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FORMABLE HOT-ROLLED STEEL WITH INCREASED STRENGTH

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ABSTRACT

HOT-ROLLED STEELS WITH GOOD FORMABILITY are normally available up to the 550 MPa (80 ksi) yield strength level. For higher strength the quenched and tempered steels are predominant. At Svenskt Stål AB, Domnarvet a new hot-rolled formable strip steel with increased strength has been developed, DOMEX 640 XP. The minimum yield strength is 640 MPa (92 ksi) and the steel is commercially available in thicknesses 3 to 8 mm.

The steel can be classified as a carbon-manganese steel microalloyed with 0,035 % niobium and 0,14 % vanadium. The high strength is achieved through controlled processing in a wide hot strip mill. Despite the high yield strength the steel shows very good bending properties as a result of (1) low carbon content (2) small amounts of non-metallic inclusions and (3) sulfide-shape control (calcium-treated). The formability has also been characterized by drawability and stretchability tests together with forming-limit diagram curves.

The new steel can be welded easily with all conventional methods. Properties as impact toughness, fatigue strength and dent resistance have also been tested and are discussed. Typical applications are in areas where low weight is of importance e.g. mobile cranes and earth-moving equipments.

INTRODUCTION

The development of as-rolled steels as alternatives to the more expensive heat-treated steels in many applications is of considerable interest for economical reasons. As-rolled steels produced in wide hot strip mills are normally available with minimum yield strength up to 550 MPa (80 ksi). In the higher strength region the quenched and tempered steels are predominant.

Svenskt Stål AB (SSAB), Domnarvet has a family of hot-rolled High-Strength Low-Alloy (HSLA) Cold-forming Steels. These sheet steels are processed in a wide hot strip mill and sold under the trademark DOMEX. This series has been available since 1978 and up to now approximately 150 000 tons have been produced. In 1978 the highest strength in the family was a minimum yield strength of 590 MPa (85 ksi) for a grade called DOMEX 590 XP. The base chemistry of this steel was 3 % manganese and 0,02 % carbon which made this grade uneconomical. Therefore a new type of steel was developed 1980-81 based on the microalloying elements niobium and vanadium and now even the 640 MPa (92 ksi) yield strength level was achieved.

The present paper describes the development and initial production experience of the new grade DOMEX 640 XP as well as some of the more important properties and typical applications.

DEVELOPMENT

REQUIREMENTS - A high-strength low-alloyed formable steel has to possess other properties than just high strength and good formability. The most important are weldability and impact toughness.

A minimum yield strength level of 590 MPa (85ksi) or if possible 640 MPa (92 ksi) was aimed at. The requirement for the bend formability was an inner radius of at least two times the sheet thickness in the transverse (most difficult) direction. Sheared edges with the shear burr in tension should be used when testing the bend formability as this is the normal practice in the work-shop. One common criteria of weldability is the carbon equivalent (E_C) which gives information of the risk for hydrogen induced cracking in the heat-affected zone (HAZ). The IIW-definition of E_C is

$$E_C = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15}$$

If $E_C \leq 0{,}41$ the risk of cracking is negligible for the sheet thicknesses of interest(3-8 mm).

As the products made of the steel would be used in cold areas good impact toughness at low temperatures was important. A minimum value of 34 Joule/cm^2 at -40°C was considered appropriate.

STEEL CHEMISTRY - For a steel processed in a continuous hot strip mill a fairly high strength can be achieved with a conventional carbon-manganese chemistry microalloyed with some of the elements niobium, vanadium or titanium. This type of steel has a ferrite-pearlitic microstructure and for such a steel it is easier to obtain acceptable ductility and impact strength values than for a fully bainitic one. Thus compositions giving a bainitic structure were excluded. For a vanadium steel the importance of an increased nitrogen content has earlier been demonstrated (ref 1-2). Raising the nitrogen level increases the strength considerably through precipitation hardening of vanadium-nitrides. In another investigation (ref 3) it was concluded that the increase in strength from vanadium was greater in a niobium steel than in a niobium-free steel. The combination of vanadium and niobium are also often used in steels with high strength for line pipe where the niobium mainly contributes to ferrite grain refinement and vanadium to an effective precipitation strengthening. From this information and from own experience it was concluded that a carbon-manganese steel microalloyed with vanadium and niobium seemed to be an attractive steel chemistry. To achieve a good bend formability for a steel with such a high strength desulphurization and inclusion shape control was necessary.

Seven heats (120 ton each) were produced in a basic-oxygen furnace. To utilize the full strength from vanadium as effectively as possible the nitrogen level was increased. Silicon-calcium injection was used to obtain a low sulphur content and to change the sulfides to a more globular shape. The chemistry range for the heats is found in table 1.

