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INCREASED POWER DENSITY OF PUSH-BELT CVTs USING A NEW MARAGING STEEL FOR BELT MANUFACTURE

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ABSTRACT - Since the commercial introduction of push-belt type continuously variable transmission (CVT) systems, customer specifications concerning power density (transmittable power, torque, transmission size, ratio coverage, and durability) have become increasingly demanding. Consequently, the increase of push-belt power density is a permanent goal for Van Doorne's Transmissie, Bosch Group.

Maximum power density is mainly determined by the ability of the push-belt rings to withstand the stresses generated during CVT operation. An increase in power density can therefore be achieved by reducing the stresses exerted on the rings and/or by increasing the fatigue strength of the ring material.

The present paper describes the study of fatigue behaviour and fatigue failure modes, for push-belts manufactured with the maraging steel currently employed for ring manufacture. The recognition of ring fatigue crack initiation at titanium nitride inclusions as a predominant failure mechanism has led to the development and validation of a new higher strength maraging steel containing fewer and smaller non-metallic inclusions. Test results show an increase in ring fatigue strength that has led to an improvement in push-belt durability by a factor of 5. More generally, the increase in ring fatigue strength will be implemented in new belt designs for high power density CVT systems.

MAIN SECTION - The market for belt type CVT systems is growing rapidly. Since belt production began at Van Doorne's Transmissie (VDT) in 1985, more than 5 million vehicles have been equipped with a push-belt CVT. Today, approximately 1 million push-belt CVTs are manufactured annually for the Japanese, USA, European and Korean markets. More than 45 different vehicle models are currently available with push-belt CVT systems. In order to further extend the application range of its push-belt, VDT's goals are to enhance the transmittable power and torque, to reduce the transmission size (pulley axis spacing or centre distance), and to increase the ratio coverage and durability. To meet these requirements the power density of the push-belt/pulley system must be increased (1). The current state of the art of push-belt performance is illustrated by the CVT system installed in the Nissan Murano, which has a ratio coverage of 5.4 and operates with a 3.5 liter V6 180 kW/350 Nm engine and a torque convertor, applying drive side torque levels on the belt over 500 Nm (2). Further extension of the CVT application range can be achieved, among other things, by continuously increasing the push-belt fatigue strength. The present paper discusses the fatigue behaviour of current belts and describes the improvement in belt performance that can be achieved by the use of a newly developed ring material with higher fatigue strength.

PUSH-BELT FATIGUE BEHAVIOUR

<u>Push-Belt Loading during Variator Operation</u>

The heart of a CVT system is the variator, i.e. the push-belt/pulley system illustrated in Figure 1. In the variator, torque or power is transmitted from the primary to the secondary pulley via friction between the push-belt elements and the pulley sheaves. Stepless shifting between the extreme LOW (underdrive) and OD (overdrive) ratios is achieved by varying the pulley clamping forces and thereby changing the axial position of the moveable pulley sheaves, modifying the effective running radius. An example of a Van Doorne push-belt is shown in Figure 2.

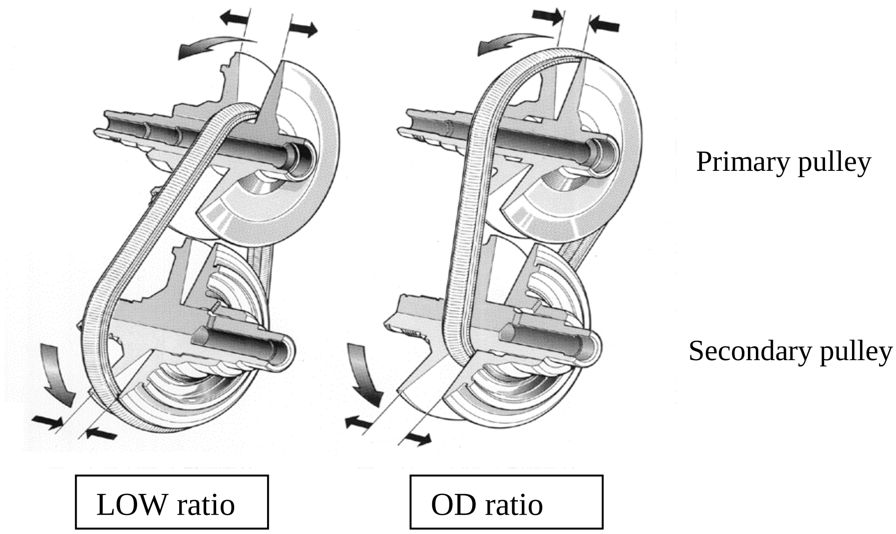

Figure 1: Example of a variator and its working principle.

During operation of the variator, the push-belt and pulleys undergo cyclic (fatigue) loading. Stress levels in the push-belt elements and pulleys are determined by the applied pulley clamping forces, rotational speeds, and torque levels. Experience has shown that fatigue loading of the elements and pulleys is less critical in practice than ring fatigue loading. The push-belt rings are mainly subjected to bending and tensile stresses (see Figure 3), although in a rather complex manner (2). In general, the bending stresses are determined by the applied running radii (transmission ratio) and the ring thickness. The tensile stresses are mainly determined by the applied pulley clamping forces, rotational speeds, and torque levels (1).

