ON THE SELECTION OF WIRES AND SURFACE ENGINEERING FOR MAXIMUM SPRING FATIGUE PERFORMANCE.

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1. Synopsis

To maximise compression spring fatigue performance one must select the raw material, surface engineering for the spring, and take account of costs. A beta titanium spring will outperform one made from air patented carbon steel, and nitriding may outperform shot peening, but by how much and at what cost?

The candidate spring materials are, in order of cost, air patented carbon steel, music wire, oil tempered silicon chromium, superclean silicon chromium vanadium or nickel, 17/7PH stainless steel and a beta titanium alloy. Since maximum spring performance is the goal, energy storage efficiency, corrosion and relaxation resistance need to be considered, but fatigue resistance is often the most critical aspect. In order to maximise resistance to fatigue crack initiation, surface engineering is essential. Again, in order of cost, the candidate processes are shot peening, duplex peening, strain peening and nitriding. This paper will quantify the performance that might reasonably be expected for each viable combination so that the reader may better appreciate when each might be selected and the costs associated with that selection.

2. Raw Materials

The ideal compression spring wire should have a high elastic limit after spring manufacture, a low rigidity modulus, low density, excellent surface quality and no inclusions >15μm in size. If corrosion resistance is also available that is a considerable bonus because corrosion protection has to be achieved for maximum dynamic performance.

2.1 *Maximum Strength / Minimum Stiffness / Minimum Density.*

To maximise the load a spring will support without risk of plastic deformation, one must consider wire size and the usual processes used in spring manufacture since both will affect the choice of the optimum material. At sizes less than 2mm diameter, music wire has the highest elastic limit after spring coiling, stress relief heat treatment and prestressing. Above 2mm chrome silicon alloys are best, but 17/7PH stainless steel is a close second, and this grade is corrosion resistant whereas the chrome silicon alloys will require corrosion protection for many applications. However, the chrome silicon alloys are very versatile – they may be supplied oil hardened and tempered for cold coiling, induction hardened and tempered above 7mm diameter, also for cold coiling, or at larger sizes for hot coiling – the harden and temper being accomplished after hot coiling.

Beta titanium alloys are less strong and have a lower elastic limit, but these materials have a very much lower modulus than any of the foregoing and a low density so, in terms of energy storage per unit volume or per weight of spring, the beta titanium alloys outperform music wire, chrome silicon alloys and 17/7PH and also have the advantage of corrosion resistance. It is 100 times more expensive than music wire, but recent developments have potential to bring down the price difference.

2.2 *Surface Quality*

Complete absence of surface defects (and partial decarburisation in music wire and chromium silicon alloys) is highly desirable for maximum dynamic performance. Shaving the surface of the wire, usually after drawing through a single die after rod rolling, is the most frequently used method to achieve defect free wire. However, excellent process control during rod rolling is capable of producing spring wire that is effectively defect free – many engine valve springs, the highest volume spring application demanding excellent dynamic performance, are often made from wire that is not shaved, and some of these engine valve springs are known to have a reliability of less than one failure per 10 million springs.

2.3 *Cleanness*

Engine valve springs are usually made from a silicon chromium alloy, and whilst the wire may not be shaved, it will be made to ‘superclean practice’. This involves deoxidising the steel with ferro-silicon that contains no aluminium and using relatively high hot rolling temperatures so as to plastically deform the silicate inclusions. The product is certainly not particularly clean in conventional steelmaker’s parlance, but there are almost no inclusions present >15μm in size within the surface layer of the finished wire (Figure 1). If there are no inclusions above this critical size, they do not initiate fatigue failure, and this very simple strategy works. Indeed it could almost certainly be applied for other steel products for which subsurface fatigue initiation is the usual mode of failures. Whether other industries ever have the courage to copy the spring industry’s successful strategy is worthy of further debate.

Figure 1 **x 174**

Any metallurgist who has looked down a microscope at a longitudinal section taken from a 17/7PH spring would not describe the steel as clean. The number of inclusions is considerable, as shown in Figure 2. However, close observation shows that these titanium carbon-nitride and aluminium inclusions are mostly in the size range of less than 10 microns. IST believe this is a full explanation of why this grade has such good fatigue resistance when springs have been glass bead peened.

Figure 2 **x 87**

3. Surface Engineering

The purpose of surface engineering on springs is to provide fatigue resistance primarily, but also wear resistance because wear can remove the surface engineering used to protect against fatigue. In addition, it is important that the surface engineering does not compromise corrosion resistance. To achieve fatigue resistance one selects a raw material with maximum strength, as has already been shown, and so the surface engineering should leave that strength substantially unaltered.