Table 1 - Chemistry Range For The Tested Heats

C	Si	Mn	P	S
0,09	0,21	1,40	0,015	0,001
0,11	0,28	1,65	0,023	0,010

N	Al	Nb	V	E_C*)
0,012	0,025	0,030	0,09	0,37
0,016	0,055	0,040	0,15	0,42

*) $$E_C = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15}$$

HOT-ROLLING AND MECHANICAL PROPERTIES - Hot-rolled coils in the thickness range 3-8 mm were processed in the wide hot strip mill which has a reversing roughing mill and six finishing stands. The maximum width and weight of the coils are 1600 mm and 15 tons respectively. The mill is equipped with an effective fully computerized cooling line which is of the greatest importance when producing high strength steels. A Slab-reheating temperature of approximately 1230° C was used together with finishing temperatures in the range 850-910°C. In order to find the optimum coiling temperature it was varied between 520°C and 640°C.

Figure 1 illustrates the yield strength levels obtained as a function of coiling temperature for different combinations of vanadium and nitrogen. Maximum yield strength was achieved for a temperature of about 590°C. This is in good agreement with ref 1 where a vanadium-nitrogen steel was examined. Adding niobium to a vanadium steel does not change the influence of coiling temperature on yield strength. The optimum in coiling temperature for vanadium-bearing steels may be explained by overaging of vanadium-nitride precipitates at higher temperatures and by incomplete precipitation at lower temperatures. From the curves in figure 1 it is also obvious that increased levels of vanadium and nitrogen strongly effects the yield strength. A steel composition with 0,09 % vanadium and 0,015 % nitrogen seems to be enough for the 590 MPa minimum yield strength level. If the vanadium and nitrogen contents are further increased to 0,14 % and 0,016 % respectively the 640 MPa minimum yield strength is attained with a fairly good marginal.

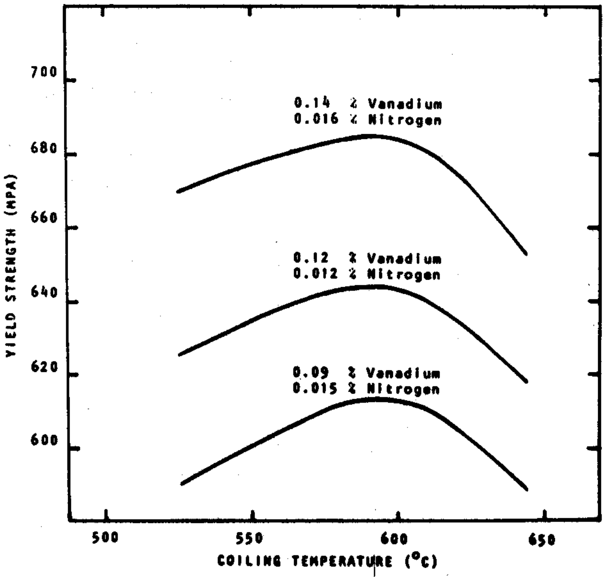

Fig. 1 - Effect of coiling temperature and vanadium-nitrogen contents on yield strength (thickness 4-6 mm). Base chemistry was 0,10 % carbon, 1,5 % manganese and 0,035 % niobium.

The microstructure of the steel depends on the processing parameters. For a coiling temperature of about 600°C the microstructure consists of a very fine-grained polygonal ferrite (grain size approximately 3 µm) with a small amount of pearlite-islands (figure 2). If the coiling temperature is decreased some bainite is found. For coiling temperatures below 550°C the microstructure consists mainly of bainite.

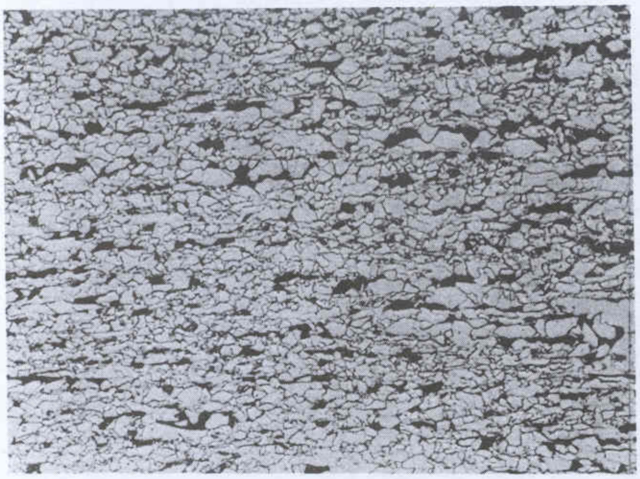

Fig. 2 - Typical microstructure of the niobium-vanadium steel (thickness 6 mm). Finishing and coiling temperature 875°C and 600°C respectively (500x).

