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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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Stress Corrosion.
Practical Considerations (7)

by

G. B. Evans (8)

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1968 (10)

AGARD Report 570

Stress Corrosion - Practical Considerations

by G.B. Evans

"In this report, on pages 14 and 16 in particular, reference is made to the long term stability of materials treated to the T73 condition. It is now believed that the work referred to has not substantiated the suggestion made and the references to the instability is not justified and should be deleted. It is regretted if this statement has caused any inconvenience."

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AGARD Report 570

"Stress Corrosion - Practical Considerations"

Addenda and Errata

A number of amendments are required to the printed version of this Report in order to bring it more nearly into line with the most recent information and to correct errors which occurred during its production. The following amendments should be made:-

1. p.1, 12th paragraph. The word "not" should be deleted so that the paragraph reads "There was support for..."
2. p.2, final paragraph. The first sentence should read "One thing would seem clear".
3. p.4, 12th paragraph. Final sentence should read "If this is so then can one expect .... crack?"
4. p.5, Third line. The word "defection" should read "defective".
5. p.5, Final paragraph of Section 3. The words "transcrystallic" and "intercrystallic" should read "transcrystalline" and "intercrystalline".
6. p.6. The sentence starting on the 11th line should read "It is interesting that the stress corrosion failures..."
7. p.8, 9th paragraph. The first sentence should read "There is no doubt that large numbers of ...".
8. p.14, 6th paragraph to be deleted. See also correction slip herewith.
9. p.15. 1st word of 8th line should read "that".
10. p.16,5th line from bottom. Insert the words "in-service" after the word "materials".
11. p.18 Section 10.2.1., point (b). Insert the word "almost" before "certainly be exposed".
12. p.19, 8th line. Delete the word "temperature" and replace by "tensile".
13. p.22, 2nd paragraph of Section 11.3. Final sentence should read "It is the random nature in complex shapes.."
14. p.23, 3rd paragraph of Section 11.6. Delete the word "Is" at the start of the third sentence and replace by "It".
15. p.33 - 44.
    Appendix III should not have been included in this part of the Report. Pages 33 - 44 should be removed by cutting approximately 1 cm. from the bound edge.

    The reference to this Appendix should be deleted from the Index of p.iv and from the second line of p.11

AGARD REPORT 570

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

STRESS CORROSION

PART I - PRACTICAL CONSIDERATIONS

by

G.B.EVANS, FIM, F Weld Inst, FRAeS, C Eng.

Hawker Siddeley Aviation Limited,
Hatfield, Herts.
England.

This report was produced at the request of the Structures and Materials Panel of AGARD-NATO

SUMMARY

The report is a study of the present position on stress corrosion from the point of view of designers and constructors, ~~made during 1968 for the AGARD Structures and Materials Panel~~. The survey is divided into two parts: Part I is a collection of information and views obtained by the author by written questionnaire and visits and is intended for designers and production personnel in the aerospace industry. Part II contains a summary of areas within the field of stress corrosion to which further research could be usefully directed, in addition to the pure research currently proceeding on the behaviour of surfaces and the various mechanisms of cracking involved. ~~This part is intended for the AGARD Structures and Materials Panel, and will not be available for general distribution.~~

GMH

RESUME

Le présent Rapport est une étude de l'état actuel des connaissances concernant la corrosion sous tension du point de vue des ingenieurs d'études et des constructeurs effectuée au cours de 1968 pour le compte de la Commission "Structures et Matériaux" de l'AGARD. L'étude se divise en deux parties. La Partie I comporte les informations et les observations recueillies par l'auteur à l'aide d'un questionnaire écrit et au cours de visites, et est destinée aux ingenieurs d'études et au personnel de production de l'industrie aérospatiale. La Partie II contient un résumé des sujets, dans le domaine de la corrosion sous tension, auxquels il serait peut-être utile d'orienter de nouvelles études, en dehors des recherches pures actuellement en cours sur le comportement des surfaces et les différents mécanismes de fissuration concernés. Cette Partie est destinée à la Commission "Structures et Matériaux" et ne fera pas l'objet d'une diffusion générale.

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CONTENTS

STRESS CORROSION

PART I - PRACTICAL CONSIDERATIONS

G.B.EVANS, FIM, F Weld Inst, FRAeS, CEng

1. INTRODUCTION

This report describes the study of the design and production aspects of stress corrosion within the North Atlantic Treaty Organization made under the auspices of the Stress Corrosion Panel of the AGARD Stuctures and Materials Panel. The study has involved some 20 visits to material suppliers' factories, accessory factories, main constructors' works and the research laboratories of Governments and Industry in Europe and North America and a written survey involving some 70 questionnaires to others not visited.

2. STRESS CORROSION - THE PROBLEM

The first and obvious problem is to define what stress corrosion is and to form the basis of the survey.

It would seem that it means different things to different people. Only one feature appears to be consistent; early failure by stress corrosion must be the result of an applied steady stress.

It is evident that some sort of environment is then necessary, but the mechanism by which failure occurs probably varies, depending on the environment and the material being discussed.

There would seem little doubt that, although serious cracking of copper alloys and caustic embrittlement of steel in riveted boilers has been known and discussed for many years, the term "stress corrosion" always seems to bring to the minds of members of the aerospace industry the failure of the aluminium alloys in the common water damp environments in which space vehicles operate.

Admittedly, of more recent years the brittle failure of stainless steels, high tensile steels and, even more recently, titanium alloys is beginning to be appreciated. Nevertheless, to all but the specialist, the term stress corrosion always brings aerospace engineers to the aluminium alloys.

Thus, following the lead of the papers at the Amsterdam Symposium and the Two-Day Symposium in Turin, stress corrosion, is here taken to mean the early brittle failure of material due to a permanently applied static stress considerably below its normal tensile strength when in its ordinary operating environment, as used in the aerospace vehicle.

This clearly means that, as nearly any material can be made to fail in a wide variety of unusual environments,as for instance, in the chemical industry, some specialist situations will not be discussed.

The paper will be restricted to those environments thought to be of interest to the majority. Sufficient to say that anyone who feels that a part is likely to be stressed in an unusual environment should make a specialist research of the very extensive literature and then conduct tests directly representative of the situation.

It is thought similarly that, while this general approach will not be fully acceptable to the specialist, who will wish to be specific in attempting to discuss the matter in its many details, this is not the purpose of the study, which has been guided towards providing a picture of the problem for the aerospace engineer.

There are many papers and books published on the detailed mechanism and some of those which have been particularly drawn to the attention of the author are referred to at the end of this report.

There was not support for this view from the engineers visited, who seemed to think there were reams of literature which discussed the mechanism of stress corrosion but few ways suggested to the practical engineer of preventing it or reducing the risk of failure from it.

This approach, of course, tends to sidestep distinctions between stress corrosion and hydrogen embrittlement and does give rise to the question "What is meant by permanent static stress"?

Almost all operational loads are cyclic, even if they occur for the full duration of the flight. Thus there must be a fringe area where the applied stress is not absolutely steady or may be repeated at very infrequent intervals.

It is suggested that, at the present state of knowledge and bearing in mind the accent required of this report, the proper procedure here is to ignore the difficult interface between failure defined as stress corrosion and failure assessed as being due to corrosion fatigue at high stress levels and infrequent applications of stress.

One aspect needs little emphasis; the failure takes place in a brittle manner.

3. THE IDENTIFICATION OF STRESS CORROSION FAILURES

Before the behaviour of materials can be assessed it must be tested in the laboratory and in operational service. While it is fairly obvious when a part has broken in service before it was intended, it is much more difficult to establish by what mode the failure occured and how it correlated with the original test results. Thus, although improvements of behaviour can be brought about by quite minor alterations of heat treatment or alloying when determined by certain laboratory tests, it is less certain that a corresponding improvement of service behaviour will result.

Similarly it is essential to correctly analyse service failures, not only to enable designers to correct the specific problems but also to ensure that the appropriate accent is placed upon the background research for the future.

This must be especially true of difficult modes of failure associated with environment, such as stress corrosion, corrosion fatigue and others. Methods of test for stress corrosion are being studied by Dr Piper[1].

The present survey has tried to take into account some aspects of the operational considerations in view of their importance to the overall assessment of the problem.

Several problems come to mind.

(i) Firstly, what does a stress corrosion failure look like?

It would seem, as stated in the previous section, that the mechanism of delayed failure is very different for different materials, and perhaps in different environments too.

In recent years electron micrograph fractography has been used. A selection of typical fractographs is given in a valuable handbook[2] , which was found in many industrial and research laboratories. Nevertheless most workers said that the identification of failures due to static stress in a corrosion environment was not positive. Bearing in mind that the electron microscope has only been in widespread use for some five years, it does not seem certain that all the failures, that were the primary cause of the accent upon stress corrosion in fact failed from this case.

From the survey, the author does not believe that then or now correct identification is being made. A significant contribution would be made by a study of this in greater depth.

(ii) The actual equipment available and the standard of the staff varies from place to place and so does the organization for examining service failure. In some countries all failures are returned to government establishments where considerable expertise is developed. In others the firm responsible for the aircraft type conducts the metallurgical examination. In this area particularly the standard varies considerably.

(iii) It is suggested that from this source arises the positive assertion that stress corrosion failures are primarily due to inherent residual stress.

If fracture faces more nearly represent the fractures seen on laboratory test specimens when examined at low power, then stress corrosion is diagnosed.

Nevertheless it has been asserted by two laboratories of some distinction that their diagnoses based on such appearances have been found, by more modern assessment, to be incorrect.

(iv) The problem is made more difficult when one examines the positions in terms of

(a) crack initiation,

(b) crack propagation.

It would seem, from the survey of failures discussed later, that fatigue is the more usual cause of failure in aircraft, although it is by no means certain whether this means the initiation and propagation or only one or the other.

One thing is clear. The failures can be divided into different classes, as follows:

(a) Initiated by corrosion fatigue.

(b) Initiated by stress corrosion.

(c) Propagated by corrosion fatigue.

(d) Propagated by stress corrosion.

In the case of corrosion fatigue it seems to be fairly widely agreed that initiation can be prevented by various surface treatments and that the serious aspect of environment can be nullified by suitable paints.

The aspects of crack propagation under dynamic stress conditions are then studied to ensure the reliability of the structures by designing to critical crack lengths and introducing crack stoppers, so far as relatively large thin structures are concerned (Safe Life Philosophy). Not as much work has yet been done to establish the behaviour in thick specimens.

With stress corrosion most of the background work on material behaviour in the past has been done on unnotched specimens and often without very serious consideration of the surface preparation. Very wide scatter of test results caused the method to fall into disrepute and the pre-cracked specimen came into use; this is a method more amenable to mathematical comparison, yet information on the nature of the stress corrosion crack initiation would seem vital.

We now know that cracks can propagate very rapidly in some thick materials under a static stress when in a suitable environment and these materials may have a very small critical length at a given stress level, as for some high strength aluminium alloys, but this does not necessarily imply that those same cracks were initiated in this manner, nor is this proved by the fact that the part may have a very high internal stress. Had the crack not been initiated, the poor propagation characteristics of the material would not have mattered.

