Learn how optimisation of steel for piston rods can improve the economics of hydraulic cylinders

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EXECUTIVE SUMMARY

Piston rods in hydraulic cylinders can fail through buckling associated with compressive (push) loading or fatigue as a result of alternating compression-tension (push-pull) or tension only (pull only). The present paper discusses how the failure threshold for both of these mechanisms can be increased by making the piston rod from higher-strength steel. This has economic repercussions in that the piston rod can be downsized, reducing both weight and cost, while maintaining the chosen margin of safety against failure.

It is demonstrated how the yield strength of the steel used for a piston rod has a significant bearing on its buckling resistance. Hence, a newly-developed steel, 180X, with about 60 % higher yield strength than the conventional choice, C45E, permits downsizing of the rod while maintaining the same resistance to buckling. Or alternatively, the hydraulic cylinder can be adapted to transmit a greater force without having to increase the rod diameter. In the same vein, the 180X-grade has a higher tensile strength than C45E resulting in improved resistance to failure by fatigue if there is a risk for such. Again this improvement can be made use of either to downsize the rod or to enhance cylinder performance.

These benefits do not come at the expense of manufacturability. Indeed, the new steel is actually somewhat easier to fusion weld than C45E. Furthermore, the analysis and method of manufacture is tailored for amenability to friction welding thereby mitigating risk for brittle areas in the heat-affected zone of friction welds. Machinists will find that the 180X-grade is at least equivalent or in some machining operations actually superior to C45E.

The 180X-steel is eminently suitable for induction hardening whereby a high surface hardness is achievable imparting good resistance to external impacts in tough working conditions. In the unlikely event that the high strength level of 180X is insufficient for some high-load applications, the steel can be cold drawn to achieve strengths on-a-par with heat-treated low-alloy steels.

Cromax 180X stands out as having the most favourable overall combination of properties in any detailed comparison with traditional steel grades used in the hard-chrome-plated condition for piston-rod applications.

1 – INTRODUCTION – PISTON RODS ARE DIMENSIONED AGAINST FAILURE BY BUCKLING AND/OR FATIGUE

In a hydraulic cylinder, the pressure imparted by hydraulic fluid against a piston gives rise to a force which performs useful work. This force is transmitted by the piston rod which must be dimensioned such that the stress in the rod (i.e. force divided by the cross-sectional area) is maintained sufficiently low that any risk for failure is minimised. The forces in piston rods can be push (compression) corresponding to a compressive stress in the rod or pull (tension) associated with rod tensile stresses. These forces are usually axial and uniformly distributed over the rod section. Bending moments can be experienced if the rod is side-loaded and the stresses engendered thereby can be very high. Hence designers of hydraulic cylinders will as far as possible strive to avoid side loading. Common sources of side loading are friction at pin joints, wear at guides and seals, and misuse.

In single-acting cylinders, the piston rod is usually loaded in push-only (compression) mode so fatigue is not an issue. In this instance, the dimension of the rod must be such that its axial stress remains below that which will give rise to buckling. This is a sudden, large and unstable lateral deflection associated with only a small increase in compressive load above a critical level, the buckling load. The corresponding stress can be far less than the yield strength of the rod material. Once it occurs, buckling leads to instability and collapse of the piston rod. Hence, it is potentially a highly dangerous failure mode which can be the cause of serious accidents.

Piston rods in double-acting cylinders feel alternating compression-tension loads.

So, in addition to a buckling risk on the compression part of the load cycle, the cylinder designer must also give consideration to the possibility for fatigue. This is a damage process whereby cracks are initiated and develop under repeated variable loads which are far less than the tensile strength of the steel in the rod. Apart from steel mechanical characteristics, other factors of importance for fatigue strength of piston rods are surface finish, stress concentrations and, for welded rods, weld quality. Piston rods that fail by fatigue inevitably do so either at thread roots or at fillets, where the stress is greater due to reduced section and stress-concentration effects, or at welds. All welds contain defects from which fatigue cracks can initiate.

Hydraulic cylinders are usually fatigue tested by locking the piston rod and subjecting it to load cycles by appropriate control of oil flow. The load cycles can be push-pull (compression-tension) or pull only (so-called pulsating tension). A typical acceptance criterion is that the rod has not failed after a stipulated number of cycles with a well-defined load/pressure maximum. Generally speaking, the failure pressure corresponding to a given number of cycles or alternatively the number of cycles to failure at a given pressure, increase in parity with the tensile strength of the steel in the rod. This is certainly true when fatigue cracks start from threads or fillets but is less clear cut for weld-initiated fatigue failure where also weld quality inevitably plays an important role.

2 – STEEL OPTIMISATION CAN PROVIDE ENHANCED RESISTANCE TO BOTH BUCKLING AND FATIGUE

2.1 Increasing the yield strength of the steel in a piston rod can very often enhance security against buckling

The classical Euler description predicts that apart from dimension and shape, resistance to buckling increases with increasing elastic modulus of the material in a body loaded axially in compression. It has long been realised that while Euler accounts reasonably well for buckling loads of slender bodies (essentially elastic buckling), it greatly overestimates buckling resistance when slenderness is less and plasticity comes into play. This is recognised in building construction codes in both Europe and North America which for bodies of lesser slenderness give cognizance to the importance of material yield strength as well as elastic modulus.

In Fig.1, the buckling stress of piston rods (buckling load divided by cross sectional area) calculated according to the method stipulated by the American Institute for Steel Construction (AISC) is plotted against the slenderness ratio, which for a circular section is $4L_e/D$ where D is the diameter and L_e the effective length.

