

## EFFECT OF FRETTING ON FATIGUE STRENGTH OF TITANIUM ALLOYS

## 1. NOTATION

|                    |                                           |                  |                     |
|--------------------|-------------------------------------------|------------------|---------------------|
| $f_p$              | 0.2 per cent proof stress of material     | N/m <sup>2</sup> | lbf/in <sup>2</sup> |
| $f_t$              | tensile strength of material              | N/m <sup>2</sup> | lbf/in <sup>2</sup> |
| $N$                | endurance                                 |                  |                     |
| $p$                | pad pressure                              | N/m <sup>2</sup> | lbf/in <sup>2</sup> |
| $R$                | $S_{min}/S_{max}$                         |                  |                     |
| $S_{max}, S_{min}$ | maximum and minimum stresses respectively | N/m <sup>2</sup> | lbf/in <sup>2</sup> |

## 1.1 Conversion Factors

Both SI and British units are quoted in the notation.

$$1 \text{ MN/m}^2 = 1 \text{ MPa} = 145.038 \text{ lbf/in}^2$$

## 2. NOTES

## 2.1 General

Fretting is the term used to describe the surface damage resulting from relative motion between two contacting surfaces. This results from adhesion between the surface asperities and may be followed by the formation of wear particles as the sliding motion continues. In an air environment the wear particles oxidise and the resulting debris further contributes to surface damage. The important factors influencing fretting are the contacting materials, contact pressure, slip amplitude, surface finish, temperature and environment. The most important factors are local contact pressure and slip amplitude because increasing these increases the fretting.

Fretting fatigue occurs as a result of surface stresses induced by fretting adding to the stresses produced by the existing applied alternating stresses. The combined stresses reduce crack initiation life and accelerate early crack growth. In the simple example of two rectangular blocks in contact, under a constant pressure, one of which is subject to a tensile load parallel to the contact surfaces, the contact pressure and slip vary over the contacting surfaces. It is found that the alternating frictional forces are highest towards the ends of the contact zone while the contact pressure may be highest at the centre. This creates high alternating surface stresses near the boundary of the contact zone and this is where fatigue cracks originate. Once a fatigue crack moves out of the area affected by the surface stresses fretting has little or no effect on crack propagation, unless the frictional stresses alter the overall stress distribution.

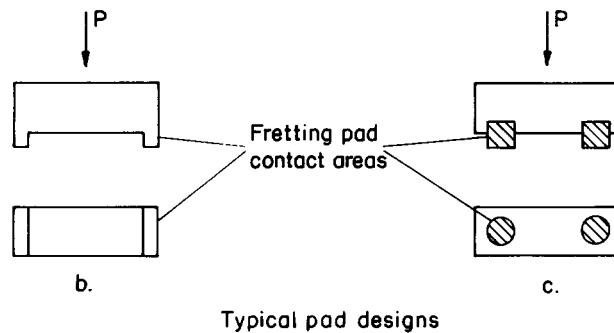
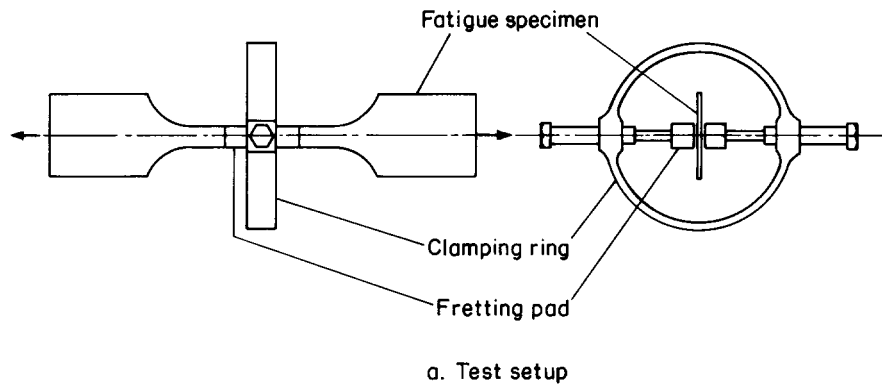
This Data Item attempts to illustrate trends that occur due to fretting fatigue. As most of the life is spent in crack propagation, a fracture mechanics approach could be useful in designing a component subject to fretting fatigue. Fracture mechanics models for fretting fatigue have been developed for idealised situations (References 13 and 22), although they are very limited in their application. It is difficult to predict where the maximum fretting stresses will occur in a complicated joint. For example, in the case of two sheets fastened together, interference-fit fasteners may shift the fretting fatigue from the edge of the holes to the contacting surfaces between the two sheets away from the holes.

## 2.2 Presentation of Data

Table 5.1 provides an index to the titanium alloys for which data are available. The table also summarises the various surface treatments used to alleviate fretting fatigue. The data are presented in the form of  $S-N$  curves. The results from all the tests are plotted as maximum stress versus cycles to failure, for given values of  $R$ . The 'fretting' and 'no fretting' conditions can be compared for a variety of surface treatments and environments. A table giving relevant information about the material and tests accompanies each figure.