Increasing the strength by precipitation hardening is detrimental to the impact toughness. Despite this, rather low impact transition temperatures were achieved for this steel obviously because of the very fine grain size. The 50 % shear fracture-appearance transition temperature (FATT) determined by Charpy V-notch tests on half size longitudinal specimens were in the range -45°C to -70°C and the impact energy at -40°C 60 to 100 Joule/cm^2. These impact properties were considered acceptable.

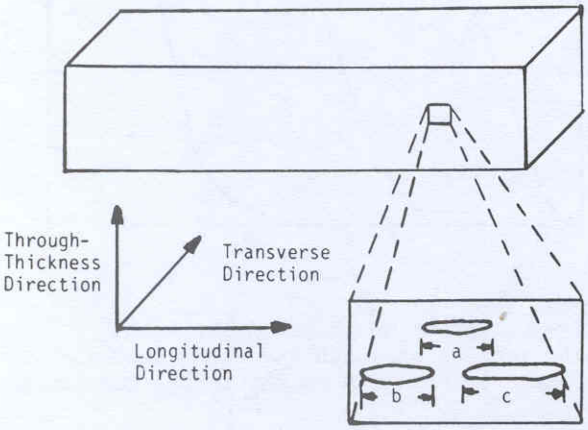

Fig. 3 - The inclusion projected length per unit area in the longitudinal direction is (a+b+c) length units per area (e.g. mm^{-1}).

BEND FORMABILITY - A low amount of non-metallic inclusions and sulfide-chape control are very important for the band formability. One way to quantify the inclusion population is to use the inclusion projected length per unit area (figure 3). This method takes into account both the amount and shape of the inclusions. For the calcium-treated niobium-vanadium steel examined here there was a good correlation between the inclusion projected length in the longitudinal direction and the sulphur content (figure 4). With reduced sulphur content (≤ 0,004 %) very low values for the inclusion projected length were achived, ≤ 0,15 mm^{-1}. Conventional steels with high sulphur content exhibit values in the range 0,8-1,3 mm^{-1}.

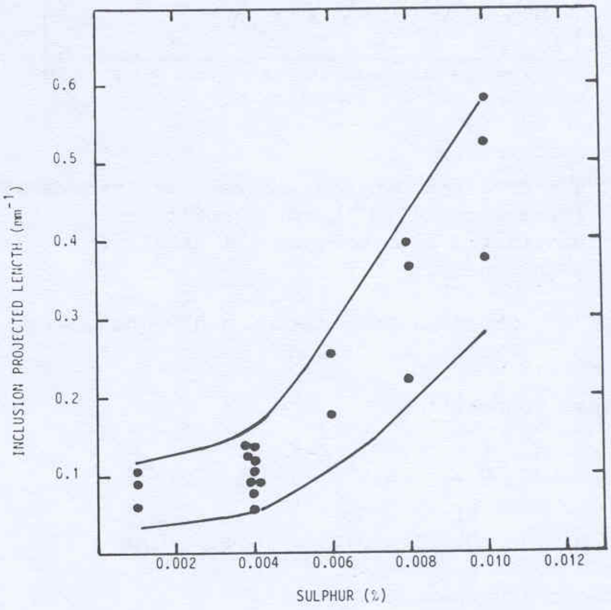

Fig. 4 - Correlation between inclusion projected length per unit area and sulphur content for calcium-treated niobium-vanadium steels.

Transverse bending tests (120° bending angle) with sheared edges were performed for different thicknesses. As expected the ratio between minimum bend radius and thickness increased as the sulphur content was raised (figure 5). From the bending results it seemed realistic to meet a requirement of 1,5x thickness and 1,8x thickness for the minimum bend radius in thicknesses 3-6 mm and 6,1-8 mm respectively if the sulphur content was maximized to 0,004 %.

THE NEW GRADE DOMEX 640 XP - During the development period the steel was also tested by a number of customers with very positive results. The new formable hot-rolled grade with increased strength, DOMEX 640 XP has been commercially available since 1981 in the thickness range 3 to 8 mm. Chemical composition and mechanical properties of DOMEX 640 XP are described in table 2.

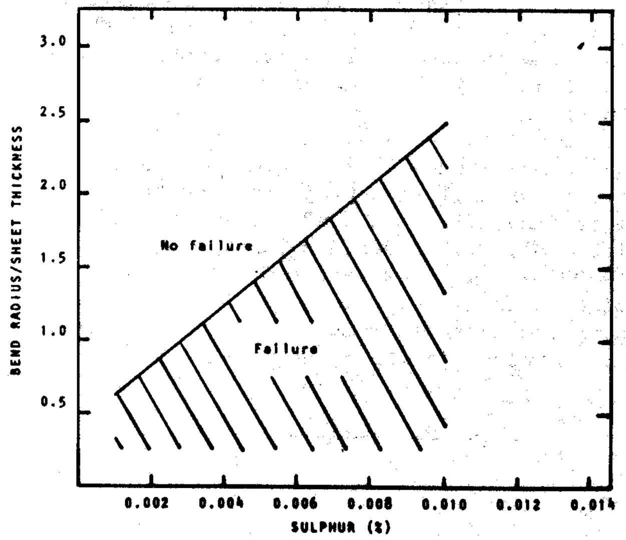

Fig. 5 - Effect of sulphur content on transverse bend formability (120° bending angle) of calcium-treated niobium-vanadium steels in 3-6 mm thickness.