For slenderness ratios < ≈100, it is clear that the Euler description overestimates the buckling stress and that in this regime, yield strength plays a significant role with higher strength conferring a greater resistance to buckling. On the other hand, Euler provides an adequate estimation of the buckling behaviour for rods with slenderness ratios above this limit. The AISC-formulation stipulates a safety factor which increases with rod slenderness. However, the relative influence of yield strength on buckling load is still the same even when the effect of this variable safety factor is considered.

The European Convention for Constructional Steelwork (ECCS) gives a recommendation for estimating buckling stress in the elastic-plastic regime which predicts results which differ only marginally from the AISC-formulation. Relatively speaking, the influence of yield strength in the ECCS-description is very similar to that depicted in Fig. 1.
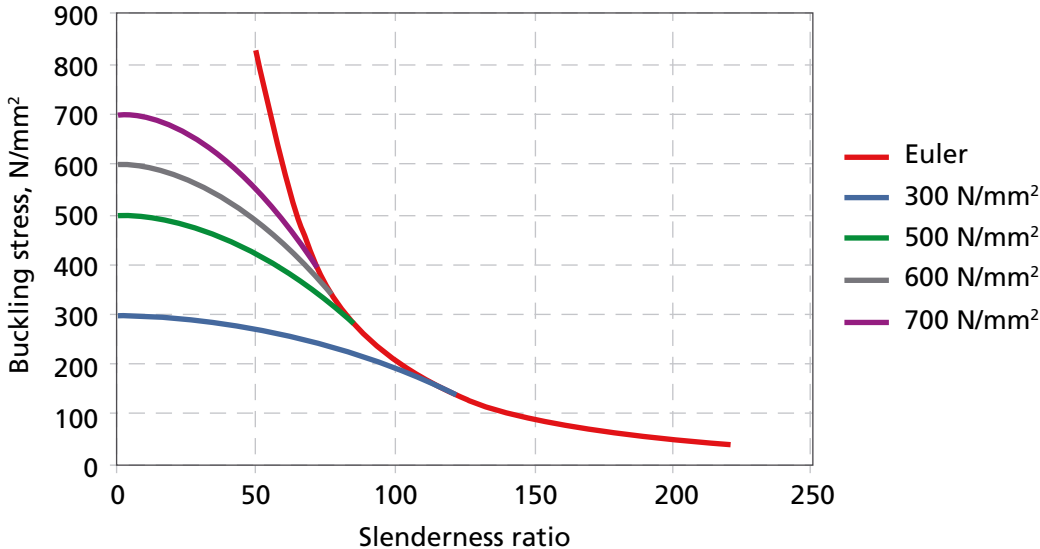

Figure 1 – Buckling stress calculated using the AISC-formulation vs. slenderness ratio for piston rods of steel with different yield strengths; Euler curve included for comparison.

A procedure for assessing buckling strength which specifically addresses hydraulic cylinders is given in the crane standard prEN 13001-3-6. This provides a useful method of calculation for estimating the effective length of a piston rod depending on how the cylinder is supported (see section 2.2 below). However, even in this standard, the predicted influence of yield strength of the base steel in the piston rod follows the same pattern as deduced from the AISC and ECCS formulations for calculating buckling load and summarised in Fig. 1.

In many instances, the geometry of piston rods is such that they fall into the regime where yield strength does indeed have an influence on buckling resistance. For example, the slenderness ratio for a 50-mm diameter rod with effective length 800 mm is 64 and its buckling resistance is close to being doubled if the yield strength of the base steel is increased from 300 to 700 N/mm².

2.2 Estimating an effective piston rod length

In terms of its propensity to buckle when loaded, the effective length of a piston rod depends on the cylinder mountings. If the cylinder is supported at the gland (Fig. 2 (a)

below), then the effective rod length can be approximated as the stroke. However, a very common arrangement is that the cylinder is mounted via pin and eye joints at the end of the rod and the bottom of the tube (Fig. 2 (b)).

For the type of mounting in Fig. 2 (b), many designs are based on the standpoint that the effective length is (L_1+L_2). This is too conservative and results in an over-dimensioned piston rod. Procedures for evaluating the effective length in the case of end mounting are given in several sources, not least the crane standard prEN 13001-3-6 mentioned previously. Calculations for a range of dimensions and lengths for both piston rod and tube indicate that the effective piston-rod length for end mounting is about 1.6 times the actual length. This estimate furnishes a reasonably accurate and conservative evaluation of the buckling strength so long as the lengths L_1 and L_2 do not differ too much. For example, considering a cylinder with rod diameter 50 mm and tube dimensions 100 mm I.D./115 mm O.D. with L_1 = 500 mm and L_2 = 600 mm, the effective rod length is 915 mm which is 1.52 times the actual length and appreciably less than (L_1+L_2).
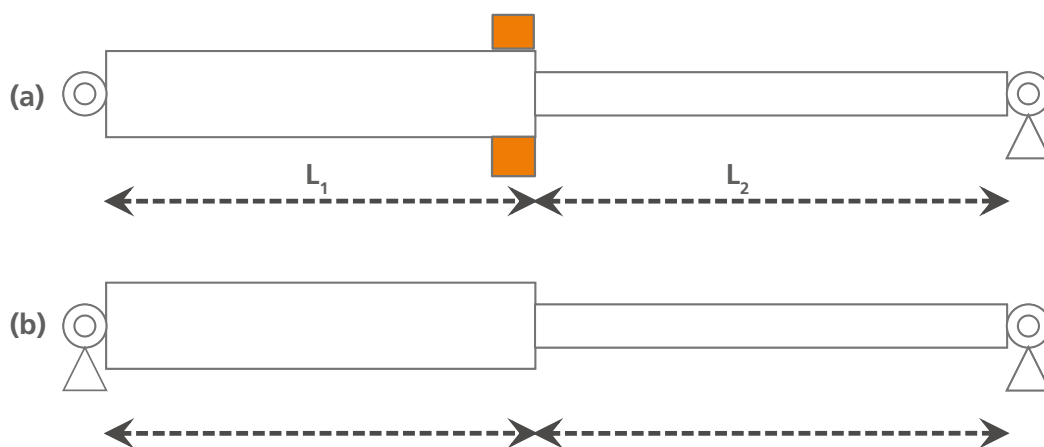