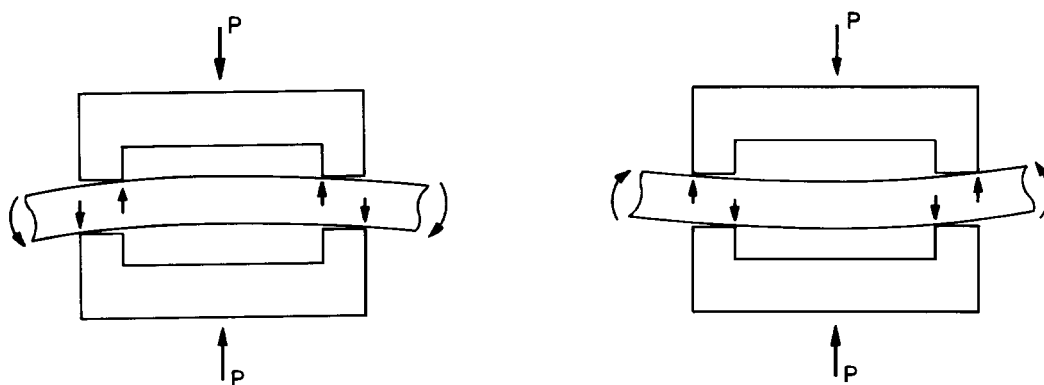
## 2.3 Test Conditions

In all cases the applied loading was constant amplitude sinusoidal using standard fatigue machines. Most of the tests took place in laboratory air at room temperature with no control of the humidity. A few tests were undertaken in other environments which are described in the accompanying table. Some tests were undertaken at elevated temperatures. The types of specimens used in the tests vary from one derivation to another. Some specimens were punched from sheet, and others were machined from bars. The fretting pads were made of the same material as the specimen. The pads consisted of either a pair of studs inserted into a pad holder or a bridge shaped pad which made contact at its ends. The pad pressure was maintained on the specimen by a calibrated clamping ring. A general diagram of a typical test set-up is shown in Sketch 2.1. The relative movement between the fretting pads and specimen is as a result of strain in the specimen which depends on the applied load, and on the distance between the feet of the fretting pad.



**Sketch 2.1 Showing typical test set-ups**

Most of the data plotted are taken from tests on axially loaded specimens; in some tests, the applied loading was bending. The points of contact with the fretting pad vary during the loading cycle, thus moving the point of maximum surface stress throughout the cycle. This is illustrated in Sketch 2.2.



**Sketch 2.2 Showing how the points of contact between the fretting pad and specimen change during a bending test load cycle**

### 3. DISCUSSION OF DATA

The reduction in fatigue strength due to fretting can be seen by comparing the  $S-N$  curves for the fretting and no fretting conditions. Fretting causes a drastic reduction in the fatigue strength of all the titanium alloys presented here, especially when  $N$  is greater than about  $10^5$  cycles. The effects of the various factors that influence fretting fatigue are described below.

#### 3.1 Loading Effects

##### 3.1.1 Effect of pad pressure

In this Data Item various pad pressures ranging from 21 to 93 MPa (3050 to 13 490 lbf/in<sup>2</sup>) have been used. Figures 7 and 9 compare the effects of different pad pressures on IMI 230 and IMI 318A. In both cases increasing the pad pressure reduced the fatigue strength due to fretting below about  $2 \times 10^5$  cycles. Above this value the effect of changing the pad pressure was slight.

##### 3.1.2 Effect of slip amplitude

Slip amplitude depends on the strain in the specimen and therefore on the applied stress range. For a given stress range the slip amplitude can be altered by varying the distance between the feet of the fretting pad. No data have been presented on the effect of slip amplitude on the fretting fatigue of titanium alloys.

##### 3.1.3 Effect on variable amplitude loading

No data have been found on the effect of fretting fatigue on variable amplitude loading, in regard to titanium alloys.

#### 3.2 Effect of Environment on Fretting Fatigue

##### 3.2.1 Salt water

A 1.0 per cent NaCl solution has been used to determine the effects of salt water on fretting fatigue life by dripping the solution on the centre portion of the specimen. Figures 1, 2, 8 and 20 show that the fretting fatigue strength in these conditions is reduced compared to that in air. The changes in fretting fatigue strength are almost negligible for IMI 130 and IMI 230 but are quite noticeable for IMI 318 and IMI 685.

##### 3.2.2 Temperature

The fatigue strength of titanium alloys under conditions of 'no fretting' is lower at elevated temperatures. In the fretting condition, increasing the temperature also causes a reduction of fatigue strength, but by a smaller factor than in the 'no fretting' condition. In both cases the loss in fatigue strength due to fretting is very large. High temperatures may reduce the beneficial effect of applied anti-fretting surface coatings. The effect of temperature on the fretting fatigue strength of IMI 318 can be seen in Figures 16 and 17, and its effect on IMI 685 can be seen in Figure 21.

#### 3.3 Effect of Surface Coatings and Treatments

Several coatings and surface treatments have been successful in reducing fretting and fretting fatigue. However, coatings that reduce fretting do not necessarily reduce fretting fatigue. In all cases only the specimen surface is treated. Some treatments are beneficial while some are detrimental to fatigue life. Full details of these treatments are given in Appendix A. The following sections describe the effect on fretting fatigue of some surface coatings and treatments.

### 3.3.1 Shot peening

Shot peening is an effective way of increasing the fatigue strength of both fretted and unfretted components. It induces residual compressive stresses at the surface of the component that make it more difficult for surface cracks to propagate into the material. Shot peening intensity of Almen A7 was beneficial to unfretted specimens; higher intensities of Almen A13 were detrimental to fatigue life. Shot peening was very effective in reducing fretting fatigue as can be seen from Figures 4, 5, 6, 10, 12, 13, 14, 15, 17, 19 and 21. However, varying the shot peening intensity on fretted specimens had only a slight effect on fatigue life. Very high shot peening intensities may result in surface damage to parts of the component away from the fretted region. Consequently fatigue failure may occur away from this region. Shot peening had a similar effect on all the titanium alloys tested.

### 3.3.2 Vapour blasting

Vapour blasting followed by coating with molybdenum disulphide in epoxy or polyimide resin had a small beneficial effect on the fretting fatigue strength of IMI 230 as can be seen from Figure 3.

### 3.3.3 Nickel diffusion

Specimens were treated by either electro-deposited or 'electroless' deposited nickel plating followed by a diffusion treatment as detailed in Appendix A. Both types of nickel plating resulted in a substantial loss of both fatigue and fretting fatigue strength for all the titanium alloys tested. The fatigue and fretting fatigue strengths were improved by applying a final shot peening process. Comparisons can be made by referring to Figures 5, 14 and 17.