As discussed later, there has not been so much activity in the study of stress corrosion prevention by surface treatments as of corrosion fatigue prevention. Such tests as became available to the author during the survey suggest that the common methods of protection, as generally applied, are not likely to prevent stress corrosion failure, yet all the replies to the questionnaires suggest that the industry believes that they do. There must be a background reason for this apparent conflict. One solution could be that corrosion fatigue is a more likely cause of crack initiation than was previously thought, another that all the failures diagnosed have not been due to stress corrosion and, finally, that for some reason the protection used in practice is generally of more value than tests suggest.

Let us now turn to the question of crack propagation. Does the case of continued static stress arise in practice in most aerospace vehicles? Almost everyone says yes and points to the hoop tension stresses in pressure vessels - hydraulic accumulators and the like. But is this right? Most parts of an aerospace vehicle in service are subjected to changes of stress, either a few quite large ones or, as with much hydraulic equipment, a small ripple upon a constant hoop stress.

Very many of the reported service failures have arisen at flash lines in forgings. From the survey this is the predominant ascribed position. Research by Hawker Siddeley Aviation has shown that, when a very sharp notch exists, the fatigue behaviour is as if each ripple were a full 0 - max cycle.

In another test case[3] by the same Company it was found that a crack may continue to propagate under corrosion fatigue conditions in a 90 tons/in^2 steel beyond the zone which, upon examination of the fracture, would have been assumed due to fatigue before the critical condition was achieved and total failure occurred.

Further to this, during a visit Dr Steigerwald, of TRW, Cleveland, USA, showed, by way of interest, the significant effect upon failure rate of a high frequency low stress vibration imposed on material being creep-tested near the extremes of its ability to reasonably withstand the static stress.

Could such a load system have a significant effect upon a material being stressed in a corrosive environment and near its limits?

There seems every chance that a very large number of service failures have not been, and are not being, properly investigated or diagnosed and this is a matter of very great importance if our researches are to be properly directed and our specific modifications to aircraft are to be of the benefit expected.

To illustrate this, a case within the author's experience may be worth repeating.

Many years ago a company in Europe used castings of the aluminium - 10% magnesium type because of their high strength and ductility. These were used in considerable quantity and for Class I applications.

Several service failures occurred, mostly at lugs or from holes in lugs. The cracks were intercrystalline and gave the appearance of being due to stress corrosion.

Work published by Fokker many years before indicated that wrought versions of a similar alloy had given trouble in the form of rivets, due to stress corrosion. It was also observed that the material was not stable and that it continued to harden, presumably by precipitation, at the operating temperatures, over a period of 5 - 10 years. The static mechanical properties at first increased but as time continued they decreased again while, throughout this period, the ductility as determined by tensile elongation gradually decreased from the original 12 - 15% to about 5 - 8%.

Separate tests indicated that this behaviour was accelerated by heating the material to about 70°C, the so-called tropicalisation, and when this was done the stress corrosion resistance, originally very good indeed, fell to a much lower order. Consequently the alloy fell into disrepute and in many cases it use was withdrawn.

The material chosen to take its place was called the Al 4% Cu alloy which, when fully precipitated, has similar mechanical properties although very much lower ductility. In a very large number of instances this material was used to directly replace the Al 10% Mg and, so far as is known, the history of trouble has not been repeated. The interesting thing about this situation is that the Al 4% Cu alloy was used to replace the Al 10% Mg in either of the two available forms as seemed expedient, i.e. in the solution-treated and naturally-aged condition or in the solution-treated and precipitated condition.

Stress corrosion tests indicated that, depending on the manufacturing conditions, the solution-treated material had extremely good stress corrosion resistance equal to the Al 10% Mg but that the precipitated material showed very poor behaviour under the same conditions - much worse than the Al 10% Mg when in its worst condition.

Further, the same type of tests indicated that the stress corrosion resistance of the solution-treated and naturally-aged material was also sensitised by tropicalisation, such that its stress corrosion resistance also became much less than the worst case with Al 10% Mg but without the accompanying loss of static mechanical properties.

Despite the fact that the tests were made on plain specimens, the difference in behaviour was so marked that it could not be attributed to scatter.

It would seem that in the USA the Al 10% Mg alloy has also fallen into disrepute as a casting alloy, although the precise reasons are not clear.

Research conducted since this time has led to a more stable and stress-corrosion-resistant version of the Al 10% Mg alloy, with similar attractive static mechanical properties, but conservatism tends to prohibit its introduction.

Thus for many years the designer has been denied the use of an apparently attractive alloy and the reason would seem far from certain.

More recently a number of service failures have been associated with local surface stress caused by grinding high tensile or case-hardened steel. Brittle cracks not unlike stress corrosion cracks can be induced in subsequent treatment or in service. Research into methods of inspection to find the local influence of grinding indicates how very small the indications may be and how difficult it is to detect them. How many people studying fractured parts in the past have conducted their examination of the surface in a sufficiently detailed manner to be able to assert confidently that they had identified all failures due to surface defects from grinding or machining?

It would seem that there can be no certain rules which enable positive diagnosis in all cases. With the aluminium alloys it is said that all stress corrosion failures are intercrystalline and fatigue failures are transcrystalline. This general statement would seem to run into difficulty when considering steel, stainless steels and perhaps titanium.

As already noted the precise mechanism of crack initiation and propagation may be different with different metals and circumstances, yet still fall within the broad band of stress corrosion so far as this paper is concerned. Consequently it would be surprising if metallographic study and fractography were, at this stage, to provide positive identification. Nevertheless, by interchange of ideas and study the experience can be correlated and more reliable diagnosis will result.

At the time of writing the aircraft industry is much exercised over the apparent stress corrosion problems with titanium alloys. Tests in sea water using a pre-cracked specimen have produced rapid failure. Nevertheless a detailed study by one research laboratory seems to suggest that under these conditions the crack does not propagate from the tip of the fatigue pre-crack, nor in the same direction, but is initiated some distance ahead of it.

In another laboratory, studying the behaviour of the maraging steels, the same general features were observed although detailed examination of the crack growth had not been made to allow the observer to note just where the crack started. It seems very probable that, in this case also, failure was initiated ahead of the pre-crack. From this the researchers have concluded that failure is caused by hydrogen or chlorine ions being transmitted to a zone of peak stress, which occurs ahead of the pre-crack tip in the three-point notch bend specimen. If this is so then one can expect a crack propagated in this way to be different from a direct stress corrosion crack.

Dr Steigerwald has shown that the environment that will promote stress corrosion is not always obvious either. In his paper he clearly demonstrated the effect of Viton sealants in contact with hot titanium alloys. Bearing in mind the care with which cutting oils for use with ultra high tensile steel are selected, especially with respect to sulphur, it would be valuable to know whether, under certain conditions, the widely used polysulphide sealants could promote failures.

It is hoped that the importance of very detailed study on the apparently simplest of service failures has been adequately emphasised:

(i) Parts must be returned to the laboratory for examination without any cleaning up or preparation in any way.

(ii) The fullest possible information must be given on the circumstances surrounding the failure.

(iii) A detailed review of the design of the part should be made.

(iv) A visual study of the defection part should be made and techniques such as micro-analysis should be used to determine the nature of any material on or around it.

(v) From this, consideration should be given to how and at what stage the fracture can be examined and a metallurgical examination should be made of the crack.

(vi) Care must be exercised at this stage to look for residual stress within the part or at the surface near the crack. Both the fracture faces and sections taken through the cracks can tell the story. Often the final decisions as to the most likely mode of failure will come from the elimination of methods which did not cause failure rather than by positive identification of a stress corrosion mechanism.

(vii) Unfortunately these studies are time-consuming and a repair of the defect is usually pressing, with the result that there is a tendency in this sort of work to make snap decisions. Of course, this may well have to be done and a "fix" produced for the aircraft. But in the interests of subsequent design knowledge it would be wise to complete the details on sometimes almost routine investigation, despite the pressure of work which always exists, and not to leave the matter because a decision for action has to be taken. In many ways it would seem that the art of service failure investigation is neglected; few, if any, textbooks are available to guide the student and, of necessity, experience is often limited. It is hoped that the volume on fractography being prepared for AGARD by Mr Ryder, an acknowledged expert on service failure investigation, will go some way towards this and will provide references to other sources of atlases of fractographs etc. which will be helpful.

(viii) In general Dr U.R.Evans[5] and Dr P.T.Gillied[6] indicate that single sharp cracks, transcrystalline in nature, are likely to be dry fatigue. Multiple cracks, transcrystalline and often blunted, are likely to be corrosion fatigue. Branching intergranular cracks are likely to be stress corrosion. Instances of partially intercrystalline fatigue cracks have been reported and there is much difference of opinion. Of course, it could be, that, depending on the stress programme, cracks are partly corrosion fatigue and partly stress corrosion.

Fractography is relatively positive in most cases with respect to fatigue, showing small steps, each step being a stress cycle. The absence of such steps, when coupled with intercrystalline failure does not of course guarantee that failure was by stress corrosion, but it points in that direction. When dealing with an unfamiliar alloy or environment, it is obviously wise to refer to published tests which define the form of fracture encountered by the material in question, in as similar an environment as possible.

The apparently different forms of crack formation would seem to suggest that different mechanisms are involved for corrosive fatigue and stress corrosion, despite the constant coupling together of these two modes in much of the published literature. This similarly raises the question of the use of a cracked specimen with a transcrystallic crack as a starter for an intercrystallic failure, and what happens during the delayed static fracture initiation period?

4. THE CAUSE OF STRESS CORROSION FAILURES FROM THE DESIGNER'S VIEWPOINT

It is clear from the survey that most companies have had stress corrosion failures and that these have occurred with all metals and alloys.

So far as aircraft are concerned, most people referred to aluminium alloys. Very few seem to have problems with steel and indeed many hold the view that steels below 90 tons/in^2 are immune to failure by stress corrosion. One person reported a failure by stress corrosion in magnesium and two or three reported failures in titanium, but only in special environments related to the halogen content.

It is therefore fairly clear that, whatever inferences are drawn in this section, must be firmly related to the aluminium alloys.

The predominant concern of those who replied to the enquiries was the failure of forgings, and in particular die forgings, in the short transverse direction or flash line. This is a little at variance with the author's personal experience, where parts made from extrusions, thick bar and heavy plate have also been involved; admittedly fewer cases have occurred in materials of these forms.

Inherent or built-in stress has been stated to be the cause, as noted earlier, although replies to questions have been insufficiently detailed to enable an exact assessment to be made. It seems that one cannot really single out a particular alloy as being the cause of trouble. Taking this into account, and bearing in mind the relative behviour of the aluminium alloys when subjected to stress corrosion testing, as far as present tests allow comparison, the reason why the Al Zinc types 7075 T6 and 7079 T6 are said to have given so much trouble in the USA could be their preponderance of use, based on their attractive static tensile strength.

In the UK there were many problems with this type of alloy also, but these do not seem to have reached such serious proportions on aircraft that had boiling water quench treatment; this treatment has not been used as widely in the USA in the past.

It would appear that there were only three areas of use which have led to stress corrosion failures from operational stresses, at least so far as the survey shows.

These are

(i) Hydraulic components, parts machined from bar or forgings and which have been subjected to prolonged internal pressure, accumulators etc.

(ii) Aluminium alloy bolts. Failures have occurred around the heads of countersunk bolts, presumably due to poor fits.

