Increasing the resistance to buckling of piston rods through induction hardening

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SUMMARY

Induction hardening of hydraulic cylinder piston rods engenders not only a protection from damage in the event of external impact but also improves the mechanical properties of the rod and in particular, the resistance to buckling failure in push mode. This increase in buckling resistance can be accounted for by considering the rod as a composite material with a tube of hardened steel surrounding a solid core. Consequently, in relation to a non-hardened rod with the same steel base, the diameter of an induction-hardened rod can be downsized leading to a number of benefits including but not restricted to reduced weight and lower costs.

List of symbols

D_o	O.D. of tube (mm)
D_i	I.D. of tube (mm)
t	thickness of induction-hardened layer (mm)
L_{eff}	effective unsupported rod length (mm)
λ	slenderness parameter
F_b	buckling force (kN)
α, ϕ	dimensionless parameters
E	modulus of elasticity (MPa)
σ_s	compressive yield stress (MPa)
σ_b	buckling stress (MPa)
σ_{be}	Euler buckling stress (MPa)
d	rod diameter (mm)

1 – INDUCTION HARDENING IMPROVES MECHANICAL PROPERTIES

Hydraulic cylinder piston rods are induction hardened in order to increase the resistance to damage from unanticipated external impact in applications where there is risk for such; examples are piston rods for hydraulic cylinders in excavators and loaders and for power-steering cylinders. An additional advantage afforded by induction hardening is improved resistance to inadvertent handling damage during cylinder manufacture.

However, induction hardening also alters the mechanical characteristics of the steel in the piston rod, a fact which is normally not recognised by engineers involved in design and dimensioning of hydraulic cylinders. A simple demonstration of the effect of surface hardening is afforded by Fig.1 in which conventional stress-strain curves from tensile testing of full-section hard-chrome plated bars in both hardened and non-hardened condition are compared (280X steel base - 19MnVS6 improved). The induction-hardened rod is characterised by higher yield strength, higher rate of strain hardening, considerably increased tensile strength and somewhat reduced elongation in comparison with the non-hardened material. These effects can approximately be accounted for using a simple law of mixtures taking into account the different properties of the steel in the hardened case and the softer core.

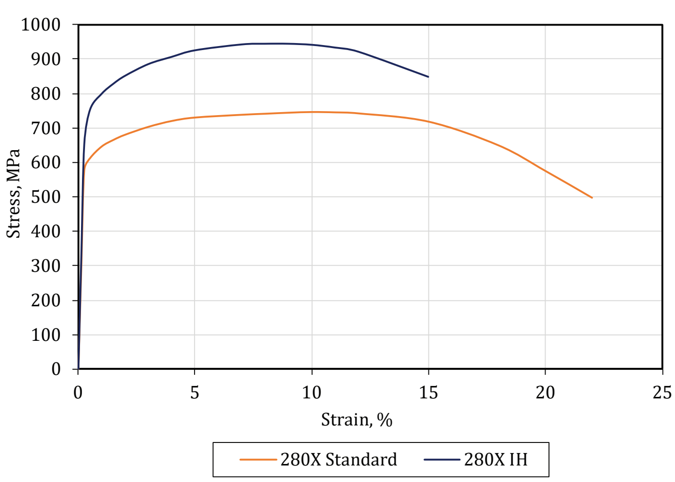

Fig 1: Stress-strain curves in tension for full section hard-chrome plated bar comparing hardened and non-hardened execution (280X-grade, diameter 30 mm). Depth of hardening for the IH-bar is 1.6 mm.

A further striking example of the influence of induction hardening on the mechanical characteristics of piston rods is provided by bend testing. In Fig. 2, stress-strain curves for full-section hard-chrome plated bars in three-point bending are compared for hardened and non-hardened bars of two different diameters, 30 and 60 mm (again, the base steel grade is 280X).