### 3.3.4 Anodising

Neither the 'Watervliet' soft anodic coating nor the 'French Military' specification hard anodic treatments were of much benefit in protecting against fretting fatigue. An additional coating of molybdenum disulphide in epoxy or polyimide resin, on the anodised surface, did not improve the fretting fatigue strength. Refer to Figures 3, 11 and 16.

### 3.3.5 Isocyanate cured epoxy resin (mixed with MoS<sub>2</sub>, graphite or BN)

These paint schemes give a small improvement in fretting fatigue strength. They are sometimes applied after other surface treatments. Above about 150°C (300°F) and up to 350°C (660°F), polyimide resin has been used instead of the isocyanate resin as it can withstand higher temperatures. Refer to Figures 3, 4, 11 and 16.

### 3.3.6 Electro-deposited chromium

Electro-deposited chromium had a detrimental effect on the plain fatigue strength of IMI 230. A combination of electro-plating and shot peening resulted in only a slight improvement to the fretting fatigue strength of IMI 230, as can be seen from Figure 4.

### 3.3.7 Coatings by the 'detonation process'

Figure 6 shows the results of tests of IMI 230 coated by copper + nickel + indium and by tungsten carbide + 15 per cent cobalt. Curve No. 8 shows that tungsten carbide + 15 per cent cobalt improved the fretting fatigue strength of IMI 230. The other curves show that the fretting fatigue life was further improved by an initial shot peening process. Figure 19 shows that a coating of tungsten carbide + 15 per cent cobalt improved the fretting fatigue strength of IMI 685.

### 3.3.8 Plasma flame spray coatings

Plasma flame spray coatings improved the fretting fatigue strength of IMI 230. The strength was further improved by an initial shot peening process as can be seen from Figure 6. The effects of various plasma flame spray coatings on IMI 318A can be seen from Figure 13. An initial shot peening process was beneficial to the fretting fatigue strength.

## 4. DERIVATION AND REFERENCES

### 4.1 Derivation

This section lists selected sources that have assisted in the preparation of this Item.

1. HARRIS, W.J. The influence of fretting on fatigue. AGARD Advisory Report Number 45, June 1972.
2. WATERHOUSE, R.B.  
DUTTA, M.K. The fretting fatigue of titanium and some titanium alloys in a corrosive environment. *Wear*, Volume 25, p. 171, January 1973.
3. HOEPPNER, D.W.  
GOSS, G.L. A fretting fatigue damage threshold concept. *Wear*, Volume 27, p. 61, January 1974.
4. HARRIS, W.J. The influence of fretting on fatigue. AGARD Conference Proceedings. Number CP-161, paper 7, January 1975.
5. WATERHOUSE, R.B.  
WHARTON M.H. The behaviour of 3 high strength titanium alloys in fretting fatigue in a corrosive environment. *Journal of the American Society of Lubrication Engineers*. Volume 32, Part 6, p. 294, 1976.
6. SYERS, G. The protection of certain titanium alloys against fretting fatigue. Unpublished research conducted by Rolls Royce, Leavesden, with the support of the Procurement Executive, MoD, 1978.
7. LUTYNSKI, C.  
SIMANSKY, G.  
McEVILY, A.J. Fretting fatigue of Ti-6Al-4V alloy. Materials evaluation under fretting conditions. American Society for Testing and Materials. ASTM STP 780, 1982.

### 4.2 References

The references given are recommended sources of information supplementary to that in this Item.

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GOSS, G.L. A new apparatus for studying fretting fatigue. *Review of Scientific Instruments*, Volume 42, Number 6, p. 817, 1971.
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MAJORS, D.P.  
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10. RYMAN, R.J.  
BILLINGHAM, A.J. An investigation of the fretting fatigue strength of BS L 65 aluminium alloy under sinusoidal and narrow band random cyclic stressing. DRIC-BR-33069, Defence Research Information Centre, Orpington, England, 1973.

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13. EDWARDS, P.R.  
COOK, R. Fracture mechanics prediction of fretting fatigue under constant and variable amplitude loading. International Committee on Aeronautical Structures. Proceedings, Lisbon, p. 505, 1978.
14. GABEL, B.K.  
BETHKE, J.J. Coatings for fretting prevention. *Wear*, Volume 46, p. 81, 1978.
15. HAMDY, M.M.  
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16. SCHIJVE, J.  
HOEYMAKERS, A.H.W. Fatigue crack growth in lugs. *Fatigue of Engineering Materials and Structures*. Volume 1, 1979.
17. WHARTON, M.H.  
WATERHOUSE, R.B. Environmental effects in the fretting fatigue of Ti-6Al-4V. *Wear*, Volume 62, p. 287, 1980.
18. POON, C.J.  
HOEPPNER, D.W. A statistically based investigation of the environmental and cyclic stress effects on fretting fatigue. *Journal of Engineering Materials and Technology*, Volume 103, p. 287, July 1981.
19. BILL, R.C. Fretting wear and fretting fatigue – How are they related? American Society of Mechanical Engineers, Paper 81-Lub-13, October 1981.
20. SCHÜTZ, W. Material evaluation under fretting conditions. American Society for Testing and Materials, ASTM STP 780, 1982.
21. BLAKEBOROUGH, A,  
CULLIMORE, M.S.G. Fretting in the fatigue of wire rope. Advances in Fracture Research Proceedings of the 6th International Conference on Fracture, New Delhi, India, 1984.
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KODAMA, S. Crack propagation behaviour in fretting fatigue. *Wear*, Volume 107, p. 245, 1986.