Figure 2 – Examples of cylinder mountings (a) support at the gland and (b) end mounting via pin and eye joints.

2.3 Cromax 180X offers the possibility to downsize piston rods while maintaining the same factor of safety against buckling…

Cromax 180X is a hard-chrome-plated bar based upon a medium-carbon micro-alloyed steel. Judicious control of minor alloy additions and optimised processing confer high strength to the base steel in spite of a lean overall analysis. The minimum yield strength of the steel in Cromax 180X is 500 N/mm² which can be compared with 305 N/mm² for grade C45E, a common steel selection for piston-rod applications. For Cromax 180X, this high level of yield strength is guaranteed in the finished, i.e. chrome-plated, condition.

It is immediately apparent from Fig. 1 that in the appropriate regime of slenderness ratio, piston rods made from higher-strength Cromax 180X will exhibit better resistance to buckling than corresponding rods based upon C45E steel. Hence, for a given effective length, a rod of Cromax 180X can be reduced in diameter in relation to one in C45E while still maintaining the same margin of safety against buckling. This is demonstrated quantitatively in Fig. 3 which depicts the diameter decrease which is attainable when rods of C45E-steel are swapped for ones in Cromax 180X. The downsizing is given as function of rod length for three different diameters, 45, 63 and 90 mm.
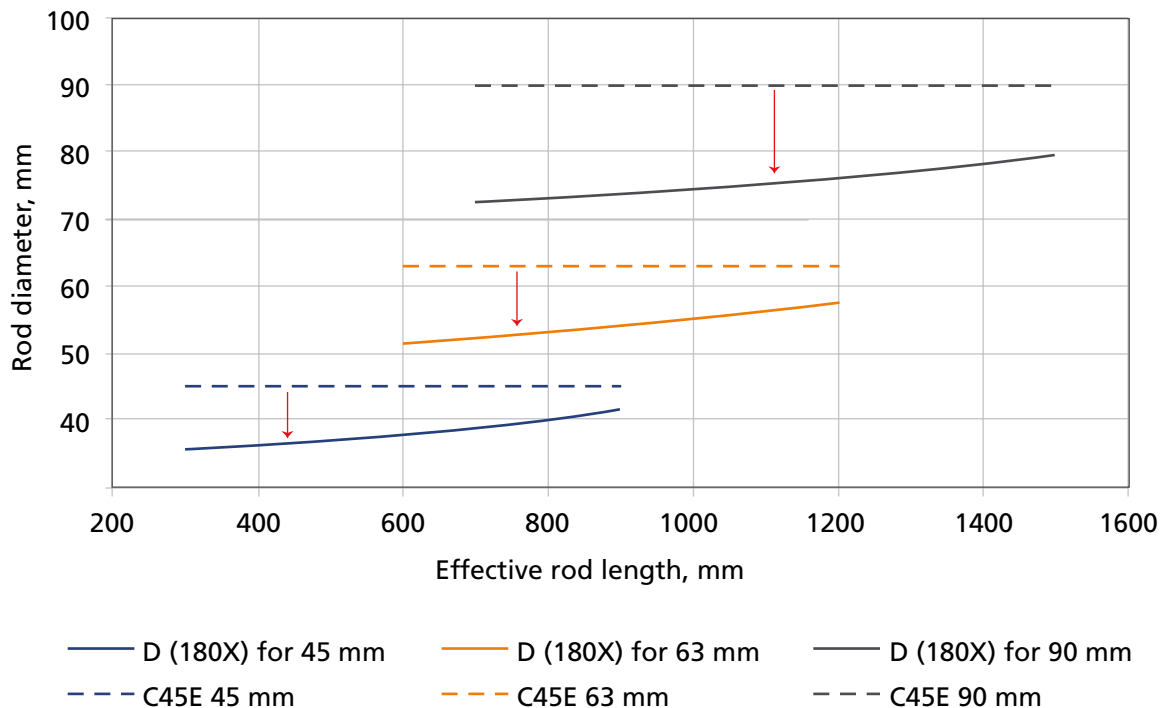

Figure 3 – Demonstrating downsizing achievable when piston rods with diameters 45, 63 and 90 mm made from steel C45E (dotted lines) are replaced by Cromax 180X (full lines).

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Obviously, the reduction in rod diameter carries a concomitant reduction of the weight of the rod. The percentage weight reduction corresponding to the downsizing depicted in Fig. 3 is shown as a function of effective length in Fig. 4. Quite apart from the benefit of weight reduction per se, there are economic repercussions in that the material cost for the piston rod is lower.