Table 2 - Chemical Composition And Mechanical Properties Of DOMEX 640 XP

Typical composition:

C	Si	Mn	P	S
0,09	0,25	1,55	0,015	0,002

N	Al	Nb	V	E_c
0,015	0,025	0,035	0,14	0,38

Mechanical properties:

YS (min) MPa	UTS (approx) MPa	Elong (min) % (L=5D)	Bend test Min mandrel radius at thickness t mm 3-6mm	(6)-8mm	Impact toughness Charpy V-notch Longitudinal direction min J/°C
640	780	12	1,5xt	1,8xt	27*)/-40

*) Full-size specimen. 23 J for 2/3-size specimen and 18 J for 1/2-size specimen.

EXPERIENCE OF THE INITIAL PRODUCTION

Approx. 10 000 tons have been produced so far of DOMEX 640 XP. The BOF-process (LD) has been used for the steelmaking. The maximum sulphur content is 0,004 % and this has successfully been achieved by injection of calcium in the ladle (TN-process) and the average sulphur value is approx. 0,002 %. Within the company only continuous casting is used. Normally continuously cast slabs produced from a niobium-vanadium chemistry are very sensitive to transverse surface cracks but with modern casting machines and by careful selection of the casting parameters these cracks have been avoided.

Processing of hot-rolled coils with high strength in the hot strip mill is more difficult than processing of softer grades. The biggest problem is the flatness of the strip. To achieve acceptable flatness (≤ 6 mm/m) the sheets have to be processed through a special leveling line afterwards. Because of these flatness problems the maximum widths for DOMEX 640 XP are smaller than for the softer grades (e.g. the maximum width for DOMEX 640 XP in 5 mm thickness is 1300 mm compared to 1600 mm for softer grades). The ranges of finishing temperature in the last stand and coiling temperature have been 830-900°C and 570-630°C respectively. The right coiling temperature is attained through regulating the rolling speed and the amount of water in the fully computerized cooling line.

PROPERTIES

MECHANICAL PROPERTIES AND IMPACT TOUGHNESS - A statistical evaluation of mechanical properties and impact toughness has been carried out for DOMEX 640 XP. In figure 6 and 7 the cumulative frequency for yield strength, ultimate tensile strength, elongation and Charpy V-notch toughness are found.

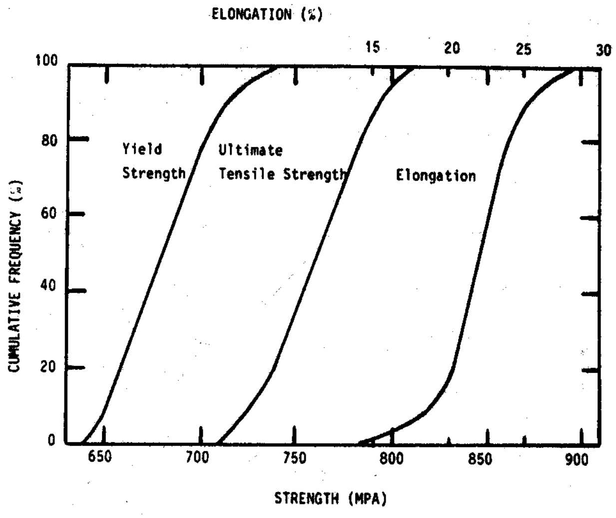

Fig. 6 - Distribution of yield strength, ultimate tensile strength and elongation (L=5D) for DOMEX 640 XP in 3-8 mm thickness. Data from 600 coils.

The difference in strength between different coils is rather small and this is valuable as it results in a small scatter in spring-back in forming operations.

The influence of thickness on yield strength and ferrite grain size is illustrated in figure 8. In the examined range of thicknesses (3-8mm) the yield strength decreases with approximately 5 MPa when the thickness is increased by 1 mm.

The main reason to this obviously being that the ferrite grain size increases with thickness. Figure 8 shows that if the thickness is increased from 3 to 8 mm the ferrite grain size change from approx. 3 µm to 3,5 µm. From Gladmans formula (ref 4).

Yield strength (MPa) = K_i + 37(%Mn) + 83(%Si) + + 2918(%N_{free}) + 15,1($d^{-\frac{1}{2}}$);
this means a decrease in yield strength of approximately 20 MPa. This value is in good agreement with the value in figure 8 (approx. 25 MPa).