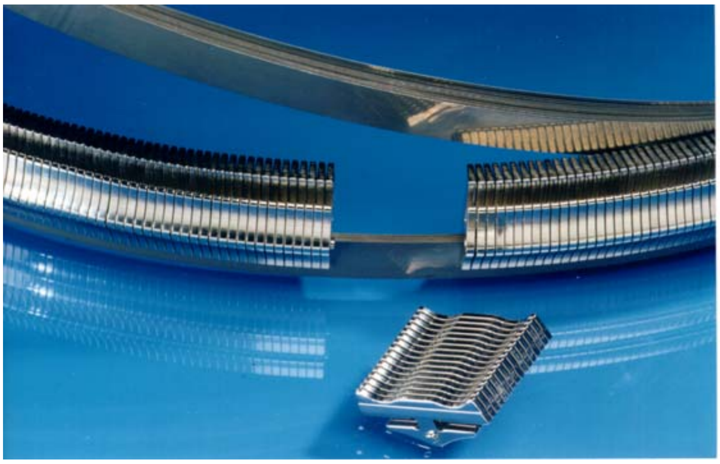

Figure 2: Example of a (partly disassembled) Van Doorne push-belt with approximately 400 elements and 2 sets of 9 or 12 rings.

Customer specifications for new applications mainly concern ratio coverage R_c, transmision size (pulley centre distance C_d), transmittable power and torque, and durability. To increase R_c and decrease C_d requires smaller minimum running radii R_{min}, resulting in higher bending stresses in the rings (see Figure 3). Enhanced transmittable torque demands increased clamping forces, resulting in higher ring tensile stresses. Increased rotational speeds cause higher centrifugal forces and thus higher ring tensile stresses. In order to meet durability demands, the total (accumulated) ring stresses σ_{total} should not exceed certain critical levels. Therefore, ring stresses are currently considered as the principal design factor determining the maximum power density of push-belt/pulley systems.

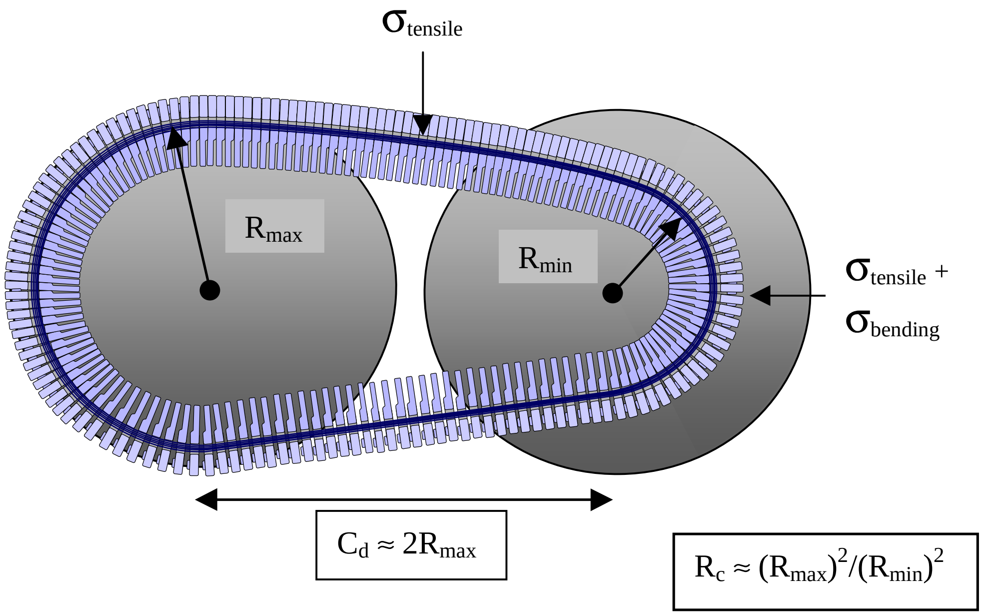

Figure 3: Push-belt loading (ring stresses, running radii, pulley centre distance, ratio coverage).

Durability Testing

To ensure proper functioning of the variator throughout the lifetime of a vehicle, new applications are released on the basis of Long Durability Cycle (LDC) tests, carried out on VDT belt boxes and test rigs (see Figure 4). The LDC comprises 420 hours full load testing in three fixed ratios: 150 hours in TOP, 250 hours in OD and 20 hours in LOW. This corresponds to about 70 000 km full load testing. The LDC test settings correspond to the most severe conditions arising in service (LOW and OD settings: maximum engine torque, smallest running radii; TOP settings: maximum engine power). These conditions correspond to the most severe belt and pulley loading encountered in practice, in terms of contact pressures, contact speeds and component stress levels. Successful performance in the full load LDC test is therefore considered to ensure proper variator functioning and durability in service.