## 5. INDEX TABLE

TABLE 5.1 Index to Titanium Alloys

| <i>Material specification/designation</i> | <i>Surface treatments</i>                                                         | <i>Figure Number</i> |
|-------------------------------------------|-----------------------------------------------------------------------------------|----------------------|
| Commercially pure                         |                                                                                   |                      |
| IMI 130                                   | None                                                                              | 1                    |
| Ti-2.5Cu                                  |                                                                                   |                      |
| IMI 230 (TA 22)                           | None                                                                              | 2                    |
| IMI 230 (TA 21)                           | Anodised                                                                          | 3, 4                 |
|                                           | Epoxy resin + MoS <sub>2</sub>                                                    |                      |
|                                           | Vapour blasted isocyanate cured epoxy resin + (MoS <sub>2</sub> , graphite or BN) |                      |
|                                           | Ni diffused                                                                       | 5                    |
|                                           | Shot peened                                                                       |                      |
|                                           | Plasma flame sprayed                                                              | 6                    |
|                                           | Shot peened + plasma flame sprayed                                                |                      |
|                                           | Coated by the detonation process with tungsten carbide or Cu.Ni.In                |                      |
|                                           | Shot peened + coated by detonation process                                        |                      |
|                                           | None                                                                              | 7                    |
| Ti-6Al-4V                                 |                                                                                   |                      |
| IMI 318 (TA 11)                           | None                                                                              | 8                    |
| IMI 318 (TA 10)                           | None                                                                              | 9                    |
|                                           | Shot peened                                                                       | 10                   |
|                                           | Polished                                                                          |                      |
|                                           | Anodised isocyanate cured epoxy resin + MoS <sub>2</sub>                          | 11                   |
|                                           | Titanium oxide film                                                               |                      |
|                                           | Shot peened                                                                       | 12, 13               |
|                                           | Plasma flame spray coated                                                         |                      |
|                                           | Shot peened + plasma flame spray coated                                           |                      |
|                                           | Ni diffused + shot peened                                                         | 14, 15               |
|                                           | Shot peened + chromium plated                                                     |                      |
|                                           | Electroplated chromium diffusion bonded                                           |                      |
|                                           | Anodised + resin bonded graphite                                                  | 16                   |
|                                           | Anodised + polyimide resin + MoS <sub>2</sub>                                     |                      |
|                                           | Anodised + epoxy resin + MoS <sub>2</sub>                                         |                      |
|                                           | Non-electrolytic anodised                                                         |                      |
|                                           | Shot peened                                                                       |                      |
|                                           | Ni diffused + shot peened                                                         | 17                   |

TABLE 5.1 Index to Titanium Alloys (Continued)

| <i>Material specification/designation</i> | <i>Surface treatments</i>                                                                                             | <i>Figure Number</i> |
|-------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|----------------------|
| Ti-4Al-4Mo                                |                                                                                                                       |                      |
| IMI 550 (TA45)                            | None                                                                                                                  | 18                   |
| Ti-6Al-5Zr                                |                                                                                                                       |                      |
| IMI 685                                   | Shot peened<br>Titanium oxide film coating<br>Coated by detonation process with tungsten carbide + 15 per cent cobalt | 19                   |
|                                           | None<br>Shot peened                                                                                                   | 20, 21               |



## 6. TABLES AND FIGURES

Tables and figures giving relevant information about each material are given on the following pages.

**TABLE 6.1**

|                                                |          |                            |                     |                     |                          |                    |                               |  |
|------------------------------------------------|----------|----------------------------|---------------------|---------------------|--------------------------|--------------------|-------------------------------|--|
| <b>Material Specimen Fretting pad</b>          |          | IMI 130<br>IMI 130         |                     |                     |                          |                    | <b>Table 6.1<br/>Figure 1</b> |  |
| <b>Composition Nominal Actual</b>              |          | Commercially pure titanium |                     |                     |                          |                    |                               |  |
| <b>Heat treatment</b>                          |          | None                       |                     |                     |                          |                    |                               |  |
| $f_p$ MN/m <sup>2</sup> (lbf/in <sup>2</sup> ) |          | Not given                  |                     |                     |                          |                    |                               |  |
| $f_t$ MN/m <sup>2</sup> (lbf/in <sup>2</sup> ) |          | 675 (97 900)               |                     |                     |                          |                    |                               |  |
| <b>Type of Loading</b>                         |          | Rotating bending           |                     |                     |                          |                    |                               |  |
| <b>Material Form</b>                           |          | 9.5 mm (0.374 in) rod      |                     |                     |                          |                    |                               |  |
| <i>Curve number and symbol</i>                 | <i>R</i> | <i>Freq.</i>               | <i>Pad pressure</i> |                     | <i>Surface treatment</i> | <i>Environment</i> | <i>Derivation Number</i>      |  |
|                                                |          | Hz                         | MPa                 | lbf/in <sup>2</sup> |                          |                    |                               |  |
| 1 +                                            | −1       | 25                         | –                   | –                   | None                     | Laboratory air     | 2                             |  |
| 2 *                                            | −1       | 25                         | –                   | –                   | None                     | 1% NaCl solution   | 2                             |  |
| 3 ○                                            | −1       | 25                         | 62.5                | 9065                | None                     | Laboratory air     | 2                             |  |
| 4 ×                                            | −1       | 25                         | 62.5                | 9065                | None                     | 1% NaCl solution   | 2                             |  |