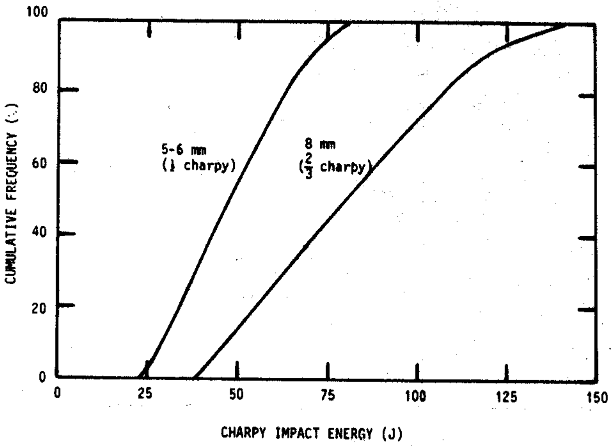

Fig. 7 - Longitudinal Charpy V-notch energy for DOMEX 640 XP in 5-8 mm thickness at -40°C. Data from 115 (5-6 mm thickness) and 30 coils (8 mm thickness) respectively.

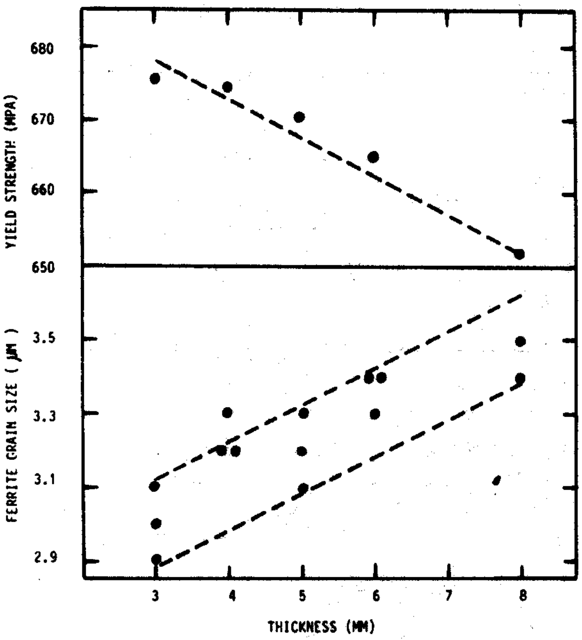

Fig. 8 - Influence of thickness on yield strength and ferrite grain size (linear intercept). For the yield strength each point represents the average from approx. 70 coils. Base chemistry was 0,09 % carbon, 1,6 % manganese, 0,016 % nitrogen, 0,035 % niobium and 0,14 % vanadium.

The tensile properties for the niobium-vanadium type of steel were correlated to chemical composition and sheet thickness by means of multiple-regression equations (see table 3).

Table 3 - Multiple Regression Equations For Niobium- Vanadium Steel (375 Data Points).

Yield strength:

YS(MPa) = 425-4,5 x(thickness, mm) + 2849 x (%N)+ + 522 x (%V) + 667 x (%C) + 57 x (%Mn)

Standard error = ±17, R^2 = 0,45

Tensile strength:

UTS(MPa) = 462 + 2377 x (%N) + 598 x (%V) + + 911 x (%C) + 61 x (%Mn)

Standard error = ±17, R^2 = 0,39

Equations applicable for:

	Average	Range ±2xStand. Deviation
Carbon, %	0,09	0,077 - 0,113
Silicon, %	0,240	0,190 - 0,290
Manganese, %	1,58	1,45 - 1,71
Nitrogen, %	0,016	0,010 - 0,022
Aluminium, %	0,027	0,017 - 0,037
Vanadium, %	0,138	0,118 - 0,158
Niobium, %	0,033	0,027 - 0,039
Lower yield strength MPa	672	628 - 716
Tensile strength MPa	764	720 - 808
Thickness, mm	5,3	3,0 - 8,0
Finish temp, °C	878	847 - 909
Coiling temp, °C	597	570 - 630

FORMABILITY - Despite the high yield strength of 640 MPa the new steel shows very good bending properties. With sheared edges and the shear burr in tension the transverse minimum bend radius (120° bending) is typically 0,8x x thickness for thin sheets (3-6 mm) and 1,2x x thickness for thicker sheets (8 mm). The corresponding value with milled edges is approximately 0,5x thickness in the whole thickness range (3-8 mm).

The formability has also been characterized by deep drawability tests, stretchability tests and the contruction of the forming-limit diagram.