(iii) Large parts of rockets, which are subject to high static loads.

Among the reasons why so few parts have been reported as failing by stress corrosion due to service loads could be:

(i) Crack propagation by stress corrosion mechanism has not been recognised in the service failures.

(ii) The aerospace vehicle is mainly subjected to dynamic loading.

It is interesting that no stress corrosion failures which have been reported in this survey have been from high residual or built-in stresses which have been sufficient to propagate the cracks to a large size, if not to completely penetrate the section. Wet fracture toughness tests might suggest that service load would have been sufficient to develop cracks, however initiated, in some cases. One can only conclude that they have not been recognised.

Alternatively, perhaps nearly all crack propagation in aircraft structures service loads is by a fatigue mechanism. One cannot help but ask if this might not mean that many of the troubles reported previously as being due to stress corrosion were of fatigue initiation also (see the previous remarks concerning flash lines).

In trying to relate this experience to the high tensile steels and titanium it would seem that most of the delayed failures of the former have been associated with hydrogen embrittlement in one form or another, so far as titanium is concerned, except for very special environment no failures have been reported in service.

Very little work seems to have been done on large pieces of high strength steel forgings to ascertain the residual stress pattern, but it is understood that this is now being rectified. One thing will be obvious: the problems of machining high tensile steel are so considerable that there is a natural tendency to remove as little material as possible after final heat treatment and this further contributes to a favourable stress situation. Finally experience has shown, presumably from the fatigue viewpoint, that it is desirable to shot-peen with high strength fittings and this is almost universally done today. It could be therefore that, although the stress corrosion resistance of these steels is usually low, circumstances have automatically caused favourable techniques to be applied.

The situation regarding titanium may well be similar. Relatively few die forgings have been made, and the nature of the material has so far precluded its use for the large round objects that caused so much trouble with the aluminium alloys. Secondly, most of the titanium alloys in use today are not subjected to a heat treatment that is likely to include significant inherent residual stress.

It is appropriate at this stage to refer to the point made by a few people that jointing compounds give rise to high residual assembly stress if improperly used. This seems to originate from the widespread use of the polysulphides as jointing and sealing compounds and the concern that the joint will be assembled after the sealant has cured.

From all points of view this is a practice which should be frowned upon. Joints that are assembled with a thick layer of inter-fay sealant are never tight and torque-tightened bolts relax as the cured material creeps. Consequently it seems unlikely that stress corrosion failures will be induced because of the relaxation. Certainly joints made in this way will show poor fatigue behaviour.

In the present state of knowledge the position seems to be as follows:

(i) Few stress corrosion failures have arisen from service loads.

(ii) Few stress corrosion failures have occurred with low alloy steel.

(iii) Some have been associated with stainless steel of all sorts.

(iv) None have occurred with titanium as used in airframes or engines.

(v) Almost all such failures have been said to be due to inherent or built-in residual stress.

(vi) Almost every sort of aluminium alloy has given trouble, yet different constructors have quite different experience with a given alloy. Some countries or companies believe a particular aluminium alloy is unacceptable, yet recommend the use of an alloy which is unacceptable to another constructor or country.

It seems that it is not so much what alloy is chosen as how it is used.

5. THE INFLUENCE OF CORROSION PROTECTION

Although corrosion protection comes last in the manufacturing scheme of things, there would seem justification to dwell upon it at this point for reasons that will unfold.

In reply to the survey, without exception, everyone thought that the protective treatment played a significant part in the operational stress corrosion behaviour of the part. Once again, this must be considered in the light that most people reported their experience to be with aluminium alloys; it seemed from the replies that by protection most people meant paint. Further, probably because of the advent of more advanced hydraulic fluids etc., most people are currently using epoxide primers.

Three features stand out from the test work on paint and the stress corrosion of aluminium alloys:

(i) The inhibitors in most paint systems today are chromates and all paint systems are permeable.

(ii) The general use of chromates does not inhibit stress corrosion failure and may promote it, depending perhaps on their effect upon the PH of the solutions and surface potential at the metal interface. This is shown by the use of chromates to reduce surface corrosion in stress corrosion tests.

(iii) Of the relatively few paint systems tested, none seems to have improved the stress corrosion life of the part.

In the same way it appears to be generally agreed from laboratory experience that the anodising of the aluminium alloys is no use in improving the stress corrosion resistance.

It is interesting that the attitude shown by the survey supports the view that aircraft constructors, at least, believe that the prevention of crack initiation has an important part to play in maintaining service life and that ways and means of achieving this should be studied.

In the main, steel parts have been cadmium plated and painted. Most static delayed failures that have been reported seem to have been ascribed to hydrogen embrittlement, the embrittlement developing from the corrosion at the point where there has been failure of the corrosion protection.

Bearing in mind that galvanic action has been shown to prevent or arrest crack propagation under stress corrosion conditions, there seems justification for assuming that, because of the different properties involved, protective methods are effective with steel.

It will be recalled that, although so far as is known the method has not been put into practice, the application of a zinc coating by metal spray has been effective in preventing stress corrosion with aluminium alloys.

Considerable work has been done with steels in corrosion fatigue tests and this suggests that not only the electropotential but the presence of oxygen in the corroding solution play an important part in failure rate. Similarly chromates are said to inhibit corrosion fatigue better than di-chromates, and some metallic coatings are said to be much better than others, although considerable variation of results exists through the literature.

Copper plate is said to have an adverse effect on steel, zinc to have a good effect and better than cadmium. Most paints, when complete, were beneficial to some degree. So far this degree of detail does not seem to have been studied with respect to stress corrosion.

The effect of various surface treatments is given by D.O.Sproul et al.[7]. Their work shows that, in general, paint coatings were more effective on the copper type high strength alloys than on the zinc magnesium containing series. Paint, such as standard zinc chromate primer, was effective providing it was undamaged, with the suggestion that epoxy and polyurethane paints were more likely to be damaged. It is almost certain that these last two materials would not leach the inhibitor.

Metallised coatings gave good protection, even to the extent of protecting at a scratch ,in the coating. Nevertheless the disadvantages of such sprayed coatings, such as their tendency to "spall", is emphasised.

The report suggests that electro-plated zinc would be very beneficial where corrosion environments were not severe and a final paint coating is especially beneficial in safeguarding the zinc.

The zinc-rich paint tested in this series did not perform well, although the authors point out that other types are available which have not been tested.

Epoxy paints, especially strontium chromate epoxy primer, afforded protection particularly upon the copper bearing alloy type, but it seems that this was a barrier coat only and were inaffective once mechanical damage occurred.

An important point made was that, when tests were done on different specimen types, so that the paint system was applied before or after stressing, very poor results were obtained when the paint was applied before stressing, even though no cracks or surface damage could be observed when the stress was first applied.

Thus one might expect that, with properly painted components as commonly used today in areas where physical damage is not too great a risk, painting would protect parts with high internal stress, but would probably be less effective when unfavourable assembly stresses were involved, because most parts are primed before assembly. Anodising did not protect against stress corrosion.

Rather less work has been done with high strength steels; indeed, most of the more recent testing on titanium and steel has been with pre-cracked specimens, so features of the protection can hardly be studied to the same extent. Nevertheless, work is going on in many laboratories to try to evaluate the behaviour at the surface in a corroding medium. It has been shown that the surface potential and the pH of the solution make important differences to crack initiation behaviour. Herr Rozenkranz, of Germany, has done work on this aspect with aluminium alloys and has also emphasised the importance of the pH.

Several people have studied the effect of different test solutions and have shown that chromates do not inhibit stress corrosion failures when used in concentrations sufficient to inhibit surface corrosion. Others are now coming to the view that inhibitors or agents at the surface can be useful in delaying the onset of failure.

6. THE INFLUENCE OF SURFACE STRESSES

The primary treatment that seems to be universally accepted as a barrier to stress corrosion is surface comcompression. This has been positively established by tests on aluminium alloy, has been widely practised with high tensile steels in service, with apparent benefit, but does not seem to have been widely studied or used with titanium alloys.

The practice may have a twofold effect:

(i) To convert the surface stresses from tension to compression.

(ii) To render normally stress-free surfaces very compressive.

Whether the benefit in preventing crack initiation is due to the compressive residual stress or to the effect the working has on the metallurgical structure is not clear. It is, of course, important that we should know. Shot-peening is expensive and very difficult to apply to complicated shapes. It is difficult, if not impossible, accurately to judge the amount of peening that has been done and it is virtually impossible to inspect the part to prove that adequate treatment has been given.

Other forms of blasting also seem effective, i.e. vacu blasting with alumina particles etc. It is probable that the surface stresses can be similar for either method but the effective depth of the treatment is much less with finer, lighter particles. It has been suggested that the greater depth of the peended layer is important, as corrosion is less likely to penetrate it.

Much more work is needed surrounding the use of surface blasting methods. They have been found to be so useful and effective that it would be nice to be certain that no features existed which could reduce the confidence currently shown in the method.

Some of the following points may be pertinent:

(i) Peening must lead to a balancing residual tensile stress below the surface. Bearing in mind the behaviour described for crack propagation for titanium wet fracture toughness tests, could this lead to a condition where a crack would start in the interfacial zone? If so, can the action of peening be controlled to make a more acceptable gradient?

(ii) Does peening a part which already has a high internal stress aggravate the problem?

(iii) Is the depth of the disturbed layer critical?

(iv) When considering the fatigue behaviour, peening is usually beneficial under conditions that are represented by rotating bending tests. Peening is usually not beneficial when the specimens are tested in axial tension. Does the same apply to peening for stress corrosion prevention?

There is no doubt that large members of aluminium alloy aircraft parts are being finished by vacu blasting and such like treatments, before the application of protective finishes and this has proved remarkably effective in improving the service life. If the life is related largely to crack initiation, as it is believed to be in corrosion fatigue, then it is the immediate surface layers that are of significance.

Proof of this could lead to great economy of production and yet, at the same time, make the treatment much more effective in that almost all surfaces could be so treated without practical difficulty. The difficulty of distortion due to the treatment would also be much reduced.

To summarise this section, it is suggested that research has shown that surface treatment and surface protection can be very important. Before selecting surface coating it would seem that they should be proved by stress corrosion tests, as not all coatings are effective, even though they may afford excellent protection from surface corrosion.

The principles of inhibition by "chromates", however applied, may very well not reduce stress corrosion unless the concentrations are higher than have hitherto been considered necessary.

Disturbance of the surface, as by a blasting treatment, would seem to be very effective and the protection of this surface layer then becomes an ordinary corrosion protection job. It is convenient to consider the surface behaviour as being due to the residual compressive stress induced, but this may not be the fundamental reason and research should be continued to identify the mechanism. This could lead to more certain and cheaper application than at present.

7. RESIDUAL STRESSES

From the visits and answers to questionnaires there seems little doubt in anyone's mind that most stress corrosion failures recognised as such are primarily due to inherent residual stresses or, to a lesser extent, subsequently built-in stresses from assembly. If it were not for these stresses, the problem of stress corrosion would virtually cease to exist.

7.1 Inherent Residual Stress

Most inherent residual stresses arise either from heat treatment, which induces a thermal gradient within the component, or mechanical work, which leaves an unfavourable residual stress.