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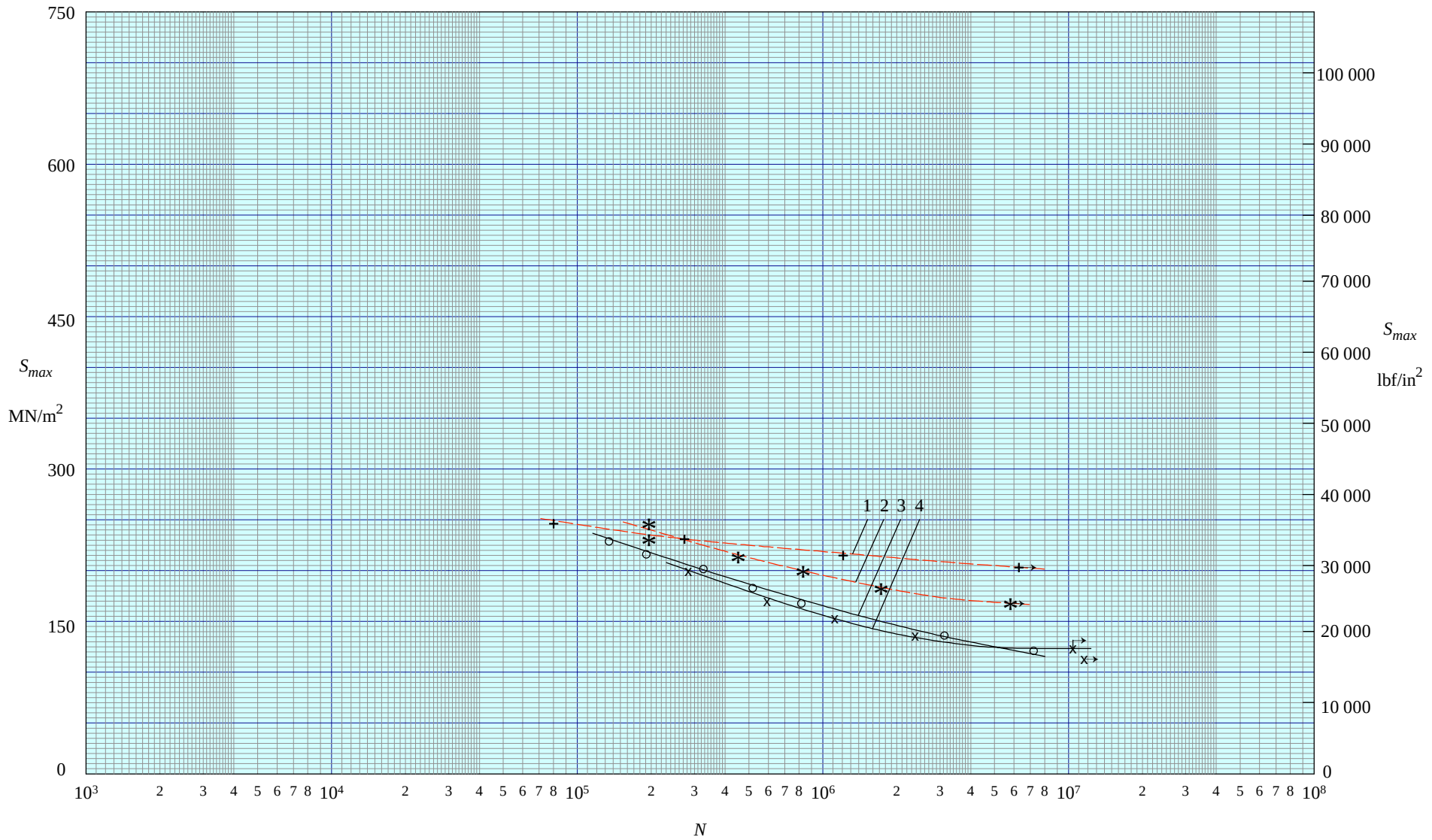


FIGURE 1 THE EFFECT OF AIR AND SALT WATER ENVIRONMENTS ON THE FRETTING FATIGUE STRENGTH OF IMI 130



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TABLE 6.2

|                                                |          |                                                        |                     |                     |                                     |                    |                          |  |
|------------------------------------------------|----------|--------------------------------------------------------|---------------------|---------------------|-------------------------------------|--------------------|--------------------------|--|
| <b>Material Specimen Fretting pad</b>          |          | IMI 230 (TA 22) (EN 2521)<br>IMI 230 (TA 22) (EN 2521) |                     |                     | <b>Table 6.2</b><br><b>Figure 2</b> |                    |                          |  |
| <b>Composition</b>                             |          |                                                        |                     |                     |                                     |                    |                          |  |
| <b>Nominal</b>                                 |          | Ti–2.5Cu                                               |                     |                     |                                     |                    |                          |  |
| <b>Actual</b>                                  |          | Not given                                              |                     |                     |                                     |                    |                          |  |
| <b>Heat treatment</b>                          |          | Not given                                              |                     |                     |                                     |                    |                          |  |
| $f_p$ MN/m <sup>2</sup> (lbf/in <sup>2</sup> ) |          | Not given                                              |                     |                     |                                     |                    |                          |  |
| $f_t$ MN/m <sup>2</sup> (lbf/in <sup>2</sup> ) |          | 578 (83 830)                                           |                     |                     |                                     |                    |                          |  |
| <b>Type of Loading</b>                         |          | Rotating bending                                       |                     |                     |                                     |                    |                          |  |
| <b>Material Form</b>                           |          | 9.5 mm (0.374 in) rod                                  |                     |                     |                                     |                    |                          |  |
| <i>Curve number and symbol</i>                 | <i>R</i> | <i>Freq.</i>                                           | <i>Pad pressure</i> |                     | <i>Surface treatment</i>            | <i>Environment</i> | <i>Derivation Number</i> |  |
|                                                |          | Hz                                                     | MPa                 | lbf/in <sup>2</sup> |                                     |                    |                          |  |
| 1 +                                            | –1       | 25                                                     | –                   | –                   | None                                | Laboratory air     | 2                        |  |
| 2 *                                            | –1       | 25                                                     | –                   | –                   | None                                | 1% NaCl solution   | 2                        |  |
| 3 ○                                            | –1       | 25                                                     | 62.5                | 9065                | None                                | Laboratory air     | 2                        |  |
| 4 ×                                            | –1       | 25                                                     | 62.5                | 9065                | None                                | 1% NaCl solution   | 2                        |  |