In addition to the LDC tests, so-called Overload Fatigue Tests (OFT) have been developed at VDT in an attempt to determine the maximum belt durability at ‘overload’ settings. The OFTs are accelerated tests performed in the OD ratio (i.e. smallest running radii), applying torques and rotational speeds considerably greater than the levels encountered in service. The OFTs are deliberately continued up to belt failure, and can therefore be used to study the fatigue behaviour of new belt designs.

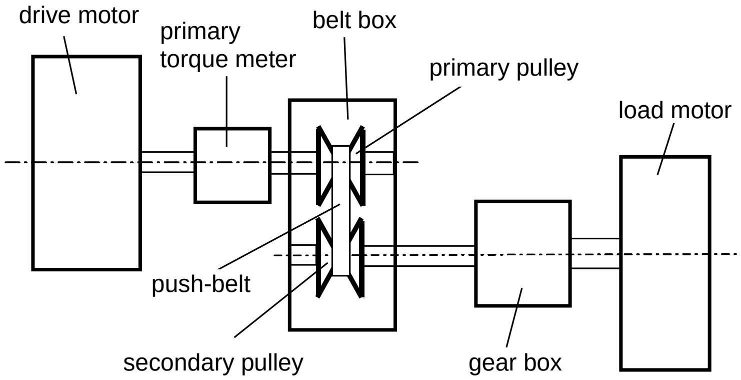

Figure 4: Test equipment for push-belt/pulley durability testing (VDT belt box and test rig).

Failure Mode Analysis

In OFT testing, push-belt failure occurs in the very high cycle fatigue regime, corresponding to a number of belt and ring cycles $N_f > 10^7$. Push-belt failure is usually caused by fatigue fracture of the innermost rings in the belt. These are the smallest rings of the two ring sets that are in contact with the element saddles (see Figure 5).

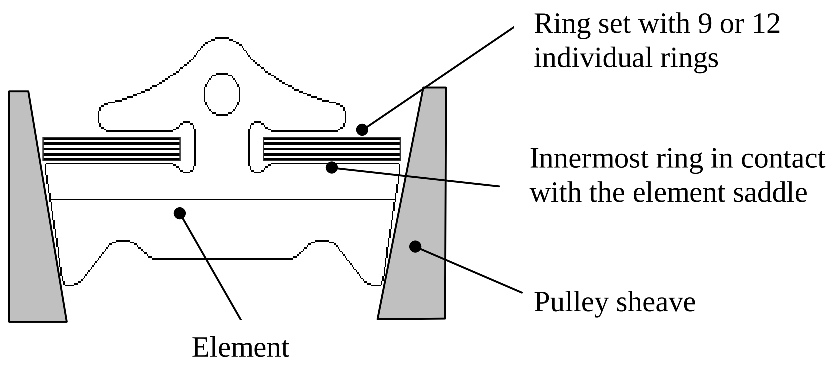

Figure 5: Cross section of the push-belt/pulley system (element, ring sets, sheaves).

Extensive analysis of ring fracture surfaces has revealed a typical and reproducible failure mode for VDT's standard belt type. The fracture surfaces show clear proof of fatigue failure, always initiated at small titanium nitride (TiN) inclusions. Crack initiation occurs near the inner surface of the rings in the transition region between the nitrided (diffusion) zone and the relatively softer ring core. A typical example is shown in Figure 6. As described in the next section, small TiN inclusions are commonly present in the maraging steel currently employed as the ring material and appear to act as local stress raisers. In the case of a new belt type recently developed by VDT, in which the residual stress distribution in the rings has been optimised (2), other fatigue failure modes are also observed, but initiation at TiN inclusions still occurs.

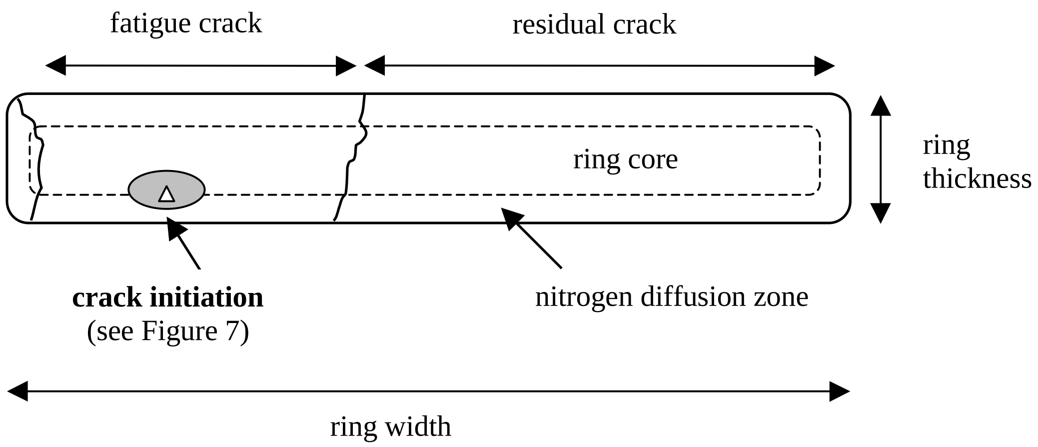

Figure 6: Schematic overview of the typical push-belt failure mode, showing the fatigue fracture surface of an innermost ring, with initiation at a TiN inclusion. The fracture surface is perpendicular to the longitudinal direction of the ring.