There appears to be widespread recognition in many quarters that inherent stresses arising from the rapid quenching of aluminium alloys is a major source of trouble and that much care must be exercised to ensure that the compressive skin is not removed, to expose the layers in tension beneath. Several people seemed to think this so elementary that they were surprised that the author enquired about it.

Nevertheless only selected alloys are controlled with respect to the quench by many people and surprisingly few have procedural systems that ensure that machining sequences are adequately carried out. Knowledge of the problem does not reduce failures. The knowledge must be put into action, and in too many places this still seems not to be the case and is often the reason for failure.

It is apparent that many of the alloys are sensitive to the quench rate with respect to the static mechanical properties and this is coupled with a widespread belief, not necessarily substantiated, that although the slower quench will reduce the internal stress the material will be rendered more susceptible to inter-granular corrosion as a result. Recent work suggests that these generalisations are by no means always true. At least, if the stresses are not grossly unfavourable the material will not be subjected to stress corrosion failure and corrosion protection can do much to look after the other aspects.

Another solution to the problem is to relieve the internal stress produced by quenching by subsequent mechanical stretching, or compressing. Unless the component is simple in shape this can be very expensive, but it is a very useful way of reducing trouble.

There are three points to consider:

(i) On large pieces very careful control is needed of cold compression to ensure that a non-uniform, and at points severely tensile, residual stress is not left at the surface, or indeed that a gradient is not induced.

(ii) The amount of cold work must, on the other hand, be limited or the mechanical properties of the material may be adversely affected with respect to fracture toughness, dynamic crack propagation rate etc.

(iii) A third way of reducing the internal stress level is to apply a stress-relieving treatment after quenching. In the case of the aluminium alloys this brings us into the field of the complex treatments developed for 7075 Al alloy, for instance. Such treatments not only reduce the residual stress but also modify the structure and stress corrosion resistance of the material as well.

The simple approach, is, of course, well known to prevent the season cracking of brass. The crazing of Perspex and numerous other plastic affords similar evidence.

Thus by means readily at our disposal we can, without undue expense, provide materials - almost any material - in a condition of residual stress that is likely to be below the threshold stress of that material. It needs considerable organisation to ensure that company instructions and purchasing, sub-contract, and shop procedures, are arranged so that this state of favourable stress is always achieved. A very high proportion of people who actually handle and process the part at its many stages of manufacture are not aware of the significance of, or the reason for, the methods. Also, personnel constantly change.

Thus, to be successful, company organisation must be such that the requirements are met, almost independently of the personnel involved. This area is the cause of most trouble. The responsible materials specialists and designers are usually well aware of the problem and its solution, but often the company does not disseminate the knowledge and failures result.

7.2 Residual Stress from Manufacturing Operations

Under this title is included stress arising from forming, bending and straightening, as well as tensile surface stresses arising from machining, grinding etc.

7.2.1 Stresses from Forming

Many parts of significant thickness are deliberately formed into another shape. Many of these are complex operations and leave complex stresses, not all unfavourable, of course. The simplest case is that of bending. When a piece of metal is bent a residual tensile stress is left in the inner surface. It so happens that very many aluminium alloy parts are so shaped that bending for shaping rarely takes place in the short transverse direction. Nevertheless, it would seem to be asking for trouble to bend any high strength aluminium alloy parts in the fully heat-treated condition; yet this appears to be the practice in several countries. Upon occasions the operation becomes unavoidable. When this happens it is suggested that a full survey of residual stresses should be made to ensure that residual stresses of a tensile nature are below the threshold stress in *all* directions relative to the grain flow.

The problem of actually measuring residual stress is discussed in Section 8. Until this is resolved the matter can only be dealt with by attempting to manufacture to an acceptable standard of residual stress by the use of empirical rules which, while not accurate, can be a useful guide when based upon stress measurements from test samples. The real problem would seem to be that although as previously stated, the stress level recommended by some countries is low, say 10,000 lb/in^2, in the transverse direction, very little is done to see this is not exceeded. There are too many areas which can lead to trouble; these include bending to form sheet and plate and bending to correct distortion arising from previous manufacturing operations. A large number of parts that are bent are of plate form and, providing they are thin, then in aluminium alloys the danger from stress corrosion may not be too great. The influence of the residual stress upon the fatigue behaviour may well be quite a different matter. As soon as thick, long sections or shaped sections are involved, then the risk of induced stresses in transverse and short transverse directions of grain flow increases, even with simple bends. Normally residual stresses from these sources do not exceed the proof stress; so, with materials which are heat treatable, the lower the strength at the time of working the better. The application of stretch-forming techniques overcomes most of the worries. Usually, for practical reasons, the softer condition is an advantage.

With steels less experiments has been done. Very high stresses may be induced but fortunately, for obvious reasons, the low alloy high strength steels are usually formed in a soft condition and heat-treated afterwards. This may well not be true with the austenitic stainless steels. Their sensitivity to cracking depends on their precise composition and the environment, but there is little doubt that everyone gets caught sometimes and there seems every justification for a stress-relieving operation after any forming whatsoever on class 1 parts.

The case for stress-relieving welded ducting etc., which frequently comes into question, is more difficult. The large, hot-air ducts used in any transports for the first stages of cabin or de-icing air etc. can be lethal if failure occurs. On the other hand, when fatigue tests are done on such ducts, early failure is usually related to examples of poor detail design, and annealing has not been shown to be of much value. This has therefore not forced the question of high temperature annealing large and difficult structures in the aerospace industry, as in some other mechanical and civil engineering projects. For the same reason very few companies anneal stainless steel hydraulic pipes after cold bending and, again, it is the precise shape at the bend (ovality) which is so important and tends to mask the residual stress problem. It would perhaps be wise to review this attitude with respect to residual stress, in deference to the risk of stress corrosion failure.

The position regarding titanium is not clear. The author's experience has only been related to parts that have been stress-relieved after forming, although not after welding. As stated earlier, very few straightforward service failures have occurred in a corrosion environment, yet tests show how dangerous the situation might be. Perhaps trouble has been avoided because the parts made of the metal are still treated as special and are given great attention by all concerned. Sufficient has been said to illustrate the importance of looking after manufacturing techniques of this sort. Fortunately all work of the type referred to is pre-planned; therefore it is not difficult to prepare simple but effective company rules to ensure that the process instructions which require the manufacturing operations to be carried out in the right sequence and in the appropriate heat treated conditions are implemented. *It will not happen* unless the instructions are simple and positive and ensure that any difficult forming problem is highlighted against the background of general work, so that measurements can be made to establish the stress patterns, if necessary, and the dangerous case can be corrected before the parts reach the final structure.

7.2.2 *Stress from Correction of Distortion*

This is the more difficult problem since parts are usually at an advanced stage of heat treatment and near final dimensions, and it is the more complex ones that give the most trouble. Correction of distortion will now lead to high local residual tensile stress unless great care is taken.

Secondly, none of the distortion is planned; consequently its correction cannot be legislated for in advance. Somehow the urge just to straighten the part on the press and carry on must be prevented. Once again, not much is written on stress corrosion, and not many examples published, but reference to any textbook on design and engineering draws attention to the serious influence residual stress can have on the fatigue behaviour. It does not need further evidence of their presence. Stress corrosion may occur, from this cause also, especially if the residual stress occurs across the transverse grain direction.

In the absence of a "residual stress meter" few companies have really tried to control the problem. If the distortion is spotted by an inspector, a wise man from the laboratory or design office goes to look, and all too frequently "uses his judgement" although, bearing in mind how small strains can result in high local stress, it is difficult to believe this helps to safeguard the situation. Of course it can prevent a hard bend made at a notch or, because of this study, perhaps it will cause parts to be returned to a lower heat treatment state when otherwise this would not have happened; but on the whole it is a rather doubtful system. One company has attempted to use a yardstick of actual measurement of the corrections needed, coupled with an empirical formula based on laboratory tests and measurements, to obtain at least a semblance of uniformity of action from part to part and factory to factory. If this is coupled with a feedback system to a stress engineer who has studied residual stress, the position is likely to be much improved. The risk of a bad case slipping through the system diminishes and at least some uniformity and control is achieved. A typical procedure sheet by that company is appended to this report to show what is being attempted. Of course this is not the final answer and some high stresses may still escape attention, but a very much improved standard is bound to result, if only from the general awareness of the problem.

7.2.3 *Methods of Correcting Distortion*

Three ways of correcting distortion need wider emphasis and study:

(i) *The correction of distortion by shot-peening*

This may be limited by the surface finish required; otherwise a remarkable degree of correction can be achieved by holding the part of a jig in the overbent, but not plastically deformed, corrected position and then peening the face originally on the inside of the curve.

(ii) *The correction of distortion by reverse bending*

This method has been reported by numerous workers but does not seem to be widely in use in the aircraft industry. It would seem worthy of more widespread consideration.

(iii) *Creep forming parts at, say, the precipitation temperature*

This needs considerable study, but may have useful applications.

Finally, if the main stress-relieving temperature of the material is not above the heat treatment condition of that material, then all is well. Straighten and stress-relieve, and this brings the problem once again in focus with the "season cracking of brass" situation that every engineer has studied at some time.

When considering any of these methods it is vital to appreciate that some materials may be inherently changed by such treatments, a further reason for ensuring that all cases are given very detailed consideration. For instance, the Al 5% of magnesium alloy tubing can be rendered less sensitive to stress corrosion by heating at 250°C for 24 hours. Small amounts of cold work applied after this treatment will render it sensitive again.

7.2.4 *Residual Surface Stresses from Machining*

As stated earlier, it is probable that a stress corrosion crack may be important in a dynamically loaded part simply because it can *promote* failure, even though the static stress is so local that the crack would not itself have led to failure. Harmful surface stresses are likely to be in this category.

The danger of cracking high tensile steels, case-hardened steels, etc. by grinding is well known. The next stage, the local high tensile residual stresses that have not cracked at the time, is less well appreciated. A full study of this has not yet been made, but already it is clear that careful etching procedures and very critical inspection, looking for the slightest variation of surface colour, shows up sufficient trouble points to justify the concern now expressed.

It seems very likely that machining by other methods may cause residual stresses in high strength steels also.

Similar surface marks, almost certainly associated with machining, have been observed on titanium parts, but the nature of any residual stresses which may have been associated with them has not been determined. It is normally said that, apart from grinding, the operations of machining, turning, milling etc. produce compressive surface residual stress unless negative rake tools have been employed.

Thus it would not be expected that aluminium alloys would have high damaging stresses from this source.

The prime trouble with the aluminium alloys, as used in the past, seems to have come from the exposure of unfavourable internal residual stress arising from quenching. However, a new situation is developing. There is widespread introduction of tape control machine tools which can remove a lot of metal from large pieces very quickly.

The influence of the cuts can be so great, if these are not carefully programmed, that the mechanical properties of very thin sections can be affected. Practical cases have arisen. Clearly there is always a risk of surface troubles, even under apparently harmless conditions.

7.2.5 *Residual Stress from Shearing*

In the past many people have had stress corrosion cracking develop at the edges of sheet etc. due to cold-shearing high strength aluminium alloys in the fully heat-treated condition. If the shears are not perfect the residual surface stresses can be high. Many companies now have instructions to prevent this happening.