The deep drawability was tested for hot-rolled steels of different strength levels and the results (figure 9) demonstrate that the deep drawability is not influenced by the strength level. The maximum drawing ratio for DOMEX 640 XP is the same as for steels with a yield strength of 240 MPa. Stretchability tests have shown that the yield strength has a big effect on the result. The bulge height for DOMEX 640 XP in 3 mm thickness was 10 % lower than for a steel of 230 MPa yield strength with the same thickness (figure 9). These results emphasize the fact that if the stretching is too severe for a high strength steel efforts should be made to increase the drawing component in the forming operation.

The maximum strain a steel can undergo before the onset of localized thinning or complete fracture is described in the forming-limit diagram (FLD). The obtained FLD-curves for DOMEX 640 XP is in figure 10 compared with the FLD-curves of a softer steel with 300 MPa in yield strength. These results demonstrate that the big increase in yield strength reduce the maximum achievable strains considerably.

WELDABILITY - The steel has been spot welded and welded with MAG and MMA methods without any problems. The reason to the good weldability is the lean chemistry of the steel.

Some part of the heat-affected zone is often softer than the rest of the welded joint but since this zone normally is so narrow the strength of the welded joint is practically not influenced. (See figure 11).

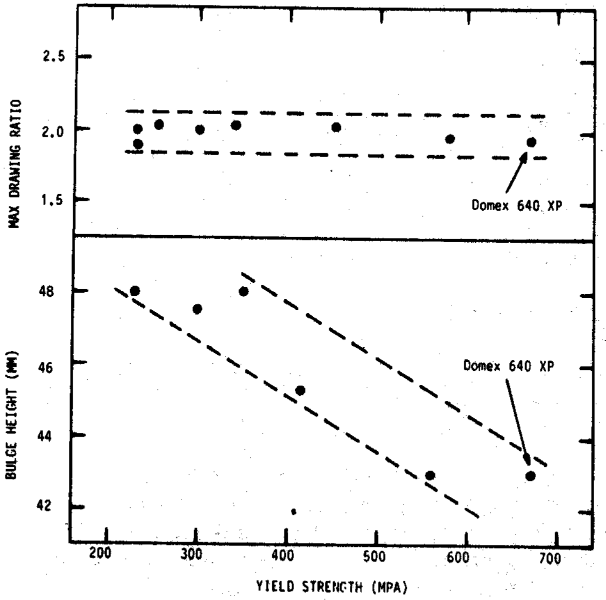

Fig. 9 - Influence of yield strength on maximum drawing ratio and bulge height of different hot-rolled steels in 3 mm thickness.

Drawing - Punch: Ø = 100 mm R = 15 mm
- Die : Ø = 109 mm R = 20 mm

Stretching - Punch: Ø = 100 mm R = 50 mm
- Die : Ø = 109 mm R = 20 mm

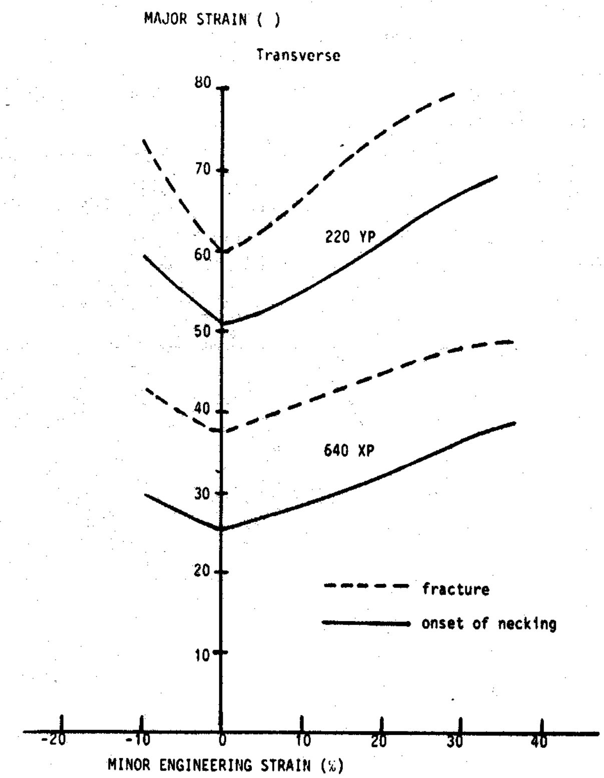

Fig. 10 - Forming-limit diagram for DOMEX 640 XP (yield strength 670 MPa) and DOMEX 220 YP (yield strength 300 MPa) in 3 mm thickness.

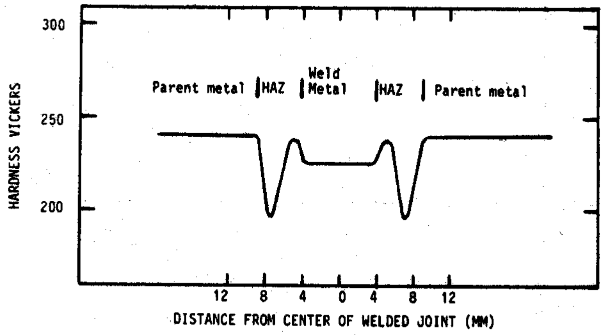

Fig. 11 - Hardness profile (1 mm below surface) in a welded joint of the steel DOMEX 640 XP. 5 mm sheet thickness and gas-shielded metal arc welding with a heat-input of 0,8 KJ/mm.