The push-belt (test rig) failure mode shown above is comparable to very high cycle fatigue failures described in the literature for high strength steels. Numerous publications describe the detrimental effects of non-metallic inclusions during fatigue loading of various components and test samples (3). When crack initiation occurs at a sub-surface inclusion, a typical "fish-eye" fracture appearance is often observed. Figure 7 shows an example of a ring fracture where this morphology is associated with a TiN inclusion.

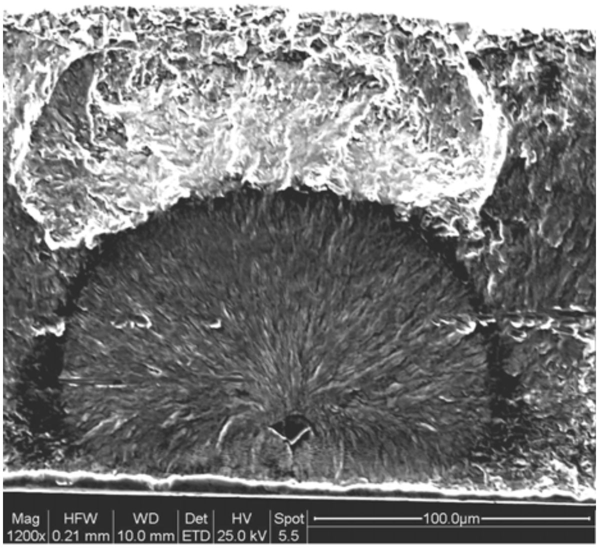

Figure 7: Typical "fish-eye" fracture morphology due to fatigue crack initiation at a sub-surface TiN inclusion in a push-belt ring.

In addition to fatigue testing of complete push-belts, fracture initiation at TiN inclusions has also been observed during fatigue testing on individual rings or ring samples. This confirms that the push-belt fatigue performance is determined by non-metallic inclusions in the currently employed ring material.

The Overload Fatigue Test (OFT) results indicate that the maximum power density of the push-belt variator is determined essentially by fatigue performance of the rings. Belts that are deliberately subjected to overload conditions finally fail due to fatigue fracture of the rings, involving crack initiation at small TiN inclusions. In order to further increase power density, the fatigue strength of the rings must be increased either by reducing the critical ring stress levels (e.g. by optimising the residual stress distribution (2)) or/and by increasing the fatigue strength of the ring material itself.

DEVELOPMENT OF A NEW RING MATERIAL

<u>Current Ring Material</u>

The rings used in VDT's current push-belt production are manufactured from X2NiCoMoTi18-9-5 alloy, a high yield and tensile strength maraging steel supplied by Imphy Alloys (Arcelor Group) under the tradename Durimphy™. Because of its excellent functional properties and its ease of implementation for the mass production of rings, this material has been employed by VDT in commercial CVT applications since 1985. The essential features of VDT's ring production process are shown in Figure 8. The incoming cold rolled maraging steel strip is cut to length and bent to form pipes, which are subsequently welded, annealed, and slit to rings. After deburring, the rings are rolled to a larger diameter and smaller thickness, then re-annealed. A calibration or pre-bending process is then carried out to bring the rings to a precise required diameter (2). Finally, an age-hardening heat treatment is performed, followed by gas nitriding to harden the surface.

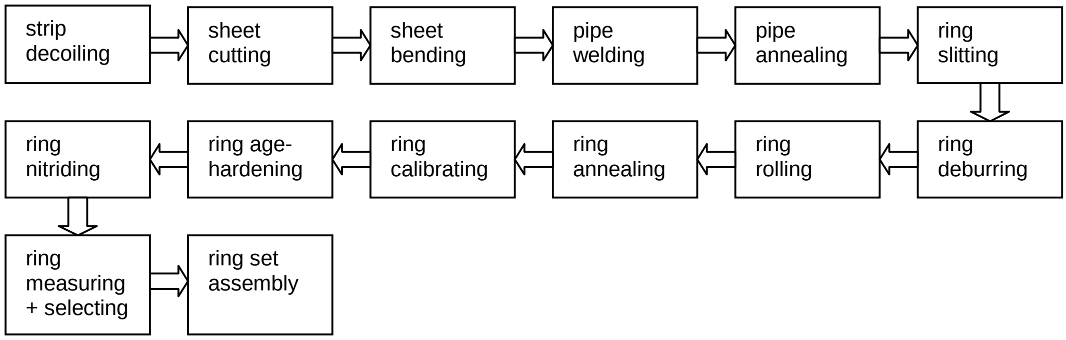

Figure 8: Ring production process at VDT/Bosch.