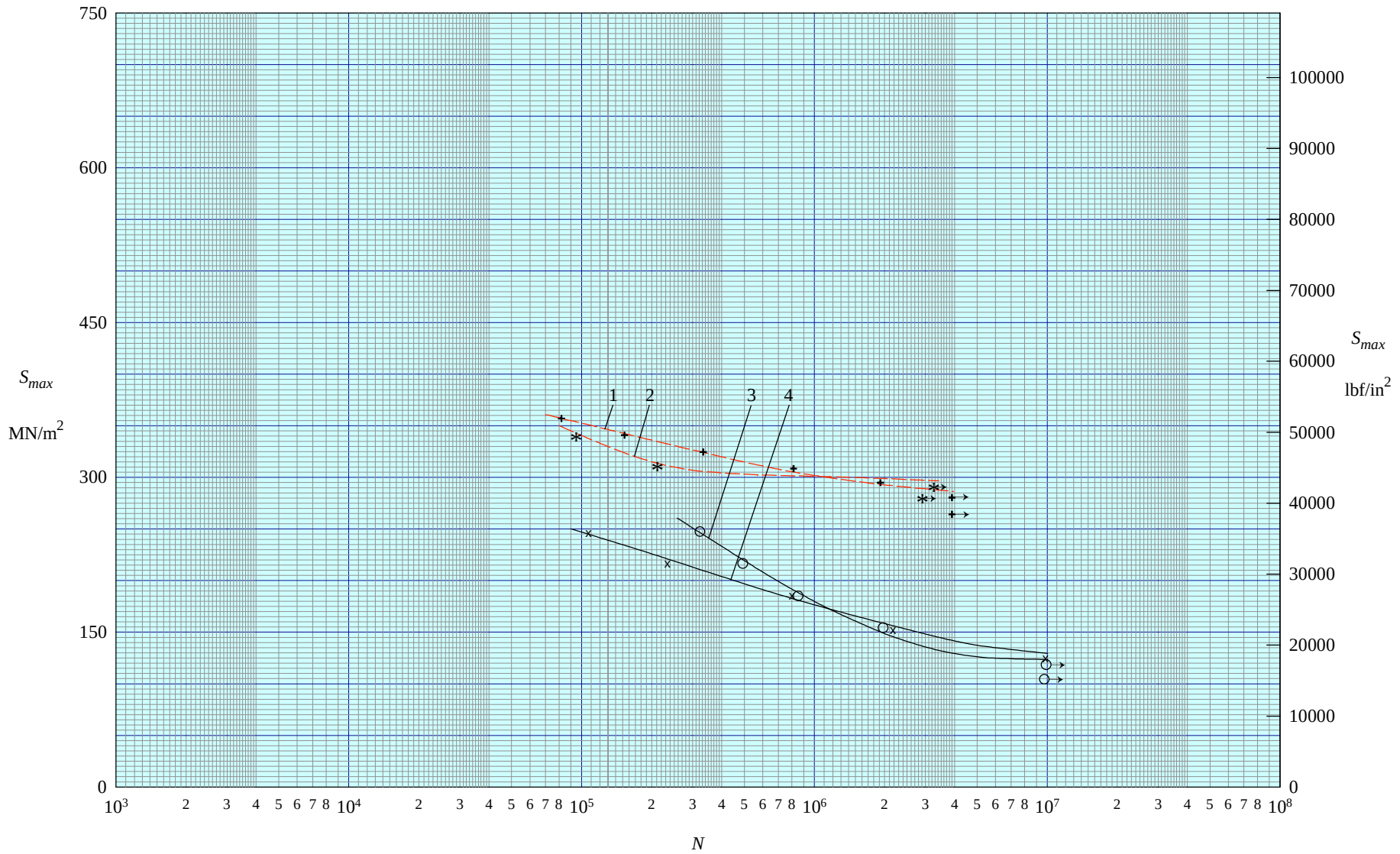


FIGURE 2 THE EFFECT OF AIR AND SALT WATER ENVIRONMENTS ON THE FRETTING FATIGUE STRENGTH OF IMI 230



TABLE 6.3

|                                                       |          |              |                                                            |                     |                                                     |                    |                                     |  |
|-------------------------------------------------------|----------|--------------|------------------------------------------------------------|---------------------|-----------------------------------------------------|--------------------|-------------------------------------|--|
| <b>Material Specimen</b><br><b>Fretting pad</b>       |          |              | IMI 230 (TA 21) (EN 2528)<br>IMI 230 (TA 21) (EN 2528)     |                     |                                                     |                    | <b>Table 6.3</b><br><b>Figure 3</b> |  |
| <b>Composition</b><br><b>Nominal</b><br><b>Actual</b> |          |              | Ti–2.5Cu–0.02Fe                                            |                     |                                                     |                    |                                     |  |
| <b>Heat treatment</b>                                 |          |              | Cold rolled, annealed 790°C (1450°F), descaled and pickled |                     |                                                     |                    |                                     |  |
| $f_p$ MN/m <sup>2</sup> (lbf/in <sup>2</sup> )        |          |              | 493 (71 460)                                               |                     |                                                     |                    |                                     |  |
| $f_t$ MN/m <sup>2</sup> (lbf/in <sup>2</sup> )        |          |              | 565 (81 980)                                               |                     |                                                     |                    |                                     |  |
| <b>Type of Loading</b>                                |          |              | Axial, zero to tension                                     |                     |                                                     |                    |                                     |  |
| <b>Material Form</b>                                  |          |              | 1.5 mm (0.06 in) sheet                                     |                     |                                                     |                    |                                     |  |
| <i>Curve number and symbol</i>                        | <i>R</i> | <i>Freq.</i> | <i>Pad pressure</i>                                        |                     | <i>Surface treatment</i>                            | <i>Environment</i> | <i>Derivation Number</i>            |  |
|                                                       |          | Hz           | MPa                                                        | lbf/in <sup>2</sup> |                                                     |                    |                                     |  |
| 1 +                                                   | 0        | 65           | –                                                          | –                   | None                                                | Laboratory air     | 1                                   |  |
| 2 *                                                   | 0        | 65           | 93                                                         | 13 440              | None                                                | Laboratory air     | 1                                   |  |
| 3 ○                                                   | 0        | 65           | 93                                                         | 13 440              | Watervliet anodised                                 | Laboratory air     | 1                                   |  |
| 4 ×                                                   | 0        | 65           | 93                                                         | 13 440              | Hard anodised                                       | Laboratory air     | 1                                   |  |
| 5 △                                                   | 0        | 65           | 93                                                         | 13 440              | Hard anodised + epoxy resin + MoS <sub>2</sub>      | Laboratory air     | 1                                   |  |
| 6 □                                                   | 0        | 65           | 93                                                         | 13 440              | Vapour blasted + polyimide resin + MoS <sub>2</sub> | Laboratory air     | 1                                   |  |
| 7 ◇                                                   | 0        | 65           | 93                                                         | 13 440              | Vapour blasted + polyimide resin + BN               | Laboratory air     | 1                                   |  |