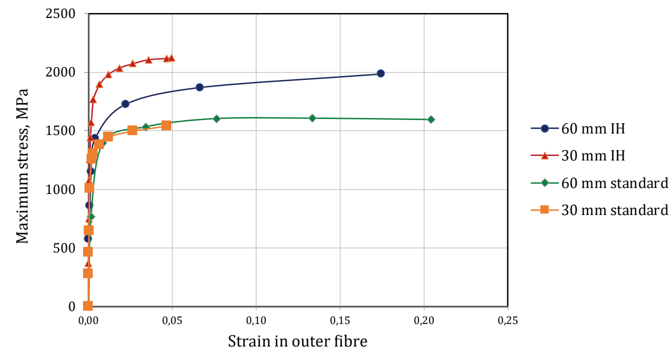

Fig 2: Stress-strain curves in 3-point bending comparing hardened and non-hardened hard-chrome plated piston-rod material (base steel 280X).

In bending, the maximum stress is experienced in the outer fibre and it is therefore logical that the resistance to deformation is markedly improved as a consequence of the presence of the induction-hardened case. Furthermore, the resistance to bending is greater for the 30 mm than for the 60-mm bar; this is because the hardened zone occupies a greater proportion of the bar section for the smaller diameter (the hardness distributions in the induction-hardened case are shown in Fig. 3). Note also that the stress-strain curves in bending are virtually independent of dimension for the standard, i.e. non-hardened, rods.

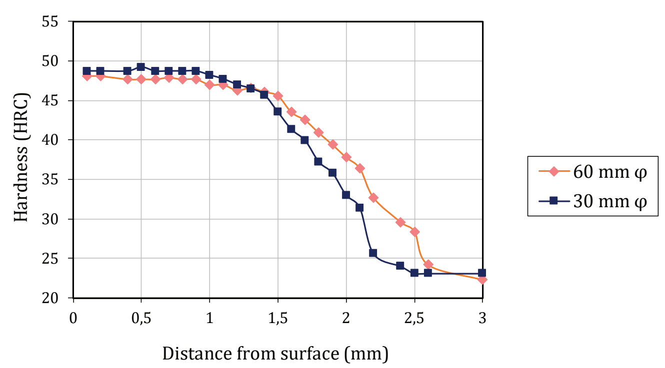

Fig 3: Hardness distribution in induction-hardened, hard-chrome plated rods giving the 3-point bending data in Fig. 2 (base steel grade 280X).

2 – INDUCTION HARDENING ALSO IMPROVES BUCKLING RESISTANCE

Since buckling is essentially a phenomenon involving bending under axial compressive stress, it is pertinent to enquire whether the pronounced influence of induction hardening on bend strength, as demonstrated in Fig. 2, is reflected in a similar improvement in the resistance to buckling. In Euler's classical treatment, the stress required for buckling is only governed by a single mechanical characteristic, namely E-modulus; in particular, the Euler buckling stress does not depend on typical characteristics of plastic deformation in tension such as yield stress or ultimate tensile stress. However, it is well known that for small values of slenderness parameter, Euler's equation is no longer valid and that the buckling resistance does show a dependence on yield and tensile strength.

We have compared the resistance to buckling of hard-chrome plated bars (280X base steel) with different diameters and lengths and in non-hardened and induction-hardened execution. The testing was performed in an instrumented hydraulic press, which was adapted for the purpose. The test data were monitored in the form of a force-time curve. Two such curves for hardened and non-hardened rods with diameter (d) 44.45 mm and length (L) 650 mm (slenderness parameter, $\lambda=4.L/d=58.5$) are reproduced in Fig. 4.