The properties that make maraging steel highly suitable for ring production are good formability and machinability in the unaged condition, excellent weldability, low strain hardening during cold working, moderate heat treatment temperatures, virtually negligible dimensional changes during heat treatments, and good nitridability. The properties of major importance for push-belt applications are obviously the high yield, tensile and fatigue strengths. Most of these properties are inherent features of the metallurgy of maraging steels, which are relatively soft and ductile in the unaged condition and attain their very high strength only in the final aging step (4,5**)**. After a solution annealing or austenitising treatment (e.g. 1 hour at 830°C), the matrix transforms from austenite to martensite on cooling to room temperature. The cooling rate is not critical. Because of the very low carbon content (C ≤ 0.01 wt.%) the martensite is relatively soft (HV1.0 hardness ≈ 300) and very tough. The high yield strength ($\sigma_y \approx$ 1700-1800 MPa) is obtained after a 'maraging' heat treatment at moderate temperature (e.g. 3 hours at 480°C). Hardening and strengthening are induced by the precipitation of intermetallic compounds such as Ni_3Mo, Ni_3Ti, and Fe_2Mo (4,5**)**. The dimensional changes associated with age-hardening are only very slight. Push-belt rings can thus be manufactured in the soft condition and then hardened with a minimum of distortion. High fatigue strength is obtained due to a combination of high yield and tensile strengths, good toughness and excellent material cleanness, with low impurity and residual element contents. Careful melting and refining practices are employed to control carbon, sulphur, oxygen, and nitrogen to very low levels, in order to limit the population of non-metallic inclusions. The processing route employed by Imphy Alloys to ensure excellent cleanness includes vacuum induction melting and vacuum arc remelting. Nevertheless, as mentioned above, small TiN inclusions are commonly observed in the current ring material, where they typically represent approximately 95% of all non-metallic inclusions (see Figure 9). Like in most maraging steels, titanium is an essential strengthening element in the Durimphy™ grade (0.45wt% Ti), and the high affinity of this element for nitrogen makes it virtually impossible to fully prevent the formation of TiN inclusions at practically attainable nitrogen levels.

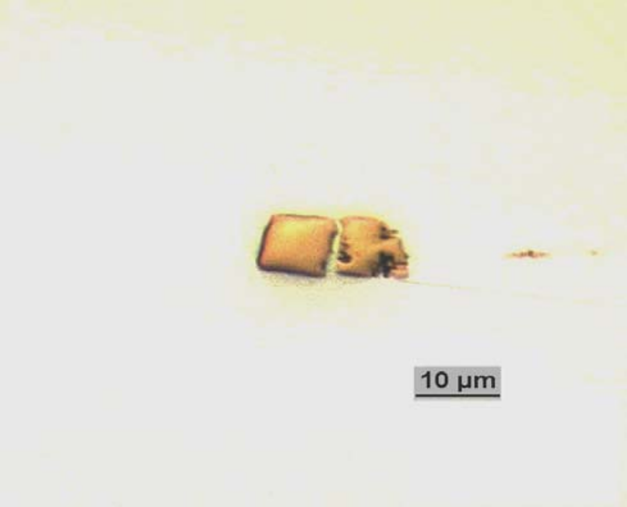

Figure 9: Example of typical TiN inclusions in the current ring material.

Development of a New Ring Material

The study of push-belt fatigue failures described above clearly indicated that push-belt power density is determined by the fatigue strength of the rings. It is well known that the fatigue strength of steels is proportional to their yield/tensile strength, up to a maximum level associated with crack initiation at inclusions (6-8). An increase in fatigue strength can therefore be sought by increasing the yield/tensile strength only when the detrimental effect of inclusions is eliminated or attenuated. A significant reduction of the number and size of TiN inclusions in the current ring material is very difficult to achieve without radical and expensive changes in the melting and refining route, particularly considering the relatively large production volumes involved. Therefore, in order to meet customer requirements for CVT systems with enhanced power density, a material development program was initiated several years ago, with close cooperation between VDT and Imphy Alloys. The aim was to develop a new higher strength ring material in which the formation of TiN inclusions is minimised or completely eliminated. The result of this work is a new maraging steel designated Phytime™.

The chemical composition of the new alloy is nominally titanium-free (trace levels of titanium may subsist due to the raw materials employed). The major contribution of titanium to strengthening in Durimphy™ and most other maraging steels is compensated by an increase in the cobalt content. Indeed, the alloy chemistry has been tailored to obtain an increase in yield/tensile strength of the order of 10%. The strengthening effect of cobalt in maraging steels is known to be associated with that of molybdenum, whose level in the new alloy was maintained approximately the same. Cobalt is believed to lower the solubility of molybdenum in the martensite matrix, enhancing the precipitation of Mo-rich intermetallic phases (e.g. Ni_3Mo, Fe_2Mo) during aging (4,5**)**. Apart from the changes in titanium and cobalt contents, the compositions of the current and new ring materials are similar (Table 1).

Table 1: Chemical compositions (weight %) of the current ring material and the new alloy.