7.3 Other Aspects of Machining

It is interesting that few of the papers and books on stress corrosion and the stress origins refer to direct surface stresses related to the operation of machining but only to the effects of exposure with stress already in the part. It is not unreasonable in a paper of this sort to draw attention to the well-known problems of surface stresses induced by machining operations in stress-corrosive-sensitive materials like the poly-methacrylate types. A study of the critical production requirements with such materials illustrates the value that control of the similar process with metals might have.

One other interesting effect of machining has been referred to by Professor R.W.Staehle[18]. When writing of Fe Cu Ni, alloys such as stainless steel, he reported a difference of behaviour with respect to stress corrosion, related to a difference of surface roughness, caused by machining or chemical pickling. Unlike the case for fatigue crack initiation, electro-polishing is said in this case to be of merit. Logan, however, reported that electro-polishing caused poor stress corrosion results with high tensile low alloy steels.

8. THE MEASUREMENT OF RESIDUAL STRESS

8.1 General

When discussing "Aircraft Corrosion Failures" by C.Bradley-Ward, Mr K.Cornfield of RCAF Materials Laboratory said, "I would like to comment that in *STRESS* corrosion the part played by stress is so large it should be spelled out in capitals". At the same time, in replying to a paper by Mr S.Goldberg called "Living with Stress Corrosion in Aircraft Design", Mr M.Berrington, of De Havilland Aircraft Company of Canada, asked the questions, "How do you control the many factors without running a laboratory test on any high strength part? How do you adequately control assembly and installation to minimise sustained residual surface stress?"

The answer would seem to be that at present, there is no method available. Therefore it is necessary to carry out laboratory tests as part of the initial test and approval system for components and assemblies. For vital parts this procedure is little different (and a good deal cheaper) from the present static and dynamic mechanical structural tests to demonstrate the integrity of the component with respect to its service life and applied stress. A good deal of this sort of work is, in fact, done by many companies, with respect to residual stresses from both quenching and forming operations. The methods do not always have to be highly sophisticated to be of immense value.

Any method and technique may be used for the approval of "first-offs" but the following are most readily available.

Measure the specimen, cut it apart, and then measure the change of shape and calculate the residual stress from the difference. This method will produce fairly accurate estimates of the hoop stress in thin tubes, or even in thick bars and sections. Thin rings are carefully cut from them. The rings are then measured with fine points, say ½ inch apart, carefully sectioned through the gauge length so measured, and the opening or closing obtained with a measuring microscope. Large pieces of metal can be gradually machined along one face, the distortion determined and the stress estimated. This is clearly not a method of great precision and it is difficult to use on complex parts. Nevertheless, it can provide a very useful guide indeed.

8.2 Strain Gauge Techniques

In principle, rosettes of strain gauges are applied at important or suspect positions on the surface of the part. Cuts are then made to relieve the stress and the relaxation is determined. Strain gauges can also provide a very good indication of the stress induced in assemblies, or models of the assemblies, by accurately determining the strain induced.

8.3 X-ray Refraction Method

This is a very refined method, more commonly undertaken by the physicist than the engineer. An X-ray beam is refracted by the atomic space lattice of the metal crystals and thus any differences of lattice form from the standard condition can be assessed and the elastic strain so determined can be converted to a stress. The method needs experience, as indeed do all the others, but it will provide a precise answer at a point in the specimen. It is therefore especially useful for determining surface stresses and gradients. It is fairly slow and costly and normally the apparatus will only hold small specimens.

8.4 *Control of Residual Stress*

It is not surprising that when different techniques are employed on the same specimen different results can be obtained, and a good deal of experience is needed in interpreting the most likely stress pattern. Unfortunately, these techniques are not non-destructive and are not suitable for *in situ* shop use. Thus, at present the only method of controlling the residual stress is as follows:

(i) *Material*

Check the sample or approval piece which has been made to a strict manufacturing schedule. Modify the manufacturing method until the residual stresses are acceptable and then ensure that every part is made exactly like the sample.

(ii) *Assembly*

Determine precisely the fits in assembly and check the induced stress if necessary.

(iii) *Correction of distortion*

Determine in advance the residual stress upon a series of samples and prepare empirical relationships to cover the correction that is likely to be required. Try to use methods such as shot-peening which do not leave residual tensile stresses.

(iv) *Induce favourable residual stress wherever possible*

For such processes as shot-peening, regularly treat the surface of samples and determine the distortion produced. (Almen Gauges).

8.5 Ultrasound and Residual Stress Determination

An entirely different approach is being made by an ultrasonic technique. The method is not yet fully developed as a production tool but may well be a big step forward in residual stress determination. A study of the method has been made by Dr R.L.Gaure[29]. His thesis provides a useful series of references to publications concerning the method. *"Product Engineering"*, Vol 30, 1959, contains an article "Acousto-elasticity" by R.W.Benson and V.J.Raelson, which provides a source of general information. "The Use of Ultrasonic Waves for Stress Determination", US Naval Research Laboratory Report 64-17, 1964, also provides further information. Such a method may well have the best chance of being developed into a "Shop Tool".

9. THE CHOICE OF MATERIAL

9.1 General

Almost any, if not every, material in use today can be made to fail by a delayed failure mechanism if a sufficiently high static surface stress is applied in an adverse environment. The problem is to know how the stress is applied, how to reproduce the application for test purposes and whether the service environment is detrimental or not.

The problem is so acute that nearly every country has set up committees attempting to produce "standard tests" for stress corrosion behaviour. Despite the enormous amount of test work carried out and published, no overall correlation is possible, because of all the variables involved, to enable materials to be placed in a genuine order of merit for design selection. Further, from the remarks made already in this survey, it is clear that apparently insignificant changes of material conditions can markedly affect the stress corrosion resistance. Equally, a review of the material behaviour in service does not give much aid in this respect. Nearly all the failures examined have resulted from lack of attention to features of design and production now known to be likely to cause trouble. The surface treatment, protective methods etc. that have been used differ very widely, and one man's successful choice is another man's downfall. This makes it seem unlikely that material choice can, or should, be considered to be the key to success and emphasises in a very positive way the importance of good design for production and a full engineering appreciation by production departments of the features involved. Thus, at this point it is not possible, from test data, to propose an order of merit for the common materials in use with any degree of confidence. Also, it would be a very lengthy task and a repetition of other reviews to survey all the papers published on the subject. Nevertheless, an attempt will be made to discuss a limited selection of the published data in the hope that it will at least provoke thought regarding some of the features of selection.

9.2 Aluminium Alloys

The most readily available and probably the most comparative data on stress corrosion of the aluminium alloys is presented in the various publications by ALCOA Limited. Their Technical Papers summarise the information in a practical form. A survey paper of the Defence Metals Information Centre, Battelle Memorial Institute, Columbus[11], also offers order of merit for the aluminium alloys.

These papers show that the choice must be associated with the manufactured form-forging, extrusion, plate - so that the component can be made with the least residual stress and the most favourably disposed grain flow. All the aluminium alloys are the most susceptible to stress corrosion in a plane normal to the short transverse direction of grain flow.

At first sight these comparisons show that the Al Zn Mg high strength alloys such as 7075 are very susceptible and so are the Al Cu Mg Si alloys 2024 and 2014; depending upon the precipitation condition, there would not seem to be real practical difference in behaviour. Thus 2024 T4 is, in fact, shown as slightly worse than 7075 T6.

Recent work has shown that different treatments, such as the use of different cooling rates, as well as different degrees of precipitation, as are provided by the various DTD series of alloys in the UK and T 73 in the USA, can radically alter the stress corrosion behaviour when subjected to the same test procedures. Unfortunately service experience is not extensive with these alloys in this condition.

Most of the de-sensitising treatments are associated with a loss of static mechanical properties, compared with the more conventional treatments, and much of the attraction of the alloys is lost.

It is clear that much more work will be done with all the aluminium alloys with respect to their heat treatment.

This accent on the influence of low temperature heat treatment and its significant effects in behaviour should not be lost when choosing the alloy and, in particular, the processing it will require. Low temperature stoving treatment, bonding for assembly etc. may easily upset an otherwise satisfactory alloy.

The other problem is that of long-term stability. Earlier in this paper reference was made to the precipitation and reduction of stress corrosion resistance of the Al Mg alloys such as BS L53 if tropicalised, i.e. heated to, say, 70°C for one month, as might occur in service. Work done by the author suggested that this would also significantly reduce the stress corrosion resistance of the Al Cu type alloys when they were in the solution-treated and naturally-aged condition, no matter in what form-casting, extrusion plate. With plate and extrusion a plane bend test was made in the short transverse grain directions only. Recent work has suggested that certain of the Al Zn Mg high strength alloys in the T 73 condition may be adversely affected by such treatments also.

The precise composition is of great significance also. This has been demonstrated by J.Fielding[15] for the DTD 5024 composition, and by BNF Research Association with the development of BS L53 to DTD 5018, to eliminate the problem already referred to. Also, as proposed by Polmear and discussed at the AGARD Turin Conference, silver additions to the Al Zn Mg alloy may be of assistance.

Despite the reference to the T 73 treatment and the possibility of instability, it must be remembered that it provides a component with very low inherent residual stress and thus might well serve its purpose even if tropicalisation sensitivity is eventually shown to exist.

It seems that the high strength 7075 T 6 or 7078 T 6 type alloys have been used the most extensively and head the list of troubles. The precipitated copper bearing alloys, such as 2014 and 2024 T 6, follow and 2014 and 2024 T 3 have given very little trouble. The static mechanical properties are, of course, widely different and this may give the key to the apparently different service behaviour, as compared with the test results. The materials with the highest proof stress are among those that give the most trouble in service. It might be expected that in general the residual stress from straightening, forming etc. would be most likely to be higher with high proof stress materials. This might not be true from the quenching operation, as the properties at the temperatures of the various intermediate heat treatment stages must be involved. However, in either alloy it is easy to introduce stresses well above the threshold stress in the short transverse direction, so this becomes of less significance with respect to selection in the case. The working stresses are higher with alloys of higher strength. In general the fracture toughness decreases as the strength goes up. The dynamic crack propagation rate increases as the strength increases.

Thus, from all these points of view, even if the stress corrosion resistance with respect to crack initiation were identical it could be expected that the material of small critical crack length would produce the most trouble in service, especially if associated with higher stress.

It is suggested that there is justification for the approach in that the same sort of experience has been observed with the high strength Al Mg Zn alloys when failures have been entirely due to fatigue initiation and propagation.

Thus it is clear that the key to selection should be to choose the material with the overall best stress corrosion resistance, assuming all other properties equal. Provided that arrangements are made to look after the residual or permanently applied static stresses in the relevant grain direction by the means readily available, it is suggested that the precise relative stress corrosion properties from current test should not be allowed to overrule the choice from other engineering viewpoints, especially crack propagation characteristics.

9.3 High Strength Steel

For obvious reasons it is not easy to obtain a true picture of failure from stress corrosion with high strength steel. Equally, there is always the problem of hydrogen embrittlement confusing the picture, a feature which does not seem to be as relevant to the behaviour of aluminium alloys. As noted by the original definition of the term "stress corrosion", the remark above refers to hydrogen occluded during processing and does not argue whether the stress corrosion is due to hydrogen from corrosion or some other mechanism.