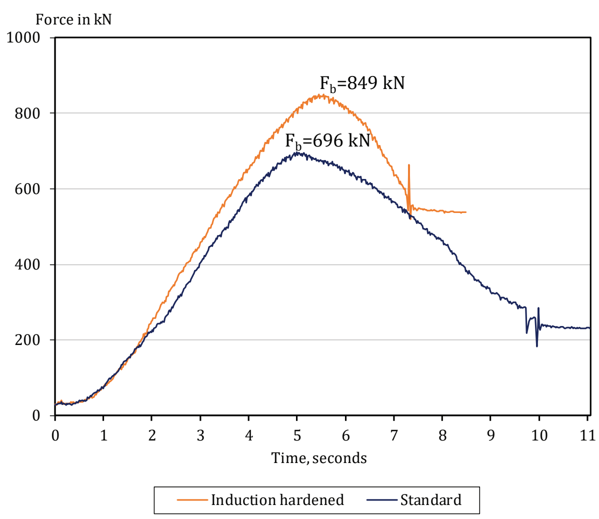

Fig 4: Comparison of force-time curves in buckling tests on hard-chrome plated non-hardened and induction-hardened piston rods (grade 280X).

Buckling occurs at the peak of the force-time curve and it is quite clear that the buckling force for the hardened rod is 22 % higher than that for the standard rod. It would seem that induction hardening does indeed have a positive effect in terms of resistance to buckling.

By testing hardened and non-hardened rods with different diameters and lengths, the buckling stresses have been established for a range of slenderness parameters from 50 to 150. The rod diameters tested were 30 and 44.45 mm; unfortunately, limitations with the equipment precluded testing of larger diameters. The results from all tests are shown in Fig. 5 as a buckling diagram, i.e. buckling stress vs. slenderness parameter (λ). It is evident that the buckling stress is increased as a result of induction hardening over the entire range of slenderness parameter investigated. There is some scatter in the data, not least deriving from the makeshift testing equipment, but the positive effect of hardening the rod surface is unequivocal. The improvement engendered by induction hardening is about 20 % at $\lambda=50$, 30 % at $\lambda=100$ and 60 % at $\lambda=150$. In other words, it appears that induction hardening improves buckling resistance even in the elastic regime at high slenderness parameters, where the Euler buckling stress is normally considered accurate; indeed, the influence of hardening is proportionally even more significant in the high-λ, so-called elastic regime.

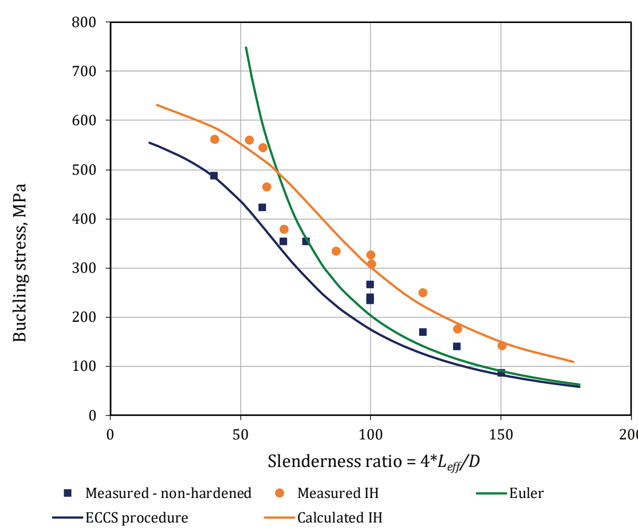

Fig 5: Buckling diagram showing measured data for non-hardened and induction-hardened chrome-plated piston rods (grade 280X) and curves calculated as described in the text.

3 – A POSSIBLE EXPLANATION FOR THE POSITIVE EFFECT OF INDUCTION HARDENING ON RESISTANCE TO BUCKLING

The observations summarised in Fig. 5 can simple-mindedly be explained if the induction hardened rod is treated as a composite material having a hardened case in the form of a tube which is filled with a solid core of base steel. Considering first a solid homogeneous rod, the relationship between buckling stress and slenderness parameter for buckling of columns is defined in a number of building standards. As an example, the essentially empirical procedure advocated by the European Convention for Structural Steelwork (ECCS) is given below. This method can also be applied to the instance of piston rods subjected to compressive (push) loading.

We define a dimensionless parameter α as:

$$\alpha = \frac{1}{\pi}\lambda\sqrt{\frac{\sigma_s}{E}}$$

where *E* is the modulus of elasticity, σ_s the yield stress in compression and $\lambda = 4.\ L_{eff}/d$ for a solid rod with effective length L_{eff} and diameter d.