As an illustration of the potential for cost savings, consider the following example: a piston rod in steel C45E, 63 mm diameter and effective length 1 000 mm is replaced by one in Cromax 180X with diameter 55 mm giving a weight reduction of 5.8 kg or 24 %. This means that Cromax 180X can be up to 24 % more expensive than chrome-plated C45E and still remain a better economical proposition.
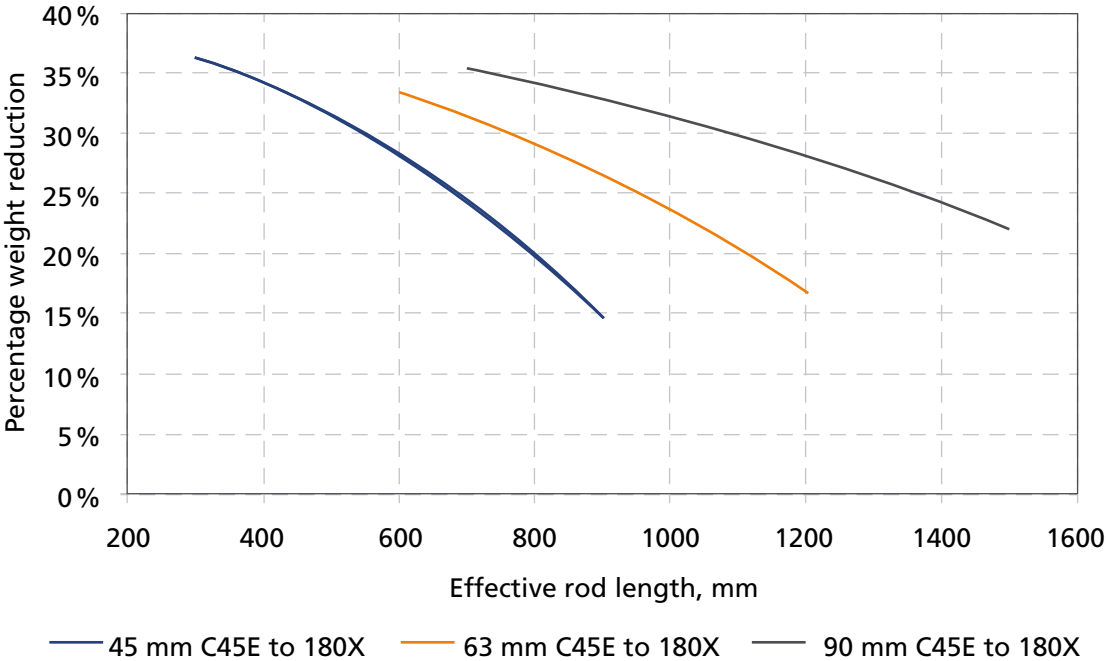

Figure 4 – Percentage weight reduction achievable when piston rods with diameters 45, 63 and 90 mm made from steel grade C45E are downsized via replacement with Cromax 180X.

2.4 …or alternatively the load rating of the cylinder can be increased

The opposite perspective is that if a rod in steel C45E is replaced by one made of Cromax 180X with the same diameter, then it can transmit a greater load while keeping the same margin of safety against buckling.

This is illustrated in Fig. 5, again for the diameters 45, 63 and 90 mm.

Obviously, to enjoy the benefit of such increased load rating, it will be necessary with a major re-design involving increased diameters of the tube, piston, gland and so on, which may not always be realistic or feasible.
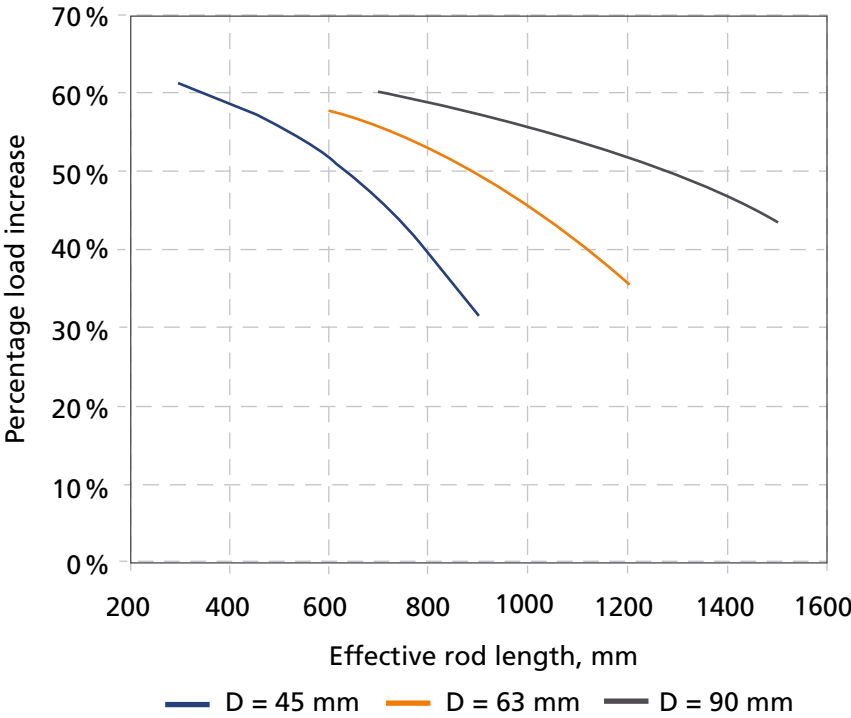

Figure 5 – Percentage increase in load rating, with no sacrifice in terms of safety factor against buckling, which is attainable by replacing a piston rod of steel C45E by one in Cromax 180X with the same diameter.