Fatigue resistance is achieved with surface engineering in two principle ways. Firstly, and most importantly, it imparts a residual compressive stress to the spring surface. This residual compressive stress may be accompanied by slight strengthening of the surface without compromising the bulk strength. Secondly, fatigue resistance is enhanced by making the surface of the spring smoother.

By far the most common way to enhance the fatigue resistance of springs is shot peening. It is often considered to be a crude method that involves bombarding the surface of a spring with small rounded particles of steel, glass or ceramic. Surely there are technologies today that can do better than this? Indeed there are, but as will be demonstrated, not much better. It remains by far the most important method of enhancing the fatigue resistance of springs, and without it, attendees of this conference would not have been able to travel to Prague. Planes, trains and all road vehicles have compression springs that have been shot peened, and without this surface engineering, fatigue failure would be inevitable.

Shot peening once with shot of a size that is 2-20% of the diameter of the wire is enormously effective. Obviously the process can be optimised, but the difference in fatigue performance from optimisation of peening is small in comparison with the fatigue performance without peening. If >80% coverage is achieved it is difficult to get the shot peening seriously wrong. Of course optimisation is recommended, but this can only be achieved by measuring fatigue performance – the appearance (Figure 3) gives few clues about whether the peening is optimum.

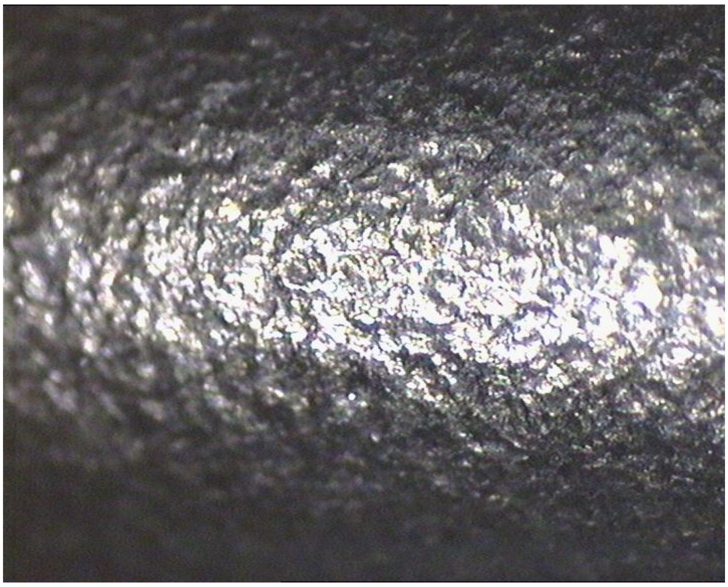

Figure 3 **x 22**

Shot Peened Surface

Duplex peening improves spring fatigue performance over that of optimised peening. It comprises optimised shot peening, stress relieving and then re-peening with a smaller diameter shot to make the wire surface a little smoother and to raise the maximum compressive stress at the surface slightly.

Strain peening may further enhance spring fatigue performance. That process involves applying optimised peening to a spring under significant strain. This method is practical and widely used for leaf and parabolic springs, but is difficult to apply to compression springs for simple practical reasons – when under strain the gap between coils is small and shot does not readily reach the critical inside surface of a compression spring.

A more sophisticated surface engineering process that enhances the strength of the surface of a spring and imparts a residual compressive stress is nitriding. This diffusion process can be applied to any size and shape of spring even those too small to shot peen. However the process temperature is at or above the tempering temperature of many of our candidate spring materials. Extensive research to reduce the temperature at which nitriding is effective has been carried out (1,2), but the process temperature needs to be about 450°C, and so music wire cannot be usefully nitrided. SiCr alloys need to be alloyed with nickel in order for this process to be fully effective. However nitriding alone does not enhance spring fatigue performance as much as shot peening (1,2), and so shot peening is invariably applied after nitriding for maximised spring performance, which means that springs too small for peening cannot be nitrided beneficially. Nitriding compromises the corrosion resistance of austenitic stainless steel spring wires, but is understood to be useful for achieving wear and fatigue resistance for titanium alloys that have an age hardening temperature greater than the nitriding temperature.

Kolsterising® is another diffusion process suitable for stainless steel, but as with nitriding, there is a risk of compromising corrosion resistance with this process.

The final surface engineering process that will be highlighted in this paper is electropolishing. It is not practical with carbon and low alloy steels because of the difficulty of avoiding corrosion, but with austenitic stainless steels it works well by providing a very smooth surface (Figure 4) whilst leaving the state of residual stress unaltered. However it is instructive to recognise the relative effect of electropolishing and glass bead peening on 302 stainless steel springs made from 2.4mm diameter wire. Without surface engineering, the safe fatigue stress range for 10 million cycles for compression springs is as small as 100-425N/mm^2. This is improved to 100-600N/mm^2 by electropolishing and to 100-750N/mm^2 by glass bead peening – hence quantifying the relative importance of residual compressive stress and surface smoothness. This relationship is further clarified when one electropolishes 25 microns from the surface of a glass beaded 302 spring, then the safe fatigue range becomes 100-800N/mm^2 (a stress range that equates to 38% of the wire UTS), as shown in Figure 5.