	Ni	Co	Mo	Ti	Fe
Current ring material	18	9	5	0.45	balance
New alloy	18	16.5	5	-	balance

In order to compare the cleanness levels of the two ring materials, inclusion measurements have been performed using optical microscopy combined with image analysis. This technique has been specially developed to detect, count, and measure all non-metallic inclusions present on the surface of carefully prepared samples. Standardized areas are evaluated on each sample and the numbers of inclusions are averaged for this area. The inclusions detected are characterised by their 'equivalent diameter' D_{circle}, and are classified in two relevant size ranges, corresponding to D_{circle} = 5-10 µm (small inclusions) and D_{circle} > 10 µm (large inclusions). For the current ring material, a large amount of data is available, corresponding to many different heats. So far, a limited number of industrial melts have been produced with the new alloy. Inclusion counting results are shown in Figure 10. For ease of comparison, the cleanness level of the current material is set at 100%. It can be seen that, in the size range D_{circle} = 5-10 µm, the number of inclusions in the new material has been reduced by at least a factor of 10, while no inclusions with D_{circle} > 10 µm are detected at all in the new material. Additional chemical analysis has revealed that the majority of the inclusions in the current material are titanium nitrides (proportion ≈ 95%), whereas those in the new material are mainly oxides (typically Al-rich). Experience to date suggests that TiN inclusions can be largely eliminated in the new alloy by careful control of the titanium and nitrogen contents, while the much smaller population of oxide inclusions is probably similar in both materials. TiN particles tend to be angular (typically cubic), whereas the aluminium-rich oxides are smaller and more globular in shape. Based on fatigue studies on bearing steels for example, oxide inclusions appear to be less harmful than Ti(C,N) inclusions of the same size, due to differences in both morphology and mechanical and physical properties (9,10**)**. Although oxide inclusions are also present in the current ring material, failure initiation at such defects has never been observed for current push-belts.

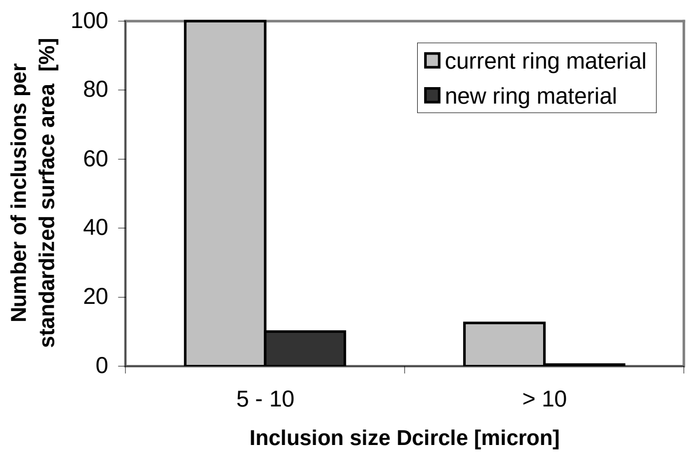

Figure 10: Inclusion counting results obtained by optical microscopy and image analysis on both the current and new ring materials.

In the solution annealed delivery condition, the mechanical properties (hardness, yield and tensile strengths, elongation) of the new material are very similar to those of the current ring material. No difficulties are therefore expected in manufacturing rings with the new material. Indeed, no serious discrepancies have been observed in development work, and experience with production trials so far indicates that the new material can be readily processed using current VDT ring production lines.

In contrast, some of the functional properties of rings made with the new alloy are quite different from those obtained with the current material. Vickers hardness measurements made in the core of the fully treated rings are 10-20% higher than for the current rings. Tensile tests performed on new rings show an increase in yield and tensile strength of approximately 10% compared to current values, in agreement with the greater hardness. These results comply with the material development targets. Furthermore, the nitriding behaviour of the new ring material is comparable to that of the current material. The thickness of the diffusion zone and the surface hardness obtained under current nitriding conditions are fairly similar.

In addition to the ease of ring manufacture with the new material, the processing route used by Imphy Alloys to produce cold rolled strip is comparable to current ring material. The melting, refining, and hot and cold rolling processes remain essentially the same, except for the steps that determine the precise chemical composition.

VALIDATION

Fatigue Behaviour of Push-Belts manufactured with the New Ring Material

To verify whether the fatigue behaviour of push-belts could effectively be improved with the aid of the new ring material, durability tests were performed with VDT's 24/9 type belt with 24 mm wide elements and 2 sets of 9 rings. The current 24/9 belt was compared to 24/9 belts made with the new ring material. The belts were subjected to Overload Fatigue Tests in order to determine the maximum belt durability, using VDT belt boxes and test rigs (see Figure 4). The OFT settings applied (primary speed and primary torque) were well above full load (LDC) settings. Increased primary and secondary pulley clamping forces were applied to maintain normal safety levels. The durability results obtained are presented in Figure 11.