The buckling stress, σ_b, is then given by

$$\sigma_b = \sigma_s(\phi - \sqrt{\phi^2 - \frac{1}{\alpha^2}})$$

in which the dimensionless factor ϕ is defined as:

$$\phi = \frac{1 + 0.21(\alpha - 0.2) + \alpha^2}{2\alpha^2}$$

For large λ (long, smaller diameter rods), σ_b calculated from the above is very close to, but always slightly less than the Euler buckling stress, σ_{be}, for a rod with pin-ended joints which are free to rotate about an axis orthogonal to that of the rod (Euler Case II), i.e.

$$\sigma_{be} = \pi^2 E/\lambda^2 \quad \text{, where obviously} \quad 1/\alpha^2 = \sigma_{be}/\sigma_s \, .$$

As $\lambda \to 0$, the above expressions imply $\sigma_b > \sigma_s$ which is not feasible and the ECCS-formulation then sets σ_b equal to the yield stress in compression. The curve calculated with the help of the above equations for grade 280X (σ_s = 560 MPa, E = 205 000 MPa) is shown in Fig. 5 previously. The agreement with the observations for non-hardened rods is reasonable, with the observed values tending to lie above the calculated curve. This can be expected since the ECCS-procedure is known to give a conservative estimate of the buckling stress and is formulated with the straightness and tolerances relevant to civil-engineering constructions in mind rather than those for precision machine components such as piston rods.

In order to explain the observations on the induction-hardened rods (see Fig. 5), it is assumed that the buckling stress is the same as for a tube with a wall thickness equal to the thickness of the induction-hardened case. The slenderness parameter for a tubular piston rod with O.D. = D_o and I.D. = D_i is:

$$\lambda_{tube} = 4L_{eff}\sqrt{\frac{D_o^2 - D_i^2}{D_o^4 - D_i^4}} = 4L_{eff} \Big/ \sqrt{D_o^2 + D_i^2}$$

If the case thickness is 1.5 mm (see Fig. 3), then D_i = D_o - 3 mm and the slenderness parameter for the “tube” of induction-hardened steel can be determined. The corresponding value of σ_b can then be evaluated from the above relationships and plotted against the true λ for the solid bar. The curve obtained in this way is plotted in Fig. 5 and it can be seen to conform quite well to the observed buckling behaviour for the induction-hardened bar lending some degree of support to the contention that in terms of buckling, an induction-hardened rod behaves like a tube with a core of softer material. In constructing the curve for the induction-hardened rods, the increased yield strength derived from the presence of the hardened case (Fig.1) has also been taken into account.

4 – EXAMPLES OF PRACTICAL CONSEQUENCES IN RELATION TO DIMENSIONING OF PISTON RODS

The present study has clearly demonstrated that induction hardening of piston rods improves not only the resistance to external impact but also the mechanical characteristics of the rod. In particular, the resistance to buckling failure is increased markedly. The implication is that an induction hardened rod can be downsized significantly in relation to a standard, non-hardened rod whilst still maintaining an acceptable safety factor in relation to buckling failure. This is illustrated by the following examples (buckling stresses calculated according to the ECCS-procedure):

Example 1 Cylinder with bore 100 mm and maximum operating pressure 260 bar.

* A non-hardened rod, diameter 50 mm and length 1 000 mm (λ = 80) in steel grade 280X (min. yield strength 520 MPa), has a calculated buckling stress of 262 MPa; the maximum stress in the rod is 104 MPa and the safety factor against buckling failure is 2.52.

* For an induction-hardened rod, diameter 45 mm and length 1 000 mm (λ = 88.9) in the same steel grade, the buckling stress calculated with the model outlined in §3 above taking t = 1.5 mm is 353 MPa; the maximum stress in the rod is now 128 MPa, and the safety factor 2.76. In other words, the smaller diameter induction-hardened rod actually offers a greater margin of safety against buckling.