Figure 4 17/7PH spring, peened and electropolished

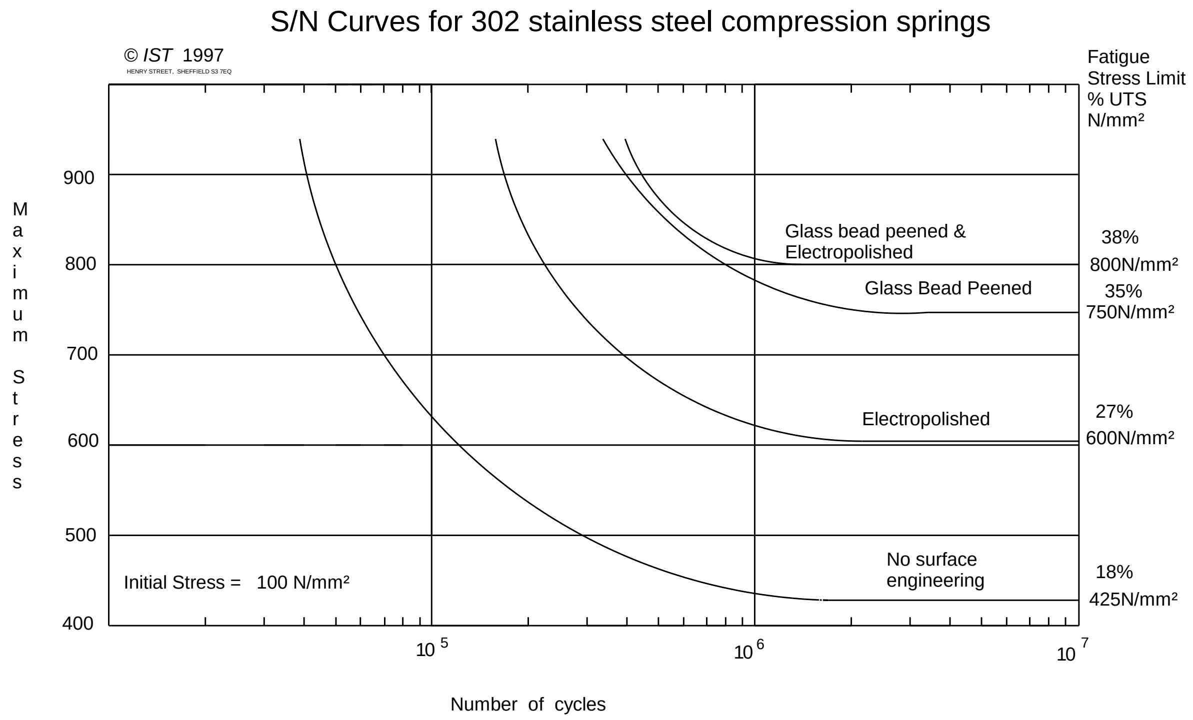

Figure 5 S/N Curve

4. Relative Costs

It is a fact that a beta titanium compression spring with suitable surface engineering would outperform all our other candidate materials for maximum energy storage per unit volume of space available and its dynamic performance would be excellent. However, such springs are seldom used, and the reason is inevitably one of cost. Not only are beta titanium alloy spring wires the most expensive to purchase, but the springs made of this material require the most expensive surface engineering processes. Shot peening alone is insufficient for titanium springs because this material has poor wear (fretting) resistance and wear will occur between the end coil and first active coils if nitriding (or electroless nickel plating) is not used to limit wear. The relative costs of candidate materials are:

Air patented carbon steel	0.5
Music wire	1
Oil tempered SiCr	2
Superclean oil tempered SiCrNi	2.5
17/7PH	6
Beta titanium	100

The relative costs of candidate surface engineering processes are:

Shot peening	1
Duplex peening	2
Strain peening	2
Glass bead peening	3.5
Nitriding	10
Electropolishing	20 (including cost of material polished away)

5. Relative Fatigue Performance

All data presented here will be given as a safe stress range at 10 million cycles during a dynamic test of a compression spring – the safe stress range being expressed as % of wire UTS. The springs were invariably tested on IST's forced motion test machines (Figure 6) at a speed less than one thirteenth of the natural frequency of the springs and with a sinusoidal loading cycle. The minimum stress applied in each test was 100N/mm^2.