2.5 Apart from better resistance to buckling, fatigue life of double-acting cylinders is also improved with Cromax 180X

As was drawn attention to in the introduction, fatigue failure of piston rods occurs either at locations where reduced section is combined with stress-concentration, at threads for example, or at welds. Fusion-welded piston rods are particularly susceptible to fatigue failure because the welds contain crack-like defects, are characterised by unfavourable tensile residual stresses and very often do not penetrate the entire cross-section of the rod. It is for this reason that piston rods, which are subjected to high alternating loads and which carry an elevated risk for fatigue failure, are usually friction welded. A properly-executed friction-welded joint is relatively defect-free and extends over the entire cross-section of the rod; it is thereby characterised by far greater fatigue strength than a corresponding fusion weld. Provided the flash is removed correctly after welding so as to eliminate potential stress-concentrations, it is relatively rare that fatigue failure originates at a friction weld.

In destructive fatigue testing of piston rods, failure is most often initiated at places where the rod section is reduced (higher stresses) and where notch-effects give rise to stress concentrations, examples being threads,

fillets and grooves. There are several ways to counteract fatigue cracks starting at such locations. While a full discourse on this subject is outside the scope of this document, one means to better fatigue performance is to use a base steel with higher tensile strength.

Ovako has developed a model to predict the conditions for fatigue failure of piston rods initiated from threads, fillets or other changes in section for which stress-concentration factors can be defined. The description takes detailed account of surface finish and size effects. Fig. 6 presents predictions from this model for fatigue failure in push-pull mode (stress ratio = -1) initiated at threads. The data used for the calculation are: rod diameter = 45 mm; cylinder bore diameter = 80 mm; thread ISO M33 x 2.0. The results are presented as the failure pressure corresponding to three different fatigue lives, after 10 000, 50 000 and 200 000 cycles of pressure reversal.

The higher tensile strength of the steel in Cromax 180X (min. 750 N/mm²) clearly confers a better fatigue performance than rods made of the conventional grade C45E with minimum tensile strength 590 N/mm². Hence, to draw a parallel with buckling, a stipulated fatigue resistance can be achieved using a smaller diameter rod with positive repercussions for weight and cost.
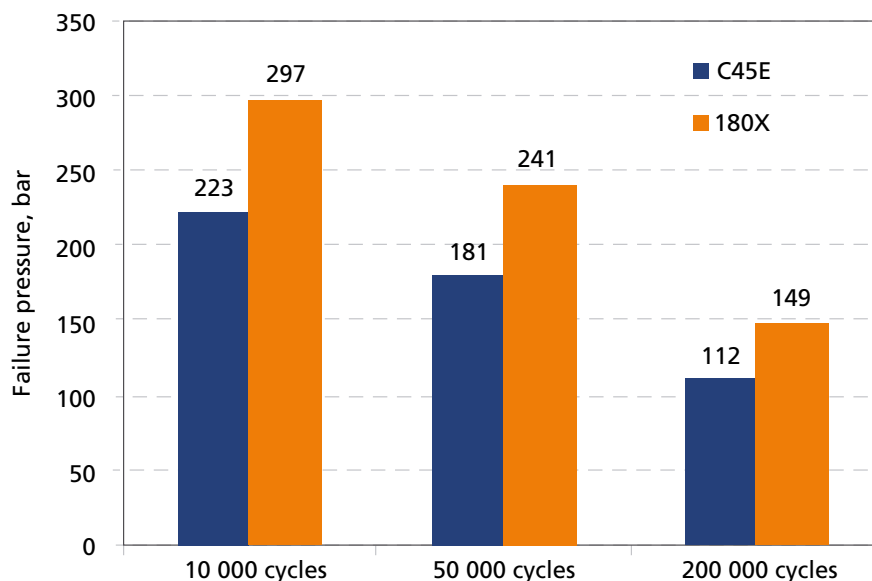

Figure 6 – Calculated improvement in failure pressure at three different fatigue lives achieved by converting from a C45E rod to one in Cromax 180X; loading in push-pull.

3 – NO PROCESSING PROBLEMS AT THE CYLINDER PLANT WITH CROMAX 180X

3.1 Good and consistent machinability

The machinability of Cromax 180X has been documented by testing in turning and threading. A Taylor-diagram for turning of Cromax 180X is given in Fig. 7. This depicts cutting speed as a function of tool life corresponding to a specified degree of tool wear. From this, the so-called V15-value, which is the turning speed for which the tool life is 15 minutes, can be seen to be 323 m/min.
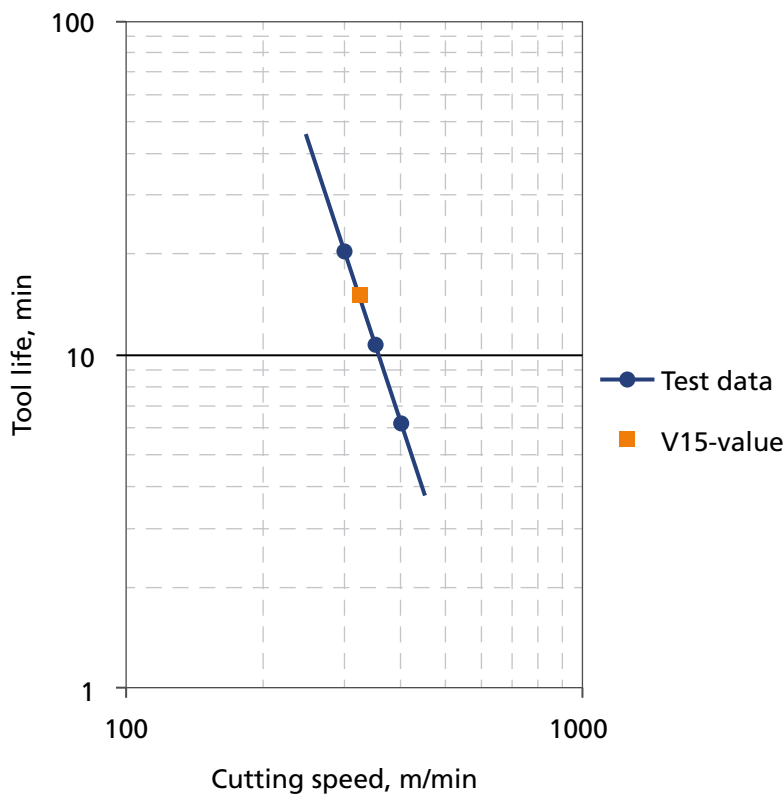