It would seem that the situation is not very different from that for the aluminium alloys. As the strength increases, so the stress corrosion resistance decreases. As the strength is reduced, so the fracture toughness is increased. Failures in general seem to have arisen more from applied, i.e. operational or built-in stresses, than from inherent stress, so far as can be determined. Nevertheless it is suggested that, with the tempering temperatures of some standard steels as low as 200°C, not much stress relief is likely and this may well be an important factor in the future. Thus, even more than with aluminium alloys, early failure due to stress corrosion may well be more directly related to the strength of the material, in that service stresses are likely to be in keeping with the maximum static mechanical properties achievable.

The second problem that may have a bearing is that the fatigue behaviour of most steels is so much better, relative to the tensile strength, than for aluminium alloys. A good deal of research has been done and only a few of the papers can be referred to in this survey. Usually the use of very strong steels is so critical that every component is given very careful appraisal.

Recent work suggests that differences of composition can affect crack initiation rate. The panacea of keeping the steel to as low a tensile strength as possible seems to make the largest contribution to safety from all viewpoints and steels below 90 tons/in^2 tensile seem to be safe from the risk of stress corrosion. When working near the maximum tensile strength there is nevertheless justification for taking composition into account from the viewpoint of delay to crack initiation; but, when doing so, one must consider also the manufacturing process than can, or has to, be employed.

It is interesting that stainless steels in general do not provide satisfactory properties when treated to very high strengths, especially from the point of view of stress corrosion. The maraging type steels are still relatively new. Little aircraft experience has been gained and test results are to some extent conflicting.

Techniques such as aust-forming etc. would appear to provide benefit and should be considered for parts which are practicable at the present stage of development of the treatment.

In relation to steel, the stress corrosion work has mostly been in the form of the pre-cracked notched specimen. It is interesting that the wet strength is, to all practical purposes, very similar indeed for widely different compositions of steel; this is also the case with the aluminium alloys. It will be the appreciation of the side issues such as processing, crack initiation, behaviour etc. which will decide the choice, once the very poor steels have been eliminated and not many of these are likely to be offered today. It is also clear that the heat treatment may play an important part and very strict control is necessary to ensure that the selected steel is as consistently satisfactory as is hoped. A minor point to bear in mind is that the stress corrosion resistance of steels of the types just referred to decreases with increased temperature. The decrease is perhaps of the order of 10 times on time between 70^{o} and 160^{o}F for a given stress level.

9.4 High Alloy Austenitic Steel

A very great deal of research has been done into the behaviour of the austenitic stainless steels for use in engineering environments such as power plants, chemical plants etc. Very wide differences of stress corrosion behaviour can be shown for the different compositions when tested with strong chemical solutions. Probably the most important aspect of the stress corrosion behaviour of these types of steels to the airframe designer is the influence of cold-work. With most of the steels the resistance to stress corrosion increases with the application up to about 25% reduction and then, by cold-work, falls off rapidly when tested at 75% of the strength. Sea coast exposure tests on cold-worked austenitic steels at 90% of their proof strength did not promote any sort of failure within 452 days. Thus, bearing in mind the type of environment that can arise in aircraft or missiles, there may well be justification for annealing, or stress-relief annealing, fabricated aircraft parts which may have severe localised areas of cold-work. A few instances of failure in hydraulic tubes which are attributed to stress corrosion have recently been observed, Other matters may determine the steel choice such as weldability, heat resistance etc. For practical purposes the principles seem clear - stress relieve and, in most aircraft environments (not special chemical cases), little trouble should result. Stabilised steels are most likely to be used, however, for obvious reasons.

9.5 Precipitation-Hardening Steels

The strong steels, such as the AM 350 type, and others, seem to be as susceptible to stress corrosion cracking as their low alloy counterpart. The same story emerges. The heat treatment is critical in this case; the inclusion of a sub-zero treatment at -70^{o}C in the sequence at the appropriate place seems to be desirable.

9.6 Other Aspects of Steels

Today it is possible to have nominally the same steel but made in very different ways, i.e., air melted, vacuum melted, double vacuum re-melted etc. These methods produce cleaner steel and improve the mechanical properties in the short transverse direction and it should be emphasised that the behaviour of steel to stress corrosion is also related to the grain direction.

Very many people will make a case for the effect of non-metallic inclusions upon the steel's stress corrosion behaviour but, as before, the overall evidence to justify the difference of expense of manufacture from the stress corrosion viewpoint does not seem strong. The value of the improved techniques in improving properties such as fracture toughness and crack propagation rates in the transverse direction are very pronounced and therefore will play a predominant part in material choice for a given purpose and will reflect in no uncertain way upon the actual stress corrosion results in service.

9.7 Titanium Alloys

The stress corrosion work seems to have been mostly made with pre-cracked fracture toughness type specimens. These all show susceptibility of the material and its alloys and would not yet seem possible to rate the material in any positive order.

A review of the stress corrosion work was given by Mr Minkler at the Turin Conference. Some further collected results for the effect of salt water on bent strips and other methods are given by Logan[30]. Because of the widespread use of titanium for turbine engine blades, such work has been concentrated upon stress corrosion with "hot salt" as the environment. From the limited data available there would not seem to be the same general trend as with other materials mentioned.

Mr Minkler said that very few service failures could be attributed to airframe environment and this is confirmed by the survey. Eight failures were known between 1957 and 1966. Five of these were reported as associated with chlorides and in operating temperatures from 300°C to 816°C. Each of the main alloy systems was involved. The other three related to special fluids, methyl alcohol at 23°C, nitrogen peroxide at 40°C and chlorinated diphenol at 375°C. The methyl alcohol is perhaps of general interest and the failure was with 6 Al 4V. Bearing in mind the use of methyl alcohol in various forms for airframe purposes - de-icing, de-frosting etc. - it is clear that we should look at this carefully.

In Mr Minkler's paper no reference was made to the influence of de-greasing fluids such as trichlorethylene. Once again the trouble seems to have been related to heating parts de-greased in such fluids after they had been cold-worked.

It might be wise in the present state of knowledge to consider the choice of titanium carefully for exposed parts likely to get hot after such cleaning and maintenance procedures as are associated with brakes or hot-air systems. Perhaps care should be given to the use of paint strippers near such parts. This aspect has not been mentioned with respect to engines because, once assembled (a controlled operation), engines are not likely to be as affected as other parts by inadvertent contamination during normal day-to-day maintenance.

9.8 Magnesium Alloys

Although magnesium alloys are now generally out of favour for airframe designs, due to the poor corrosion resistance, this attitude may not be completely universal nor necessarily permanent. The questionnaire associated with this survey provoked the statement that one failure by stress corrosion was known. No others have come to light and tests in England seem to indicate that the cast materials are relatively immune. In the light of present knowledge it does not seem that stress corrosion behaviour need be taken into account when selecting one of the modern magnesium alloys.

9.9 Copper Alloys

Copper based alloys are generally used for electrical equipment, internal piping and, to a lesser degree, hydraulic piping for low pressure circuits and bushes for bearings. The incidence of failures is remarkably low, bearing in mind the significant stress corrosion susceptibility of some of the alloys. It seems that, with the techniques currently adapted, the choice of material does not have to depend on stress corrosion behaviour.

9.10 The General Attitude to the Choice of Material

It would seem, from the accounts of laboratory tests, that most of the engineering alloys currently available suffer considerably from environmental effects when stressed. Unfortunately this sensitivity appears to be influenced by the method of test. In general materials in thin sheet form will have less sensitivity than thick ones. Critical thicknesses are discuss by Dr Piper in the interim report published at the AGARD Lisbon meeting.

Thick materials can be made with low residual internal stresses and the material choice should take this into account. This will mean that design properties may have to be accepted at a lower strength than is possible in the interests of a heat treatment that keeps the residual stress low. This seems to be good counsel, no matter how resistant the alloy may appear to be from laboratory test work. Subsequent service, or a feature not taken into account, may give trouble later.

The case of the Al 10% Mg alloy was referred to in Section 3. The high strength Al Zn Mg alloys in the T 73 condition and the approximate Al 4% Cu alloys have all been shown to be affected by subsequent heating at low temperatures for long periods. The first and last of these two were certainly adversely affected with respect to stress corrosion. Yet the Al 4% Cu alloy in the solution-treated and naturally-aged condition has given excellent service. It could be that the T73 will also, as perhaps its main attribute is that it will afford parts of extremely low inherent stress. It is suggested that with alloys of this sort it would be unwise to take advantage of the presumed stress corrosion resistance by producing a design that could only be made with a high residual stress from bending. Low temperature, prolonged heating after cold-work might lead to increased sensitivity and the residual stress would still be present.

The next consideration is the question of fracture from some initiation. Clearly it is important to choose an alloy with the best crack propagation rate characteristics commensurate with the other required properties. This would not seem to be the prime criterion, just a wise precaution.

Consideration from these viewpoints, of some of the materials may be interesting.

(i) Almost everyone, in reply to the survey, pinpointed die forgings as being the most troublesome from a stress corrosion viewpoint.

(ii) 7079, 7075, and the equivalent alloys in other countries, feature in everyone's list of troublemakers,

(iii) Titanium alloys do not feature in any list of failures.

It would seem that 7079 and 7075 die forgings were mostly quenched in cold, or just warm, water and had high internal stress in almost every case. In Europe, where modifications to the alloy have allowed retention of properties even when boiling water quenching has been used, there has been much less trouble; yet, in either case, the alloys are very sensitive in the T6 condition on un-notched specimens in the short transverse direction. These aluminium alloys all have a fast crack-propagation behaviour.

The titanium alloys in general use in Europe have low or nil internal residual stress. They do not seem easily to initiate cracks from plane surfaces in common corrosion environments, yet they are very susceptible to water and, when wet, have very poor crack propagation characteristics, as shown by a pre-crack specimen in laboratory tests. This would lead one to believe that the inherent stress corrosion resistance can be quite bad, provided that the parts are of low internal stress; and it helps if the crack initiation time is very long. It also suggests that it is not pertinent to assume that all structures are "cracked". If they were, the titanium alloys should have been in serious trouble, yet this has not been the case.

There is little doubt that small changes of composition can make a considerable difference to the test behaviour but may not be as overriding as the other features mentioned.

9.11 Grain Size

The aluminium alloys all show a tendency to grow large crystals during the conventional manufacturing processes and it is clear that this has a bearing upon stress corrosion, as does the grain shape. Numerous cases have been published to show that a directional structure is better than an equiaxed one and the finer the crystal size the better, depending of course on the direction of the damaging stress. These broad statements are true for other properties, such as ductility and tensile strength, except for use in hot regions where creep becomes a consideration.

Thus a great deal can be done to improve the materials at our disposal by aiming at very fine grain sizes. Unfortunately this is very difficult to specify and inspect. Non-destructive test methods are really necessary, as for die forgings, extrusions and castings. The grain size tends to be related to shape, size, etc. and may only be present as a surface layer or may be present for much of the section.

