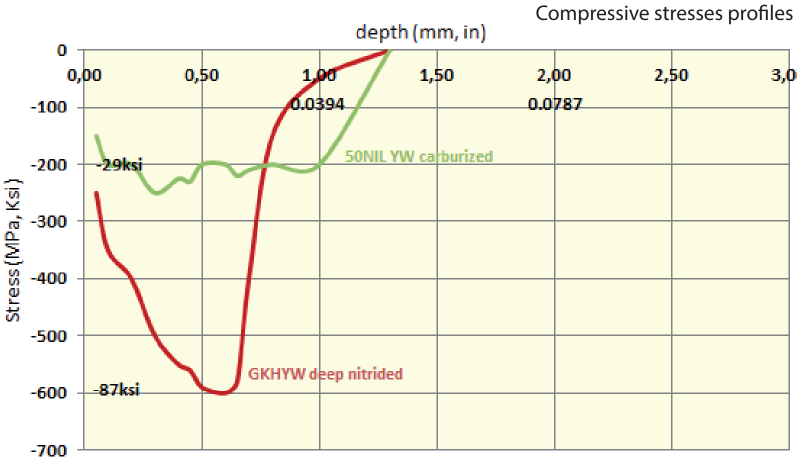
Fatigue Testing Conditions
Rotative Bending mode R=-1 – frequency 100Hz
Kt = 1.035 sample polished in the longitudinal direction
Fatigue limit at for 20.10[6] cycles with stair case method



Hardness Profiles



Compressive stresses profiles



Deep nitrided GKHYW, already used for other mechanical applications, offers a very good solution to the complex and numerous problems of modern bearings, provided the depth of the case is deep enough to be compatible with Hertzian stresses :

- Hard surface and extremely tough core
- High compressive residual stresses in the subsurface
- Treatment performed at relatively low temperature (450°C - 600° C, 842°F – 1112°F), giving low distortions

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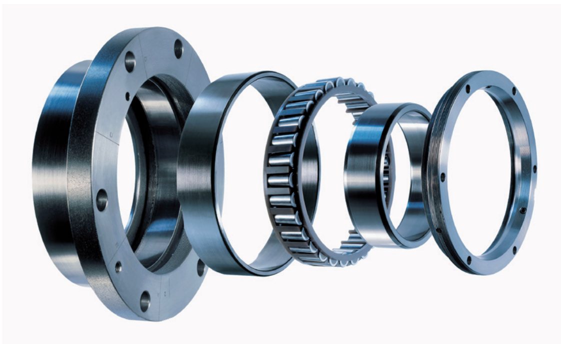
Results on bearings

Tests performed by bearings manufacturers in both Elasto-HydroDynamic lubricating and boundary lubricating conditions show that GKHYW has longer fatigue life compared with existing solutions M50 and 50NIL. All these features make the deep nitrided GKHYW an excellent solution for high reliability and safety aerospace components.

	Bearing Type	Flash washer	6309	NJ212
Test condition	Axial load (daN)	1075	530	300
	Radial load (daN)	-	1600	1200
	Hetrzian stress (MPa)	4200	3200	3100
	Speed (min^{-1})	1500	2200	1200
	Lubrification	ISO 46 oil	ISO 46 oil	ISO 46 oil
	Temperature (°C)	40	Room Temp.	Room Temp.
L_{10}Life (h)	GKHYW	≥1300	3863	1240
	M50	≥1300	942	560
	M50 Nil	850	-	980
	X20WCr10	990	-	-

Bearing Type	M50NiL	M50	GKHYW
Boundary lubrification	L_{10} (h)	>900	>900
Dented raceways	L_{10} (h)	503	>900

Rolling contact fatigue results from NTN-SNR in Elasto-HydroDynamic and boundary lubricating conditions
Extract from paper 1



Short litterature review on GKHYW for bearings applications :

1. Deep Nitrided 32CrMoV13 Steel for Aerospace Bearings Applications - Daniel Girodin - NTN TECHNICAL REVIEW No.76 2008 - Dowload paper www.ntn.jp/english/.../NTN_TR76_en_p024_031.pdf
2. Deep Nitriding of the 32CrMoV13 Steel (AMS 6481 0.32% C-3% Cr-1%Mo-0.2% V) and its Application for Aerospace Bearings - Pierre Joly and Daniel Girodin - Toronto, May 2005
3. Comparison of fatigue performances of 32CrMoV13 and M50 steels in presence of surface indents - Vincent, Nelias, Jacq, Robin, Dudragne - journal of ASTM International, Vol. 3, No. 2, 2005, pp. 1-11
4. Physical Properties of Contemporary and New Alloys for Aerospace Bearing Applications - Ragen, Anthony, Spitzer - Bearing Steel Technology, ASTM, STP1419, pp383-384, Jul 2002
5. Metallurgical and tribological evaluation of 32CrMoV13 deep nitrided steel and XD15NW high nitrogen martensitic steel for aerospace applications - Pichard, Girodin, Dudragne, Moreau - STP1327 Bearing Steels Into the 21st Century, Hoo JJC

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APPLICATION IN TRANSMISSIONS
GKHW / YW FOR GEARBOXES

Technical challenges on gearboxes

The major challenge for gearboxes is to achieve a very high power density, i.e. transmit very high loads with minimum weight and casing. Regarding material and technology, this means withstanding the highest pressure on contacts area (tooth roots and flanges) resulting in very high fatigue performances requested on both tooth bending fatigue mode and the rolling/sliding contact fatigue mode.