Figure 7 – Taylor diagram for turning of Cromax 180X. Testing conditions: tool SNMG 120408 ISO P15, depth of cut 2 mm, feed 0.4 mm/rev., cutting fluid Peralube 5 %, tool-life criterion 0.4 mm flank wear.

These and similar data for threading form the basis for the following machining recommendation for Cromax 180X.

Operation	Tool (coated)	Cutting speed, m/min	Depth of cut, mm	Feed, mm/rev	Cutting fluid
Rough turning	ISO P15–P30	280–350	2–5	0.3–0.6	Yes
Fine turning	ISO P10–P15	350–400	0.2–2	0.05–0.3	Yes
Fine turning	Cermet	350–400	0.2–2	0.05–0.3	No
Threading	ISO P20–P30	200–250	6–8 passes for thread pitch 2 mm	–	Yes

Machining parameters presented in the above table indicate that Cromax 180X can be processed efficiently by machining. Thanks to steel manufacture with careful analysis control, Cromax 180X has equivalent or better machinability compared with hard-chrome bars based upon steel C45E even though its strength and hardness are considerably higher.

3.2 Easy to arc weld…

The manufacture of piston rods often involves welding and weldability of the steel in the rod is in such instances an important processing characteristic second only to machinability. In fusion welding, the primary metallurgical consideration is that the formation of hard, brittle constituents in the weld heat-affected zone (HAZ) should as far as possible be avoided. The influence of steel analysis on the propensity to HAZ-embrittlement is usually expressed by a carbon-equivalent formula, and that advocated by the International Institute of Welding (IIW) is the one which finds widest usage:

$$CEV = \% \, C + \% \, Mn/6 + (\% \, Cr + \% \, V + \% \, Mo)/5 + (\% \, Cu + \% \, Ni)/15$$

For the steel in Cromax 180X, the maximum CEV is 0.65 % which about 0.1 % less than for C45E but somewhat higher than lower-carbon steels used for piston rod applications.

For example, CEV(max) for 19MnVS6 is about 0.60 %. The CEV(max) of 0.65 % implies that Cromax 180X rods up to dimension 60 mm can be fusion welded without preheating; for larger diameters, preheating is recommended in order to counteract fast cooling after welding and so lessen the risk that brittle constituents are formed in the HAZ.

3.3 …and tailored for friction welding

Welded piston rods subjected to heavy loads, especially loads of reversed push-pull (compression-tension) character, are best manufactured via friction welding. Correctly executed, such a weld has equivalent strength and fatigue resistance to the base steel in the rod. In friction welding, the steel adjacent to the joint is deformed plastically and flows in a transverse direction creating a flash, see Fig. 8.
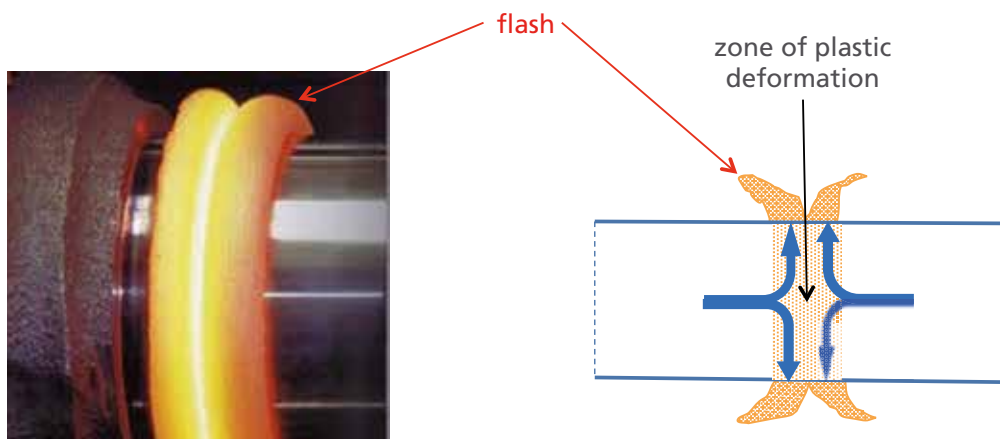

Figure 8 – Schematic of material flow in friction welding of a chrome-plated bar. Flash formation is accompanied by outward transport of material from the bar centre. A consequence is that features which are oriented longitudinally in the original bar are re-disposed transversely in the deformation zone (see also Fig.9).