The only way to have some measure of grain size control on components at present, on a production basis, seems to be to examine very thoroughly the first-off samples of the product throughout by destructive means, to freeze the manufacturing technique and then to examine the grain size at the surface at selected positions of the production components. Any change of grain size compared with the approval specimen would indicate a change of technique and justify further study of these particular components. Obviously the problem is less difficult with plate and extrusion than with parts made to shape. Some firms in Europe already control their incoming parts in this way and, although it appears a frightening prospect at first sight and does, of course, raise a few problems, it can soon be made a simple routine. Limited experience seems to show that the titanium alloys may well be sensitive to grain size also. By inference one would expect steels with very fine inherent austenitic grain size to be superior to coarse grain ones.

9.12 Directionality

The very significant difference of stress corrosion behaviour of the aluminium alloys in the three major directions of grain flow has so often been emphasised that it is only referred to in the study for completeness.

It would be true to say that, provided that the grain size and shape is correct, the aluminium alloys would not be classified as bad from a stress corrosion viewpoint if it were not for the poor, short, transverse grain characteristics. The same features appear to apply to steel, although such extensive stress corrosion testing has not been done to demonstrate the feature. The very poor ductility in the short transverse direction in even low strength steel has been known for many years, but it has been said in the past that titanium does not show this variation of properties with grain direction. It is suggested that, at the present state of knowledge, this should not be taken too literally, especially for the short transverse direction.

9.13 Review of Designer's Choice of Material

When choosing the material it is necessary to consider the form required, so that acceptably low residual stress can be obtained. In the author's opinion this is more important than intercrystalline susceptibility, as shown by laboratory tests.

If a slow rate of cooling is necessary to achieve the low inherent stress, this seems the safer, despite the fact that a high cooling rate is said to improve intercrystalline corrosion susceptibility. Next choose a material with the best toughness for the given job. The high strength materials with the proof and ultimate strengths close together may work very well in compression but, in the interests of integrity, use a tougher, and if necessary weaker, material for parts subjected to tensile loading. If possible, after this select the alloy which shows the best corrosion resistance. This is usually so critical, however, that at this time it is not likely to show much benefit if all else is ignored.

Next, design so that high applied stresses are not normal to the short transverse direction. This means that the form of the material must be very carefully considered and specified on the drawing. A change of form from the optimum should not be accepted.

As die forgings seem to be the source of so much trouble, seriously consider the applied hoop stress from service operation before using them for pressure vessels. This applies to any material. The next most likely trouble will be at lugs. Use forgings with stepped die parting lines so that the flash line is not at the critical point when the lug is drilled out.

Finally, choose the manufacturer and method that will give you the most favourable crystal structure and press for the finest possible grain size.

It is not intended to give lists of merit for materials. It is apparent that almost any common structural material will fail in one of the possible environments, as shown by tests, and service experience has shown that most have done so, somewhere or another. It is also evident that the precise nature of the tests has an influence upon the result and as yet no standard test has come into use. This after all, is the basis of the survey and subsequent evaluation work being conducted by Dr Piper for AGARD. Consequently no sure correlation is yet available. It is recommended that the extremely useful comparative collected data published by ALCOA will form a guide on stress corrosion for aluminium alloys, but must be monitored by thoughts about the other properties of the alloys considered.

No similar data are known to the author for high strength steels and titanium alloys and the reader is referred to the suggestions for further reading in Appendix I. These will, in turn, refer to further sources of information.

10. *OTHER DESIGN CONSIDERATIONS*

10.1 General

There are numerous other features which designers can utilise or consider to the benefit of the integrity of the component, apart from the material selection quoted in the previous section.

It is widely stated in the literature, and has been reiterated in these notes already, that the most important method of keeping stress corrosion failures to a minimum, in the light of present knowledge, is to eliminate the residual static stress. It cannot be too strongly emphasised that the two sources of stress are inherent tensile stress, mostly from quenching and secondly from assembly. Strangely, stresses due to forming are rarely as strongly emphasised, but these should be given serious thought also. All these aspects can be very strongly influenced by the skill of the designer. He must look much more at the methods at his disposal and the problems of the production department. It is not adequate to design a part with extreme skill and accuracy so far as the applied service stresses are concerned and ignore other production aspects.

10.2 Selection of Form and the Associated Features

At present the problem of internal residual stress from quenching has been considered from the viewpoint of the aluminium alloys. Most of the titanium used in production quantities has been in the annealed condition and consequently has been stress-relieved at any time. The techniques about to be discussed have had to be applied to steel for other reasons.

10.2.1 Die forgings

Close-to-form die forgings are economical with aluminium and titanium alloys. Until recently the aluminium alloys could not be stress-relieved after quenching and, although cold compression is possible, it is costly and not yet in wide use, thus, subject to the use of a stress-relieving treatment such as T 73 or other forms of prolonged ageing, the design should make provision for a proper sequence of machining, heat treatment and machining, so that the beneficial compressed layer is not removed or penetrated.

Two aspects are necessary to control this economically:

(a) Some guidance as to the section which may be fully heat-treated before machining.

(b) Control by drawing of the amount that can be removed after quenching. Most companies seem to consider 0.04 in satisfactory for this, but others feel that this is too small for large parts. If it is too small for large parts, then they should not be made to these rules, i.e. form, as tensile stresses will certainly be exposed.

Point (a) is always open for discussion. The safest way is to rough machine everything before solution treatment. Some companies have found that the small section forgings are not likely to give trouble and use a rule for design as follows:

'Forging to be machined in the annealed condition:

(i) Forgings with a cross-section in which the distance from the centre to the nearest points of the external surface is 1.25 in or more must be supplied and machined in the annealed condition if either of the following conditions is relevant:

The metal removal on any face will exceed 12½% of the depth of the cross-section being machined.

Any boring or drilling is required in cross-section over the specified minimum.

(ii) Drawings must cover three stages of manufacture and allocate a number for the part at each stage".

This compromise is certainly a help to production costs and has not led to failures.

The titanium forgings at present in use have low residual internal stress; consequently these precautions are not necessary from this viewpoint. Attention is drawn to surface contamination from heat treatment, however.

Most steel parts are fully machined all over at present and the strongest steels are machined as far as possible in the soft condition, for reasons of machining economy rather than considerations of residual stress. It is strongly suggested that the question of residual stress in very high temperature steels needs very careful thought when tempering temperatures are only around 200°C

10.2.2 *Hand Forgings*

The problem is very much simpler with hand forgings in that, as the shapes are not complex, the aluminium alloys can be cold-compressed after solution treatment. So far this is not necessary with titanium or steel. Another advantage with hand forgings, is that they do not have flash lines, but the grain flow in general may not be as parallel to the stress pattern as with die forgings.

One advantage of this method is that the machanical properties are not sacrificed, as may be the case with hot quenched alloys.

The main problem with cold-compression and hand forgings lies in the control of the overlap of the anvil for compression. The work can only be compressed in small "bites" and it is quite possible to leave unfavourable stresses. The cold-compression techniques for a given piece must therefore be as critically developed, leading to an approved sample in the same manner as for the forging itself, and the supervision must be equally as strict, to ensure that every piece is like the approved sample.

10.3 Extrusion, Bar and Plate

Heavy sections of extrusion bar and plate in aluminium alloy can be controlled-stretched after solution treatment. This process does not eliminate the residual stresses but reduces them to an acceptable level. This is a specialist field and need not be considered by the designer, except that components must be so designed that they can be machined from the stretched part and have an acceptable grain flow relative to the stress patterns. As shown by the literature, materials made in this way are just as susceptible to stress corrosion in the short transverse direction as die forgings.

It is the forming of thick sections which must therefore be given due attention at the design stage. A section of bar or plate will have just as unfavourable an internal residual stress as a die forging of the same direction if it is not stretched after solution treatment. This is not yet a matter of concern with the titanium alloys, but soon could be with new alloys and methods, and each development must be watched with care.

10.4 Castings

Castings are not usually of heavy sections and are rarely machined all over. Consequently the risk of exposing tensile stress from heavy machining is less likely. Naturally the design must be looked at from the viewpoint of high internal stress, owing to the complexity of shape that may be required.

10.5 General Considerations

Other very important features have to accommodated if the design is to be successful. It has been shown that two protective measures can be successfuly applied to reduce the incidence of stress corrosion.

(a) Surface compressed stressing, as by a blasting technique.

(b) The application of a protective coating.

Both these requirements benefit from simplicity of shape.

Bores, re-entrant angles and complex shapes in general become almost impossible to blast properly in a uniform controlled manner and, although (a) is the more difficult, despite the ingenuity with which angle nozzles have been used, sprayed metal, electro-plate and organic paint coatings are often patchy and of doubtful value at inaccessible positions. It is therefore vital to design with the final protection in mind.

10.6 Limits and Fits

A good many failures of the aluminium alloys have resulted from assembly stresses. It is easy with the heavy, stiff sections in use today to induce a high residual tension, when bolting the structures together, as the result of quite small strains.

Thus, it is wise to add up the tolerances permissible within the assembly and ensure that, when all are adverse, too high a strain is not applied somewhere along the line of joints and especially in the short transverse grain direction.

The damage due to stresses induced by accident or deliberately, due to interference for bolts etc., are too well known to need further comment.

10.7 Jointing Compounds

Several publications and replies to enquiries from this survey pointed out the dangers of residual stresses induced by bolting together against cured jointing compound. Strangely, except in the UK, the use of jointing compounds does not seem to have featured in as many assemblies as would have been supposed. They have several functions to perform. One is to keep the water out, another to act as interfacial adhesive and improve joint fatigue strength and at the same time reduce fretting between the joint interface. More recently studies have been made with riveted joints with "cold cure" adhesives, but in general this would not seem the best approach as such adhesives are rarely inhibited and often are of epoxide base and thus may be sensitive to water in the long term. Experience recommends caution in the use of such methods.

If a sealant-adhesive, say a thiockol elastomer, is to function properly the joints must be tight and remain tight and this can only be achieved if the joint is fully tightened before the material has cured. Joints made in any other way will have poor fatigue behaviour relative to the optimum. The interest of stress corrosion is served by the demands of assembly for other reasons. It does mean, however, that a design must take into account the assembly time and method so that the characteristics of the jointing compound can be met. This is often difficult on the large aeroplanes being built today.

Most modern jointing compounds are two-part mixtures and, if pre-cured before application, problems can arise with large joints. Approaches to overcome this problem are necessary on large aeroplanes so that the two parts are mixed when the joint is closed. This is possible with the "Viton" type of sealants and work now in hand with encapsulated sealants of the polysulphide type may well solve it for this type also. Inter-mixing at the actual bolting-up stage is obviously necessary to break the pot-life work-life time relationship which otherwise controls the design.

With the increasing accent on the necessity for jointing compound in construction, now discernible in the USA reports and studies, new developments may be expected in this hitherto rather neglected field.

10.8 Permissible Design Stresses

Although the accent has been to reduce internal and assembly stresses and to protect as fully as possible as the means of preventing stress corrosion, it must not be forgotten that occasionally situations do develop where high static stress may be designed into the part.

The design of airframe and engines, which is so much controlled by the fatigue requirements makes it less likely that prolonged static operational tensile stresses will be a problem in these vehicles. It would seem that this can quite well be the case in rocket design and very high static stresses have been deliberately used in some designs.

It is also interesting that, with vehicles like aeroplanes, people are more conscious of a long operational life and protect accordingly, as a necessity; whereas perhaps, because of the even more critical weight problems or perhaps because rockets are looked upon as expendable, the long period of waiting before use in a civil rocket programme seems not to have been taken into account.