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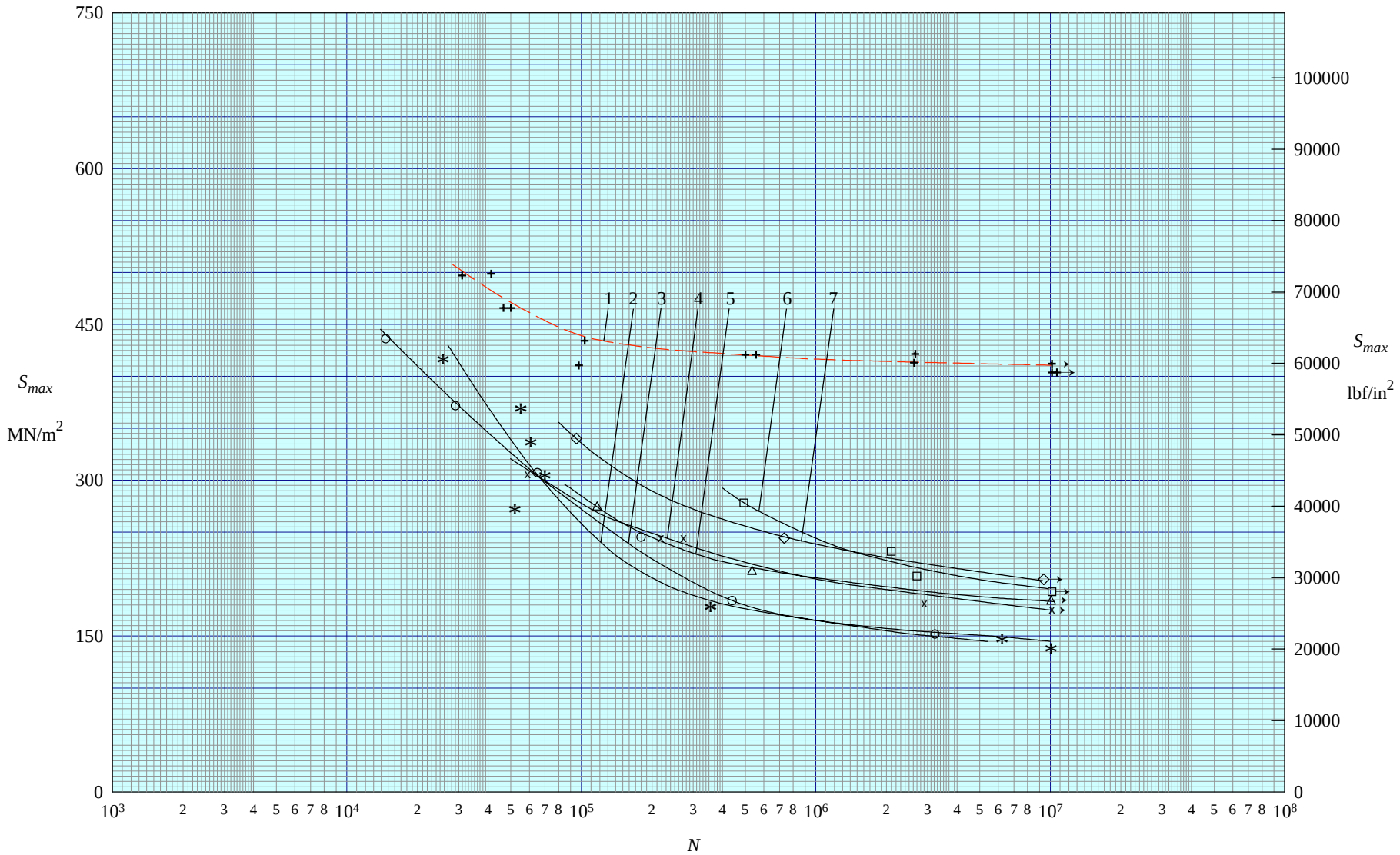