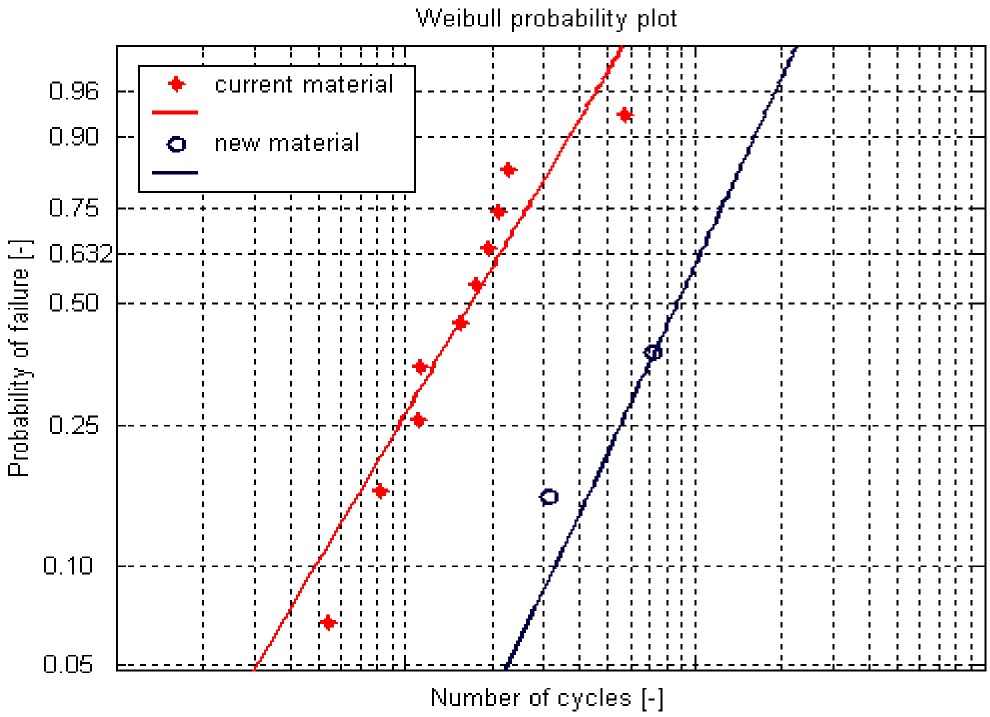

Figure 11: OFT belt durability results: current material compared to new ring material.

All belts with the current ring material failed due to fatigue fracture of ring 1, initiated at a TiN inclusion (i.e. the usual push-belt failure mode under overload conditions). Two belts with the new ring material also failed due to fatigue fracture of ring 1. The corresponding failure mode has not yet been clarified, but there are no indications that initiation occurred at non-metallic inclusions. Two other belts with the new material did not fail at all within the predetermined maximum test duration. Weibull analysis shows that the durability of belts made with the new material is a factor of 5 times higher than that of belts with the current material.

The ring fatigue strength obviously has been increased, and it can be concluded that the power density of push-belts manufactured with the new material is clearly greater than that of current belts in OFT testing.

APPLICATION OF THE NEW RING MATERIAL

If future durability requirements for current belt types become more severe than their present levels, the new ring material can be used to obtain increased life (see Figure 11). Although the test results shown in Figure 11 refer to 24 mm belts, similar behaviour has been observed for belts with 30 mm wide elements.

These observations indicate that the S-N-curve for belts made from the new material is shifted to higher values, as shown schematically in Figure 12. This figure demonstrates that the improved fatigue strength of the new material can also be exploited to allow higher total ring stresses (σ_{total}) at current durability levels.

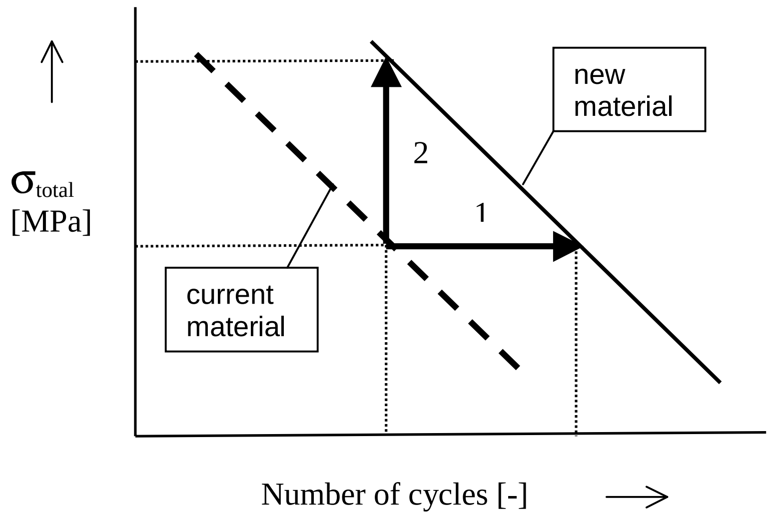

Figure 12: S-N-curves for push-belts with the current and new ring materials. Total ring stress (σ_{total}) versus number of cycles to failure.