Tensile strength of welded joint:

-779 MPa; reinforcement left (fracture in parent metal)

-762 MPa; no reinforcement left (fracture in HAZ)

Determination of Charpy V-notch toughness for MAG and MMA butt welded joints in 5 mm thickness have shown impact transition temperatures (longitudinal direction, 10x4 mm specimen size, 15 Joule) for the weld metal and HAZ in the range -30° to -80°C and -25° to -50°C respectively. The best values are connected with low heat inputs.

FATIGUE PROPERTIES - For unwelded parent metal the fatigue strength of a steel is improved with increasing static strength. For welded joints the fatigue strength in the endurance range 10^5-$2x10^6$ is mainly dependant upon the weld geometry and is therefore roughly the same irrespective of the static strength of the steels. For making full use of an increased static strength for a steel subjected to severe fatigue special attention must be paid to the configuration of the welds. After welding, grinding or TIG-treatment can be used to improve the weld geometry. The notch effect at the weld toe is decreased and the fatigue properties can be improved. Another solution is to place the welds in areas where the stresses are low.

The fatigue resistance was examined for DOMEX 640 XP. Pulsating load with R=0 (R=min stress/max stress) was used. From the results of the fatigue testing (figure 12) it is obvious that the fatigue strength for the parent metal is high. The endurance ratio (endurance limit/ ultimate tensile strength) is approx. 0,70 which is quite good for this tensile strength and is at least equal to the values of corresponding quenched and tempered steels. The beneficial effect of TIG-treatment on the fatigue strength of welded joints was confirmed also in this investigation (figure 12).

DENT RESISTANCE - High-strength low-alloy steels are often used in applications (e.g. earth-moving equipments) where a high dent resistance is wanted. If the construction is exposed also to abrasion this is often concentrated to the dents which leads to increased wear. It is therefore important to reduce the dent depths as much as possible. One way is to use thicker plates. A better solution is to use steels with higher yield strength as this also decrease the dent depths.

Dent resistance experiments have been performed with DOMEX 640 XP and another steel of lower yield strength (DOMEX 350 XP with a minimum yield strength of 350 MPa) for comparison. Weights falling from 2,9 m height with a nose radius of 50 mm were used. The dimension of the tested sheets were 600x600 mm and the thicknesses 3 and 5 mm. The evaluation of the dent depths (figure 13) demonstrates the positive effect of an increased yield strength. For example, a sheet of 3 mm thickness in DOMEX 640 XP has almost the same dent depth as a sheet of 5 mm thickness in DOMEX 350 XP.

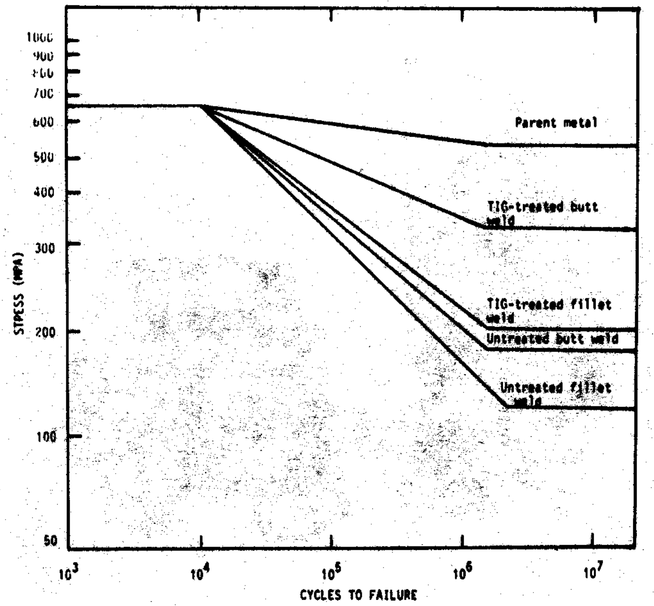

Fig. 12 - Fatigue strength for DOMEX 640 XP. Standard-Wöhler-diagram (log-log scale) with pulsating load (R=min stress/max stress=0). Sheet thickness 5 mm and ultimate tensile strength 767 MPa.