In addition to this strong challenge, we face specific requirements:

- Resistance to oil loss
- High reliability and high TBO needed (Time Between Overhaul)
- Control of excitation sources (noise reduction, fretting, loss of torque) requiring damage tolerant material
- Function integration by being able to build a single part combining structural, gear and bearing functions and using the same material
- Process cost savings

Nitrided GKHW for gearboxes

Many companies made the choice very early to develop nitriding and deep nitriding technologies to replace carburizing. There are several obvious advantages :

- Due to high tempering, no influence on material properties to run gears up to 250°C, 482°F in oil-off condition
- Low distortion process given the opportunity to design thin walls on gears
- High surface hardness given high resistance to pitting/scuffing/fretting and the opportunity to integrate other functions on parts (bearings races for instance)

This process of nitrided gears necessitates a very careful selection of the choice of steel in relation to the gear application. In this field, the use of GKH (single air melted, remelted or VIM/VAR) covers all the gears design considerations and bring the highest value of this technology:

- Exceptional bending fatigue performance
- Very deep case requirement (0.75mm, 0.0295in achieved in 120Hrs nitriding)
- Limited influence of ageing during nitriding on core properties
- Exceptional compromise of core hardness and damage tolerance
- Surface metallurgy with limited depth and favorable compound layer
- Weldable material (EBW for instance) giving the opportunity to avoid mechanical assembly

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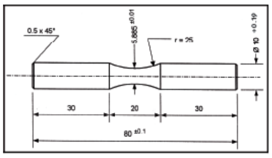
The table below summarizes typical mechanical properties obtained for best-in-class gears material (under remelted condition for A&D grades) comparing carburizing and nitriding technologies

Usual name	A&D name	Technology	Operating tempe-rature (°C, °F)	Case properties		Core properties			Lf case hardened material (MPa, ksi) *
				Top hardness (HV10)	Case depth (mm, inch)	UTS (MPa, ksi)	YS0.2 (MPa, ksi)	K1c (MPa.Vm, ksi.Vinch)	
10NiCrMo13-5 AISI 9310	FADCW		150, 302	700	1.4, 0.0551	1150, 167	900, 130	120, 109	1050, 152
16NiCrMo16-5 BS S82	FADSW		150, 302	700	1.4, 0.0551	1450, 210	1150, 167	100, 91	/
14NiCrMo13-4 AMS6548	FADHW	Carburizing	150, 302	700	1.4, 0.0551	1350, 196	1000, 145	130, 118	1100, 159
AMS6308	/		200, 392	700	1.4, 0.0551	1172, 170	965, 140	126, 114	/
15NiMoSiCr10 AMS6495	FNDW		250, 482	700	1.4, 0.0551	1350, 196	1030, 149	120, 109	1093, 159
AMS6475	/		450, 842	850	0.45, 0.0177	1240, 180	1150, 167	/	/
40CrMoV12-9	GH4W	Deep nitriding	450, 842	820	0.7, 0.0276	1350, 196	1100, 159	110, 100	1100, 159
33CrMoV12-9	GKHW		450, 842	820	0.7, 0.0276	1250, 181	1060, 154	180, 164	1140, 165

Remelted gears grades comparison – typical value

* Fatigue Testing Conditions
Rotative Bending mode R=-1 – frequency 100Hz
Kt = 1.035 sample polished in the longitudinal direction
Fatigue limit at for 20.10^6 cycles with stair case method



While standard carburized solutions can no longer be used at high operating temperatures (>250°C, 482°F), nitrided gears are one of the existing solutions today that can cope with oil-off requirements. Best-in-class FNDW carburized can be used with a high temper but still presents some disadvantages as any other carburized solutions in term of distortion management.

In addition to that, some customers report a Total Cost of Ownership lower than 10% when comparing deep nitrided GKHW to other standard carburized solutions using legacy remelted grades (AISI 9310, BS S82 or 14NiCrMo13-4).

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Short literature review on GKHW and GKHYW for gears applications :

1. Role of Carbon during nitriding and influence on mechanical properties, G Fallot, Thèse de Doctorat 2015, ENSAM Paris and MSMP - Laboratoire Mécanique, Surfaces, Matériaux & Procédés
2. Influence des carbures intergranulaires induits par la nitruration sur la propagation de fissures de fatigue de contact d'acier allié pour engrenage - Le, Villen, Klebern, Buffiere, Cavoret, Sainte Catherine, Briancon - JIFT 2016, 22ème Congrès Français de Mécanique 2015
3. 3D Observation of Rolling Contact Fatigue Crack Network in Nitrided Alloyed Steels - Le, Villen, Klebern Buffiere, Cavoret, Sainte Catherine, Briancon - 42nd Leeds/Lyon symposium on tribology 2015
4. Modeling of distortions induced by the nitriding process - Depouhona, Sprauela, Mailh, Mermozb – 21ieme Congrés Français de Mécanique 2013
5. Residual Stresses and distorsions simulation of nitrided disc - Barrallier, Goret, Vardon, Deloison - JCPDS-International Centre for Diffraction Data 2009 ISSN 1097-0002
6. Phase transformations and induced volume changes in a nitrided ternary Fe{3% Cr{0.345% C alloy) - Jegou, Barrallier, Kubler - R. 2010 Acta Materialia 58 pp. 2666 2676, Elsevier
7. Experience with large, high speed loaded gears - Dehner, Weber - Geartechnology 2007
8. Influence des éléments d'alliages sur la genèse des contraintes résiduelles d'aciers nitrurés - Jegou - 2004 Thèse de Doctorat
9. Link to https://www.youtube.com/watch?v=oD4jKBOIBwc (EC225 - Bevel Gear Vertical Shaft Process)

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NOTES:

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