The potential to employ higher total ring stresses with the new material can be exploited in several ways:

1) The new material can be used for applications involving increased transmittable power and torque. Higher power and torque levels can be transmitted since the new rings can withstand the larger tensile fatigue stresses resulting from increased pulley clamping forces, faster rotational speeds, and the higher torque levels themselves.

2) The new rings can be exposed to higher bending fatigue stresses. Consequently, smaller minimum running radii R_{min} can be employed, leading to increased ratio coverage R_c and/or reduced centre distance C_d (see Figure 3).

3) The new material can be applied in belts with a reduced total ring volume, e.g. a reduced number of rings (i.e. a smaller number of belt components). For example, VDT's current 24/12 type belt with 2 sets of 12 rings was compared to 24/9 type belts with the new ring material. The 24/12 and 24/9 belts were subjected to identical OFT settings. The durability results obtained are quite comparable, as can be seen in Figure 13.

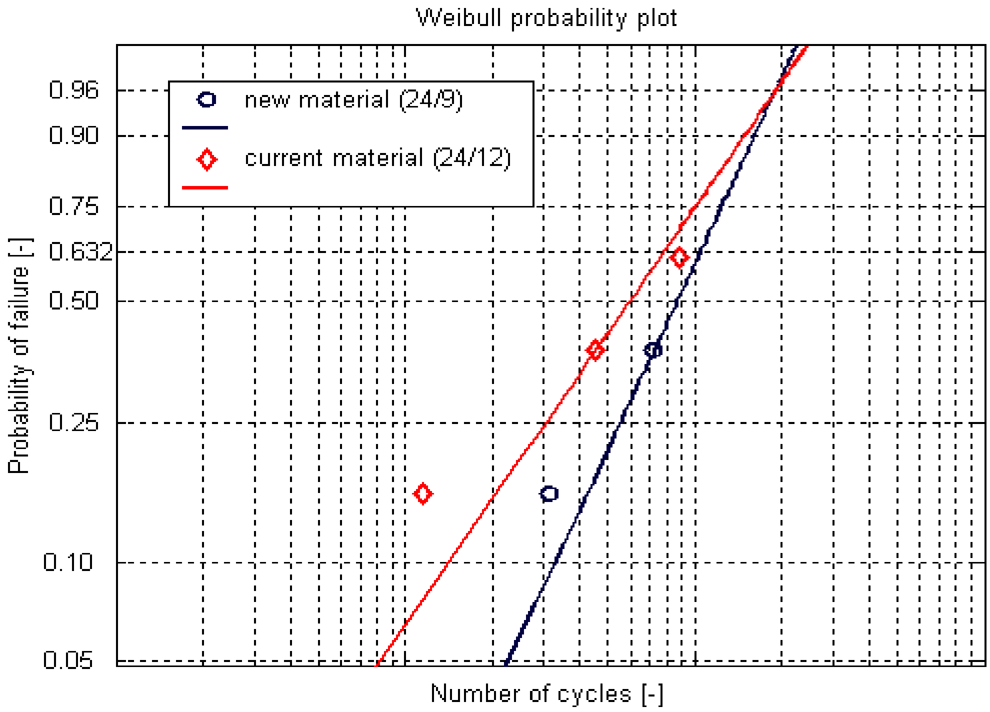

Figure 13: OFT belt durability results: 24/12 type belts with current material compared to 24/9 type belts with new ring material.

The first industrial application of the new ring material is in VDT's newly developed "Phase 7" belt design for increased power density. This Phase 7 belt incorporates a new element design and an optimised ring design. The ring design comprises, among other things, the new material and an optimised residual stress distribution (2). One of the features of the new element design is to allow a higher loading, enabling the increased power density resulting from the new ring material to be fully exploited. The Phase 7 belt is initially a 30 mm application. Start of production of this new belt design is planned in the 4th quarter of 2005.

CONCLUSIONS

1. Test results have demonstrated that the durability of push-belts can be significantly improved when the rings are manufactured from a higher strength material containing fewer and smaller non-metallic inclusions. Durability was enhanced by a factor of 5, representing the potential for a marked increase in power density of 24 mm and 30 mm push-belt designs.

2. The new ring material is a maraging steel designed to have yield and tensile strengths 10% higher than the grade currently employed, together with fewer and smaller non-metallic inclusions. In particular, the presence of inclusions with equivalent diameter D_{circle} larger than 10 μm is eliminated, while the number of inclusions with sizes in the range 5-10 μm is reduced by at least a factor of 10.

3. Push-belts can be readily manufactured with the new ring material using current VDT/Bosch production lines. Furthermore, the processing route used by Imphy Alloys to produce the cold rolled strip is comparable to that of the current material.

4. A higher power density can be used to increase transmittable power and torque, to reduce transmission size (pulley centre distance), to raise the ratio coverage, to enhance durability, or to decrease the total ring volume, e.g. via a smaller number of rings. Test results show similar durability for 24/12 type belts with the current material and 24/9 type belts with the new ring material.

5. Given these promising results, the new ring material will be implemented in a new belt design also incorporating other features aimed to increase the power density of the push-belt CVT. This first application of the new ring material is planned to go into production in 2005.

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