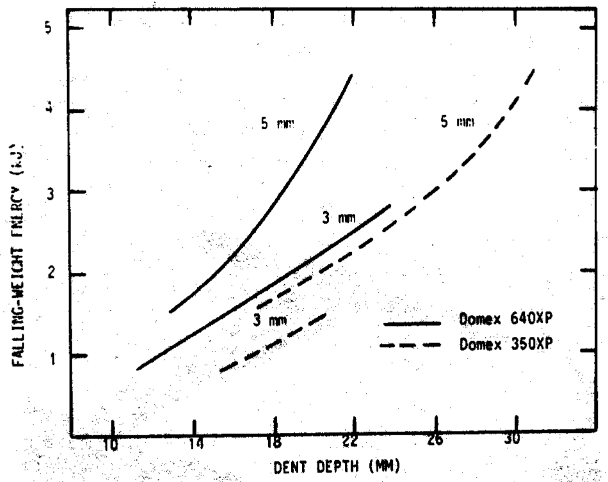

Fig. 13 - Dent resistance measurements of DOMEX 640 XP (yield strength 655 MPa) and DOMEX 350 XP (yield strength 380 MPa) in 3 and 5 mm thickness.

APPLICATIONS

DOMEX 640 XP is mainly used in applications where low weight is of importance and where some kind of cold-forming is involved in the fabrication of the product. Such typical applications are for example earth-moving equipments (figure 14) and mobile cranes (figure 15).

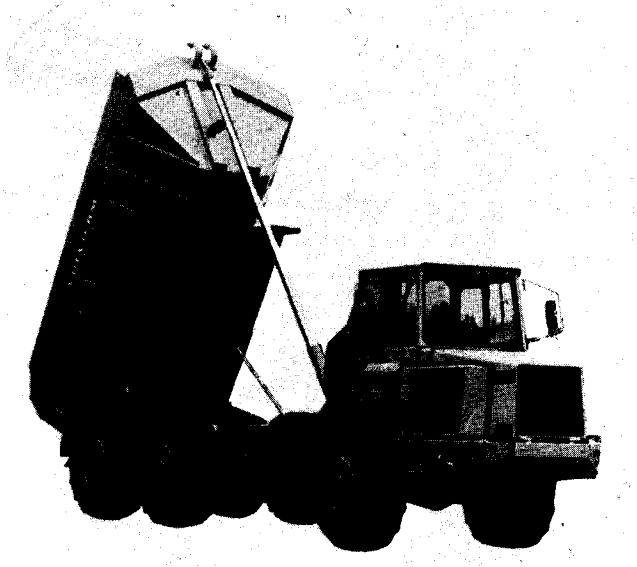

Fig. 14 - A typical application for DOMEX 640 XP. The front wall and the "ribs" in the body are made of this steel.

In some parts of the earth-moving equipments the limiting factor is often the static strength of the steel and not the fatigue strength. The reduction in fatigue strength for welded joints is therefore of no importance in this case. Mobile cranes are subjected to a high degree of dynamic loads but as the weldments often can be placed in areas of low stresses the high strength of the steel can be utilized.

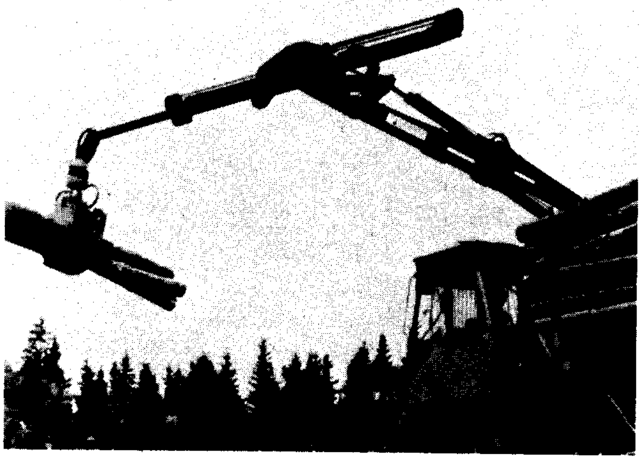

Fig. 15 - DOMEX 640 XP is used in different types of mobile-cranes.

SUMMARY

A new formable hot-rolled steel with increased strength has been developed with a minimum yield strength of 640 MPa (92 ksi). It is a carbon-manganese steel microalloyed with 0,035 % niobium and 0,14 % vanadium. The high strength is caused by a very fine grain size (3-3,5 µm) and precipitation hardening of vanadium carbonitrides. This is achieved through a controlled processing in a wide hot-strip mill.

The bend formability of the steel is very good with respect to the high strength. With sheared edges the transverse minimum bend radius is typically 0,8xthickness for thin sheets (3-6 mm) and 1,2xthickness for thicker sheets (8 mm). The formability of the steel has also been characterized by drawability and stretchability tests together with forming-limit diagram (FLD) curves. The drawability was found independant of strength level while the stretchability decreased with increased strength.

Because of the lean chemistry of the steel the weldability is good and all conventional methods can be used. The increased strength was found beneficial to fatigue strength and dent resistance.

ACKNOWLEDGEMENTS

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