FIGURE 3 THE EFFECT OF VARIOUS SURFACE TREATMENTS ON THE FRETTING FATIGUE STRENGTH OF IMI 230



TABLE 6.4

| <b>Material Specimen</b>                       |          |              | IMI 230 (TA 21) (EN 2528)                                  |                     |                                                                                               |                    | <b>Table 6.4</b><br><b>Figure 4</b> |  |  |
|------------------------------------------------|----------|--------------|------------------------------------------------------------|---------------------|-----------------------------------------------------------------------------------------------|--------------------|-------------------------------------|--|--|
| <b>Fretting pad</b>                            |          |              | IMI 230 (TA 21) (EN 2528)                                  |                     |                                                                                               |                    |                                     |  |  |
| <b>Composition</b>                             |          |              |                                                            |                     |                                                                                               |                    |                                     |  |  |
| <b>Nominal</b>                                 |          |              |                                                            |                     |                                                                                               |                    |                                     |  |  |
| <b>Actual</b>                                  |          |              | Ti–2.5Cu–0.02Fe                                            |                     |                                                                                               |                    |                                     |  |  |
| <b>Heat treatment</b>                          |          |              | Cold rolled, annealed 790°C (1450°F), descaled and pickled |                     |                                                                                               |                    |                                     |  |  |
| $f_p$ MN/m <sup>2</sup> (lbf/in <sup>2</sup> ) |          |              | 493 (71 460)                                               |                     |                                                                                               |                    |                                     |  |  |
| $f_t$ MN/m <sup>2</sup> (lbf/in <sup>2</sup> ) |          |              | 565 (81 980)                                               |                     |                                                                                               |                    |                                     |  |  |
| <b>Type of Loading</b>                         |          |              | Axial, zero to tension                                     |                     |                                                                                               |                    |                                     |  |  |
| <b>Material Form</b>                           |          |              | 1.5 mm (0.06 in) sheet                                     |                     |                                                                                               |                    |                                     |  |  |
| <i>Curve number and symbol</i>                 | <i>R</i> | <i>Freq.</i> | <i>Pad pressure</i>                                        |                     | <i>Surface treatment</i>                                                                      | <i>Environment</i> | <i>Derivation Number</i>            |  |  |
|                                                |          | Hz           | MPa                                                        | lbf/in <sup>2</sup> |                                                                                               |                    |                                     |  |  |
| 1 +                                            | 0        | 65           | –                                                          | –                   | None                                                                                          | Laboratory air     | 1                                   |  |  |
| 2 *                                            | 0        | 65           | 93                                                         | 13 440              | None                                                                                          | Laboratory air     | 1                                   |  |  |
| 3 ○                                            | 0        | 65           | 93                                                         | 13 440              | Isocyanate cured epoxy + MoS <sub>2</sub>                                                     | Laboratory air     | 1                                   |  |  |
| 4 ×                                            | 0        | 65           | 93                                                         | 13 440              | Isocyanate cured epoxy resin + graphite                                                       | Laboratory air     | 1                                   |  |  |
| 5 △                                            | 0        | 65           | 93                                                         | 13 440              | Isocyanate cured epoxy resin + BN                                                             | Laboratory air     | 1                                   |  |  |
| 6                                              | 0        | 65           | –                                                          | –                   | Electroplated chromium: diffusion bonded + shot peened (Almen A8–12) + electroplated chromium | Laboratory air     | 6                                   |  |  |
| 7                                              | 0        | 65           | 93                                                         | 13 440              | Electroplated chromium: diffusion bonded + shot peened (Almen A8–12) + electroplated chromium | Laboratory air     | 6                                   |  |  |

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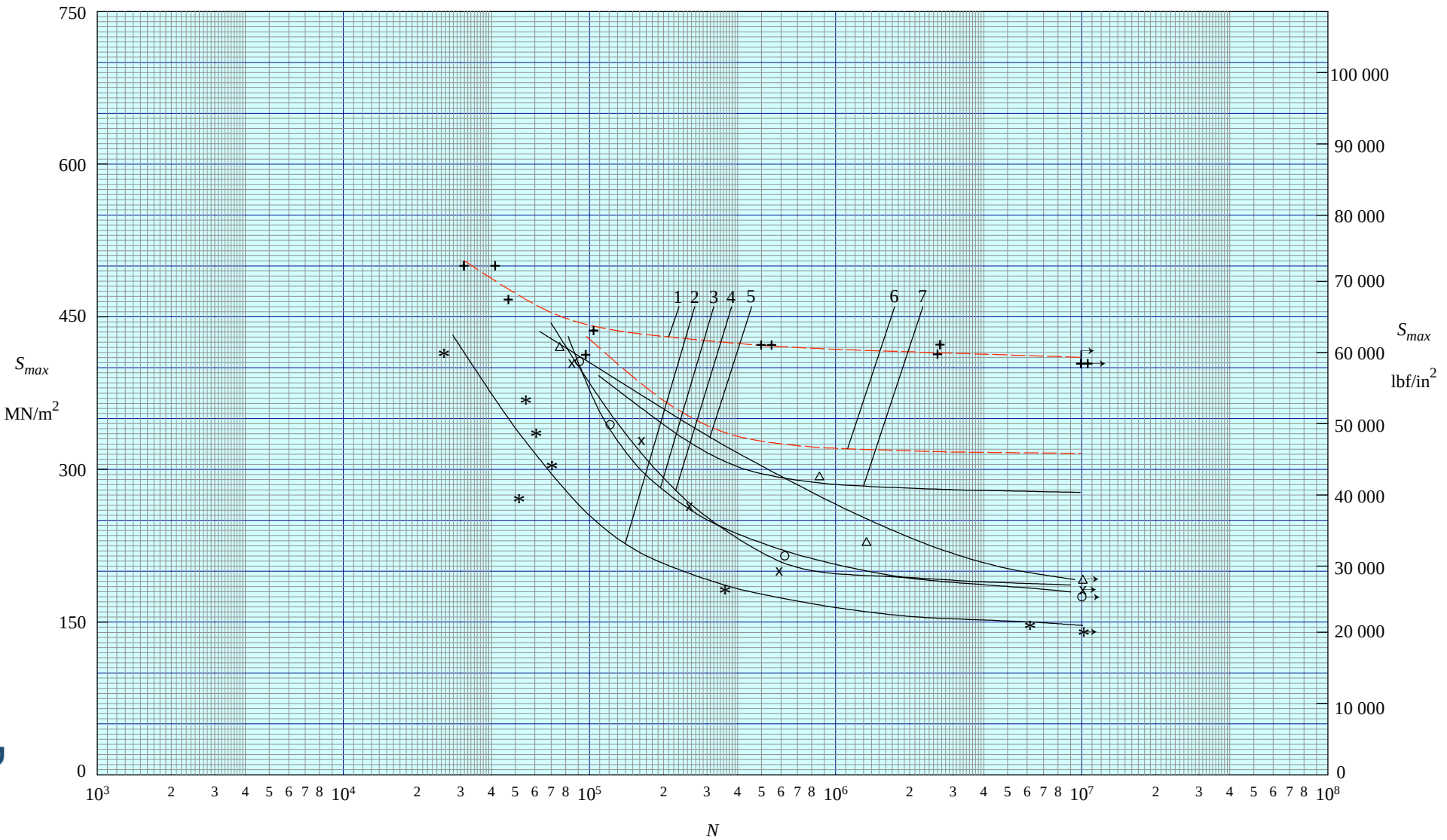


FIGURE 4 THE EFFECT OF VARIOUS SURFACE TREATMENTS ON THE FRETTING FATIGUE STRENGTH OF IMI 230