This transverse flow of material brings the consequence that centre segregation and associated elongated non-metallic inclusions, which are stretched out along the axis of a steel bar during hot rolling, are re-oriented in the HAZ of the friction weld. Such segregated regions can harden during cooling after welding resulting in bands of embrittled material at right angles to the principal direction of loading of the rod. These phenomena, which can be the cause of premature failure through fatigue, are illustrated in Fig. 9.

Just as with fusion welding, the influence of steel analysis on the risk for formation of brittle zones in friction welds can be assessed by a carbon-equivalent formula suitably modified to take into account the effects of segregation. However, an additional factor is sulphur content. Excessive centre-segregation of manganese plus carbon is associated with bands of elongated manganese sulphide inclusions which are re-oriented transverse to the rod axis along with the regions of segregation. This is clearly undesirable from the point of view of joint strength.

The steel in Cromax 180X is designed to mitigate the risk for HAZ-embrittlement in connection with friction welding. The content of manganese is restricted so that the degree of centre segregation is limited, at the same time as the amount of sulphur is carefully controlled. Both these additions are necessary, manganese for strength and sulphur for machinability, but strict control of their levels is essential if hard zones with elongated inclusions in the HAZ of friction welds are to be avoided.

Longitudinal direction in rolled bar

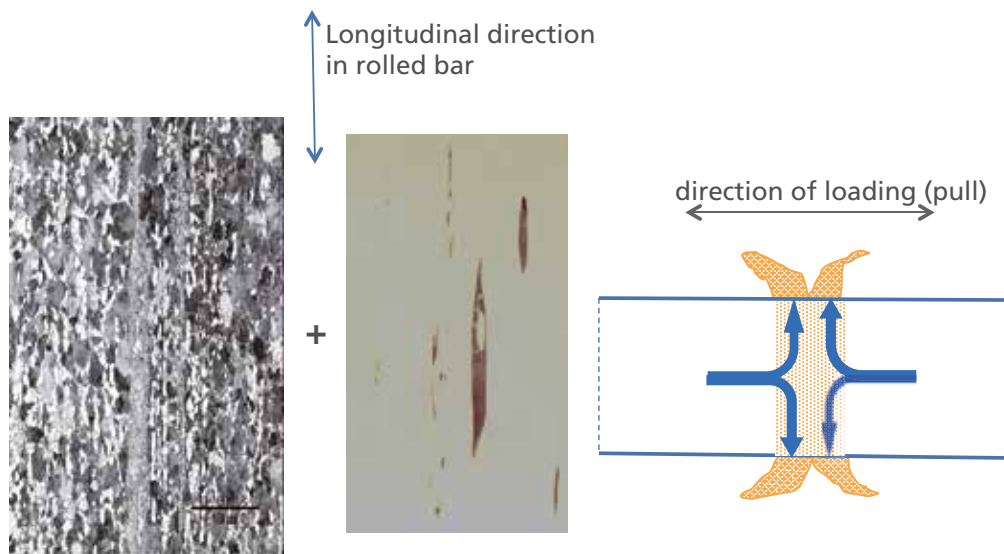direction of loading (pull)

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Figure 9 – Illustrating how segregation bands and elongated inclusions are re-oriented in the deformation zone during friction welding of a chrome-plated bar. Such features end up perpendicular to the direction of loading and constitute planes of weakness.

4 – OTHER EXECUTIONS, INDUCTION-HARDENED AND COLD-DRAWN

Cromax 180X in induction-hardened execution is available for applications where there is risk for damage to the piston rod as a result of external impact. The base steel is characterised by medium carbon content so a high surface hardness, >55 HRC, is achievable via induction hardening. A typical hardness profile for a diameter 60 mm is shown in Fig. 10. The depth of hardening, i.e. the distance from the surface corresponding to 40 HRC, is in this case about 1.5 mm.

For piston-rod applications requiring extremely high strength, Cromax 180X can also be offered in a cold-drawn execution having minimum yield strength 690 N/mm² which is on-a-par with quenched-and-tempered low-alloy steel with considerably higher alloy content, grade 42CrMo4 for example.

HRC
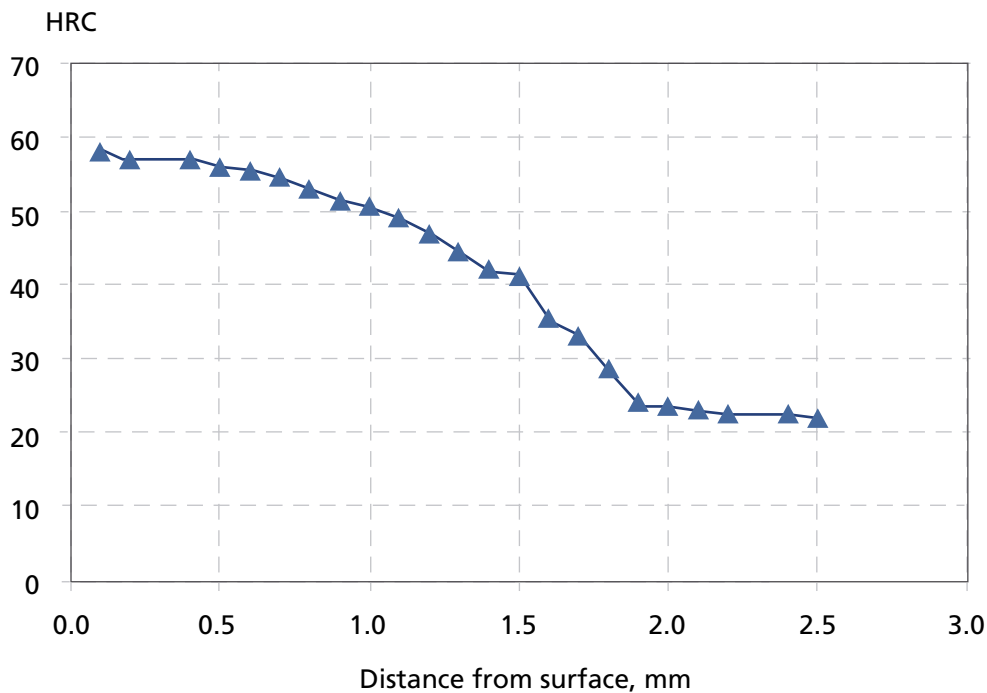

Distance from surface, mm

Figure 10 – Showing typical hardness profile in the induction-hardened layer of Cromax 180XIH.