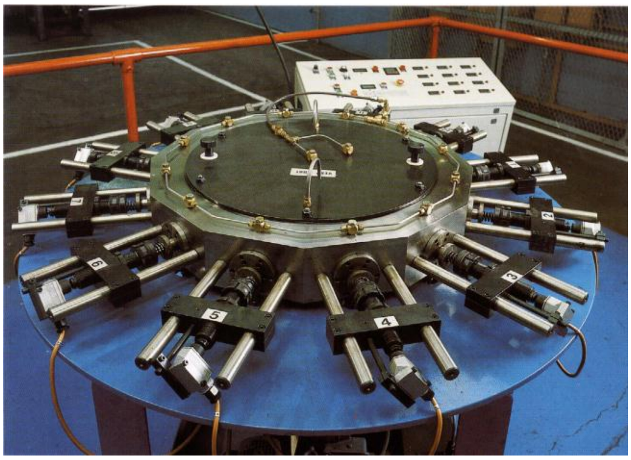

Figure 6 Fatigue Test Machine

On a recent visit to India, the author was reminded of the considerable potential of air patented carbon steel as a dynamic spring material. Very widely used for mattress springs (which are not our concern here because they have no surface engineering and do not fail by a fatigue mechanism usually), but in India this material is used for suspension springs for two wheel vehicles (which in India includes those with three wheels). These springs are shot peened and have a reliable fatigue performance that, in cost terms, is the best of all our candidates. The fatigue stress range at 10 million has not been measured, but at 1 million is 40%, which might equate to about 37% at 10 million.

Music wire has better fatigue performance than air patented carbon steel. Nitriding can be accomplished but the softening of the music wire is such that there is no gain(1), so shot peening remains the only viable surface engineering process for music wire springs. The fatigue stress range at 10 million cycles is 39% (3).

Silicon chromium oil tempered wire (not shaved, not superclean, but to EN 10270-2 SiCr VD quality) is better than music wire for compression spring fatigue performance. Shot peening gives a fatigue limit of 41%. This grade is softened by nitriding, but it is nonetheless possible to nitride SiCr springs and obtain a fatigue performance unattainable with shot peening alone. However, the nitriding process parameters that will always yield the small improvement to 42% sometimes observed, were not narrowed down accurately enough in an extensive Europe wide research project concluded in 2004(1). Indeed it was demonstrated that regular SiCr with a little decarburisation at its surface was completely unsuitable for nitriding.

For nitriding it is necessary to utilise shaved, superclean SiCr. Then the fatigue stress range measured was 43% when optimum nitriding was used. However, with shot peening alone the stress range was close to 43%.

To gain a reasonable performance increase from nitriding it was found to be necessary to use shaved, superclean SiCrNi, a grade with better temper resistance than regular SiCr and so the nitriding could be accomplished at 450°C without softening the wire significantly. Post nitriding peening was essential, but then the fatigue limit was 50%(1).

The stainless steel most often used for dynamic spring applications, like the engine valve springs in diesel engines, is 17/7PH (EN 10270-3 CrNiAl 17-7). This material is shot peened (and pickled and passivated) or glass bead peened. In this condition the fatigue limit is comparable with regular grade SiCr wire i.e. 40%, and of course this wire is corrosion resistant.

Finally, it would be very interesting to compare all the above with springs made from beta titanium wire. Insufficient research and testing has been undertaken to quantify this accurately, but the grade's energy storage capacity is 30% greater than that of SiCr, and its fatigue performance has provisionally been estimated to be about 50% UTS at 1 million cycles.

6. Conclusions

The lowest cost combination of spring material and surface engineering that gives spring engineers good scope for designing compression spring products with excellent performance is air patented wire that is shot peened after spring forming. Together with hot prestressing, a stable product with reliable room temperature performance is obtained at a remarkably low cost.

Higher performance is gained by using music wire and silicon chromium grades, but the performance gain is at a significant cost. If corrosion resistance is essential, 17/7PH will be the likely choice.

For springs with a fatigue life well in excess of 10 million cycles, superclean SiCr alloys are essential. However the economic case for use of superclean shaved SiCrNi and nitriding is doubtful, because the fatigue performance is only improved by a relatively small amount.

The economic case for use of beta titanium has seldom been made as yet, but the author predicts that surface engineered titanium springs will be used much more widely in the next ten years, and it will cease to be the almost exclusive domain of the aerospace and motor racing industries.

7. References:

1. Final report, CRAFT project No. CRAF1999-70483.
2. 'High Strength Wire for Springs' M.P. Hayes WAI Conference Proceedings, Stratford October 2001.
3. 'Influences on Spring Fatigue' M.P. Hayes Wire Industry, December 1985.

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