Example 2 Cylinder with bore 80 mm and maximum operating pressure 140 bar.

*For a non-hardened rod, diameter 40 mm and length 1 500 mm (λ = 150), the calculated buckling stress is 85 MPa and since the maximum stress is the rod is 56 MPa, the safety factor is 1.52.

*An induction hardened rod, diameter 35 mm and length 1 500 mm (λ = 171.4) has a buckling stress of 117 MPa and the maximum stress in the rod is now 73 MPa giving a safety factor of 1.60.

The weight saving gained by switching to an induction-hardened rod in the above examples is 19 % and 23 % respectively and in addition, the extra cost of induction hardening is normally more than compensated for by the lower weight of the rod. A further advantage afforded by the downsized induction-hardened rod in relevant applications is a greater pull force because of the increased annular area.

5 – SUMMARY

Induction hardening of hard-chrome plated piston rods not only provides protection against damage from external impact but also confers enhanced mechanical properties, such as better compressive strength, greater bend resistance and improved buckling strength. The latter in particular is hardly ever given cognizance in dimensioning of the rod. The present exercise demonstrates that induction hardening confers significantly higher resistance to buckling and of particular interest is that the improvement is achieved even in the so-called Euler regime at high levels of slenderness, where it is usually upheld that altering the mechanical characteristics of the base steel is of no consequence for determining buckling strength.

A simple argumentation is presented whereby the improved buckling strength derived from induction hardening can be ascribed to the induction-hardened layer behaving like in a thin-walled tube in relation to moment of inertia but with a solid core as support. This approach permits a quantitative description of the buckling stress as a function of rod slenderness which is in reasonable agreement with observations from buckling tests.

The conclusion is that an induction hardened rod can be downsized significantly in relation to a standard, non-hardened rod whilst still maintaining an acceptable safety factor in relation to buckling failure. Such downsizing can confer benefits in terms of reduced weight; furthermore, the extra cost of induction hardening is often more than compensated for by the lower weight of the rod:

FURTHER READING

ECCS "Manual on stability of steel structures", June 1976

Design Manuals Eurocode 3 "Design of steel structures", ISBN13: 97834330313531993 (ECCS, 2015)

"Hållfasthetsteknisk Dimensionering", Ingvar Rask & Staffan Sunnersjö (Sveriges Verkstadsindustrier, 1992) (in Swedish)

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Mattias Awad is a Swedish citizen having a degree in Mechanical Engineering with specialisation in hydraulics and pneumatics from the University of Linköping (1997). After completion of studies, he has worked in R&D around fluid technology and systems and, immediately prior to joining Ovako, for a leading manufacturer of mining equipment in hydraulic system design and development of methods for testing and validation. Since 2017, he is responsible for marketing and technology within the Ovako Cromax Group which specialises on hard-chrome plated products for the hydraulics segment.

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Joakim Hultgren is a Swedish citizen with an MSc degree in Mechanical Engineering from the Royal Institute of Technology in Stockhom and a BSc in Business Administration from the University of Stockholm. In his career, he has held various management positions in engineering companies where the principal focus has been on hydraulics. Hultgren has ten years' experience within Ovako Cromax in both production and plant management. His current position is President of the Ovako Cromax Group with overall responsibility for the operations in Hallstahammar (Sweden), Twente (The Netherlands), Redon (France) and Molinella (Italy).

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William Roberts is a native of the UK where he received the degrees of BSc and PhD in Physics from the University of Newcastle upon Tyne. After moving to Sweden, he was employed for ten years (1975-1985) at the Swedish Institute for Metals Research and based upon published works was in 1979 conferred the title of DSc by the Royal Institute of Technology in Stockholm. Roberts continued his career in Swedish industry and has worked in R&D, production and sales and marketing. At the time of retirement in 2011, he was employed by Ovako Cromax as responsible for sales and marketing of hard-chrome-plated bars and tubes to the hydraulics segment. He remains active in the capacity of a technical advisor within the areas of materials science and strength of materials.

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