5 – COMPARISON WITH OTHER STEEL GRADES USED FOR HARD-CHROME-PLATED PISTON RODS

In the table below, the steel in Cromax 180X is compared with other grades commonly encountered in hydraulic piston-rod applications. Apart from C45E, data for the low-carbon steel 19MnVS6 and 38MnVS6, a medium-carbon micro-alloyed steel with elevated manganese content, are included.

From this comparison, it will be evident that hard-chrome-plated bar based upon steel 180X offers the best overall combination of properties.

Property/grade	180X	C45E	19MnVS6	38MnVS6
Yield strength, N/mm² min.	500	305	390	520
Buckling stress, N/mm² AISC (*)	375	259	314	385
Buckling stress, N/mm² ECCS (*)	338	248	294	344
Buckling stress, N/mm² according to prEN 13001-3-6 (+)	246	200	225	248
Tensile strength, N/mm² min.	750	590	600	800
Pressure giving thread failure after 100 000 cycles in push-pull mode, bar ($)	219	165	177	231
Machinability;overall assessment, turning and threading (5-best, 1-worst)	5	5	4 Low carbon content: risk for built-up-edge formation	3 High hardness and higher content of pearlite in microstructure
Fusion weldability, CEV(max) %	0.65	0.75	0.60	0.85
Amenability for friction welding; overall assessment (5-best, 1-worst)	5	4 Higher carbon, sulphur content not controlled	4 Higher manganese, sulphur content not controlled	2 Higher manganese, sulphur content not controlled
Min. surface hardness after induction hardening, HRC	55	55	40	55

Calculated based on minimum yield strength for piston rod diameter 63 mm and effective length 1000 mm, slenderness ratio 63.5. AISC-value without safety factor.

+ Calculation based upon minimum yield strength for piston rod diameter 50 mm in a cylinder having a tube 115/100 mm end mounted with pin-eye joints (rod and tube with same length 600 mm; effective length of rod is 1.58 times actual length = 947 mm).

$ Calculated from minimum tensile strength for cylinder with bore diameter 80 mm, rod diameter 45 mm with failure at thread ISO M33 x 2.

6 – SUMMARY – WHAT DID WE LEARN?

A new steel grade, 180X, has been developed with focus on piston-rod applications in hydraulic cylinders. In hard-chrome-plated execution, Cromax 180X is characterised by higher strength than traditional grades used for hydraulic-cylinder piston rods.

Improved yield strength means that piston rods can be downsized without compromise to the margin of safety against buckling under axial compressive loads. This has positive repercussions for both weight and cost. Alternatively, the load rating of the cylinder can be increased without having to increase the rod diameter. However, this would involve a major re-design and may not always be feasible.

Resistance to fatigue failure under reversed or pulsating pressure cycles is improved thanks to higher tensile strength. Again, this improvement permits downsizing of piston rods in applications where there is a risk for fatigue failure with concomitant reduction in weight and cost.

The above improvements are not gained at the expense of processing characteristics such as machinability or weldability. Indeed, for friction welding, Cromax 180X is optimised so that the risk for failure derived from brittle zones in the welded joint is minimised.

Cromax 180X can be supplied in an induction-hardened execution having a hard, impact-resistant surface and also as a very high-strength, cold-drawn version.

The new product, Cromax 180X, offers the most favourable overall combination of properties in any detailed comparison with traditional hard-chrome-plated steels used for hydraulic-cylinder piston rods.

7 – REFERENCES FOR FURTHER READING

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8 – ABOUT THE AUTHORS

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Erik Bohman is a Swedish citizen with degrees of MSc in Industrial Engineering and Management from Chalmers University of Technology and MSc in Business Administration from Gothenburg School of Economics and Commercial Law. He also spent one year at Eidgenössische Technische Hochschule in Zurich Switzerland. After finishing studies in 1997, he worked as a management consultant at McKinsey & Company for six years and after that has held different management and business development positions in the Swedish manufacturing industry. Bohman is at present the Managing Director of Ovako Cromax with overall responsibility for the operations in Hallstahammar (Sweden), Redon (France), Twente (The Netherlands) and Molinella (Italy).

Per Israelsson

Per Israelsson is a Swedish citizen who in 1998 received a BSc-degree in Mechanical Engineering with emphasis on product and process development from the University of Dalarna (Högskolan Dalarna). Directly after completion of studies, he started to work for the Ovako Group and has held different development and managerial positions within the hot-rolling operations of Ovako's bar business. Israelsson has also been responsible for marketing, development and technology at Ovako Cromax which manufactures and markets hard-chrome-plated products mainly for the hydraulics segment. Currently, he is the Plant Manager for the hot-rolling operations of the Ovako Group in Boxholm.

William Roberts

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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