At this point in time, even with the resources that are being directed to produce materials with better stress corrosion resistance, the property of stress corrosion resistance cannot be ignored. New materials are susceptible and even those thought to be safe by laboratory tests may let one down.

Thus, we must design to the material's threshold value, unless it is certain that the protection will be effective throughout the expected life of the part; this threshold seems surprisingly independent of the corrodent involved, for the given grain direction. Bearing in mind the very high strains occurring in designs of this sort, it is essential that the elasticity of the protection will enable it to extend with the component.

Not many constructors conduct tensile tests as part of the paint approval testing. The flexibility, as shown by the bend test for paints, for instance, does not properly measure the property which would become involved.

10.9 Conclusion

This section has covered several major design features which must be resolved and legislated for on the drawing before issue for production. In Section 9 the choice of material was discussed. Further features considered in this section will also bear on the selection of material.

The need to keep internal residual stresses and assembly stresses to a minimum have been emphasised and methods of achieving this have been outlined. The influence of form upon grain flow has been discussed and the overall need to consider the method of manufacture and protection, even when choosing the origin of the material and certainly when considering its final shape, has been reiterated. Some features have not been included. For instance, the need to precipitate in the case of the high strength alloys or some steels, or to stress-relieve in the case of others and the time at which this should be done.

Residual stress from bending or shaping, or to correct distortion, has also been left to be considered in the next section.

11. PRODUCTION MANUFACTURING METHODS

11.1 General

In the previous section some of the requirements of the initial design were considered. If these are not attended to from the start, the product is always likely to suffer from stress corrosion. Even if the design is satisfactory, there is still much that requires attention during the manufacturing stages if a good design is not to be ruined. It will be appreciated that, as more and more operations and processes become involved, the problem becomes more difficult to solve. Each major factor will be taken in the same order as before, but dealing only with features not covered by the drawing.

11.2 Residual Stress

The most important ways in which Production Departments are likely to introduce unacceptable residual stresses are as follows:

(i) *Cold Bending*

It is surprising how few Production Departments are aware of the very high residual stresses that can be induced by bending the material in the fully heat-treated condition. It is to be expected that any plain bending will leave a residual tensile stress nearly equal to the proof stress of the material in the condition in which it was bent.

Because parts are usually bent in a direction normal to the longitudinal axis, and by design the grain flow tends to be in this direction, more trouble has been saved than has been recorded.

The problem is, of course, to ensure that a simple bending operation has not induced a more complex stress pattern than has been supposed, and has thus left high residual stresses in the short transverse direction. This can occur and many instances are on record of failures arising from the expansion of tube ends etc.

It is, of course, necessary to distinguish between the gradient induced through the material by simple bending and the compression which is induced by a stretch-forming operation. This would seem to be so complex a situation that it is suggested that all bending operations which cannot be achieved by a stretch-forming operation should be carried out with the material in the lowest possible strength condition. Much more attention should be given to the study of residual stress patterns in first-off components.

This leads to another vital, but often neglected, production edict. Once the first-off has been made and approved, all the remainder must be made to exactly the same process without deviation. Should any change become necessary, for reasons of economy, bottlenecks on production parts to the new technique must be studied before production continues. It is therefore recommended that, so far as possible, stretch-forming methods should be used and, if the material is such that it cannot be stress-relieved afterwards, all final forming should be done in the softest possible condition, that is, immediately after solution treatment for aluminium alloys and in any event before precipitation treatment when this is applicable. These remarks also apply to some of the stainless steels and titanium alloys.

The cold-forming by bending of low strength low alloy steels does not seem to have been a problem, but clearly it is unwise with high strength material. The simplest way to control this is to agree amounts of forming permissible for the different materials and to deviate from these agreed standards only in exceptional cases when full controls can be applied. A few authors have proposed that the aluminium alloys can be bent safely in the precipitated condition by carrying out the operation at 300°F or thereabouts. A good deal of test work fails to prove that the residual stress from bending is reduced by this operation and it is recommended that it should be approached with extreme caution.

(ii) *Machining Stresses*

Very considerable surface stresses can be induced by machining. These are said to be compressive except when produced by negative rake tools or from grinding. The latter is said always to produce residual surface stresses in tension.

Much more work needs to be done on machining and residual stress from machining, especially as modern machining processes are so fast that severe thermal gradients may be induced. A few positive instances have given trouble with the aluminium alloys and these give rise to concern; for instance, shearing will almost always cause edge cracking of a stress corrosion nature in the Al Zn Mg alloys. It is therefore suggested that, because it has not caused cracks in a short time with the Al Cu alloys, this does not mean that some unpleasantly high residual stress may not have been induced and similar care should be exercised. Equally, even though the stresses from machining may be compressive, this does not prevent them from causing the part to bow or distort. When this happens, more often than not the consequent straightening operation will introduce tensile stresses.

Should local residual tensile stresses be induced in the surface from machining the aluminium alloys, stress corrosion cracks may well propagate. This should not be too serious a matter from a stress corrosion viewpoint if the part has been properly made to that stage, but of course such initiation is most dangerous from the fatigue aspect, depending upon the location and the material.

As previously stated, most high tensile steel will be machined in the soft condition, heat-treated and ground afterwards. There is no doubt that grinding is a most dangerous operation and it is doubtful if the full importance has been appreciated in service failure examination. Equally, although many companies use etch inspection techniques in an attempt to detect grinding defects, it seems likely that quite high residual tensile stresses have been missed by such examinations.

Almost no research has been done to determine the effect of grinding on titanium. Now that very high strength titanium alloys are coming into use extensive grinding is a possibility. Great care will be needed to prevent hazards from surface damage from machining.

The position with high strength stainless steel would seem to be very similar.

Thus there is every good reason, from these viewpoints, to machine as far as possible in an intermediate heat-treatment stage, as for the aluminium alloys, unless the alloy in question will permit an adequate stress-relieving treatment finally.

More recent methods of machining need very careful study. Contour etching, spark erosion, electro-polishing etc. may all leave material with poor surface condition relative to either stress corrosion or fatigue. Unfortunately the manufacturing variables are so numerous that it is unlikely that many actual rules can be laid down which would have much overall validity; the best that can be achieved in this paper is to emphasise the need for awareness of the problem.

11.3 Correction of Distortion

It is interesting that, although the influence of the correction of distortion with respect to fatigue behaviour has been very well authenticated, surprisingly few aircraft companies have made much effort properly to control shop practices. It is most surprising therefore that even less regard seems to have been given to residual stresses from this score with respect to stress corrosion.

The problem is extremely difficult, as no tool exists at present which can examine a surface *in situ* for residual stress. For parts of complex shape the only method of analysis is to straighten the part with strain gauges attached or to cut it up afterwards, or to reduce it to such size that checks can be made by X-ray crystallography as representative of the remainder. Unfortunately parts rarely distort similar amounts and thus a first-off sample tested destructively may not provide the necessary guide for subsequent pieces. It is the random nature of complex shapes which make the problem more difficult than that of residual stress from forming operations, which are controllable.

In any event it is suggested that aluminium alloys should never be straightened in the short transverse direction. Only limited amounts should be permitted in the others, depending upon the heat treatment condition at the time. It is therefore recommended that high strength aluminium parts should at least be machined in the solution-treated, stretched and naturally-aged condition, so that any distortion that may arise can be corrected in the lowest heat-treated state possible. The subsequent precipitation may afford some relief or can be designed to do so.

Even so, it would seem wise to quote some limiting stress. One company has studied the residual stress at the surface of simple bends of various aluminium alloys at different heat-treatment conditions by means of X-ray crystallography and strain gauge techniques and has then devised an empirical relationship with the measured strain required to correct the distortion. In this way a yardstick which leads to some consistency has been achieved. The other way of resolving the problem would seem to be to reform the part by shot-peening. This leaves both surfaces in compression. It is argued that fatigue test specimens of aluminium alloy peened and tested in axial tension may lose some fatigue strength by this action, whereas a significant gain is noted when tested in bending. General experience has shown very few cases in service where peening has not benefited the structure, probably because few parts are loaded in pure axial tension. Stress gradients are always present, due to changes of section, notches etc.

Thus the risks of adverse changes of fatigue strength would seem small compared with the benefits that can accrue from the stress corrosion viewpoint.

Very little work has been done with titanium but stress-relieving by heating would seem a more likely solution in most cases for many of the alloys in use today. The furnace atmosphere must be carefully controlled.

Most high tensile steel parts are too strong and it is difficult to correct their distortion by bending, careful machining in the final form being the only solution. Fortunately, as many of the high strength steels are developed from die steels, they have been developed with a high dimensional stability. Lower strength steels are not a problem with respect to stress corrosion. Both titanium and steel will respond to shot-peening to a limited degree.

11.4 Control of Processing

In Section 9 dealing with the choice of material, it was shown that even relatively low temperature heat treatments would interfere with the behaviour of the material from the point of view of stress corrosion, even though no change of static mechanical properties was observed after the treatment. It is therefore of vital importance that parts are heat-treated, formed, stress-relieved and subsequently processed with the utmost regard for the approved schedule of the part, without any deviations whatsoever. Not nearly enough attention is paid to this aspect of manufacturing.

11.5 Corrosion Protection

There is little doubt that much can be done to prevent stress corrosion failures by the use of protective methods and it is to be hoped that these will be fully specified by the design department. Nevertheless it must be admitted that the attitude of too many production departments is that such processes, coming as they do at the end of the Schedule, are a nuisance. They are a vital part of the integrity of the structure, not from just the visual aspect of subsequent corrosion, which is usually the least damaging, but from the viewpoint of the actual physical performance of the structure. This cannot be emphasised too strongly. Every detail of processing is critical and the numbers of such details are legion.

Without wishing to promote a Design / Production feud it must be appreciated that poor treatment is bound to show in the end. Hence, if Production feel that the design does not permit proper finishing, they should say so and not to try to get by.

11.6 Assembly

It is absolutely vital that no assembly stresses are built into the structure. Drawing limits must be maintained and the importance of accurate protective treatment will show up in this case. Especially must the proper requirements for jointing compounds be met to the letter, even though this becomes increasingly difficult with large structures.

It is the author's opinion that Production Engineers who develop new tools which build the parts faster and cheaper, but do not accommodate the proper requirements for protective treatments, have failed in their purpose and do a dis-service to the industry.

In this respect it is not out of place to reiterate here the essential need for Production Engineers to take into account the performance of the end product. It is not difficult for a case to be made by the Production man that doing a job in such and such a way will be cheaper but leave greater residual stress, or leave out a protective treatment. Is is often nearly impossible for the designer, with the limited knowledge at his disposal, to predict with accuracy the increased likelihood of failure which may result from this change to a speedier, cheaper job. Of couse this is not to say that there is not nearly always a better, cheaper way of doing it. It is merely being reiterated that all aspects of subsequent behaviour must be taken into consideration when selecting the manufacturing schedules.

11.7 Conclusion

It has been shown that the Production Engineer has the responsibility equal to that of a Designer to ensure that a material is not spoiled by otherwise apparently harmless deviations from the approved practice and that he does not introduce unfavourable stresses in an otherwise acceptable design. It is believed that a much greater awareness of the importance of accurate processing must be developed at shop floor level.

The Designer is expected to take all aspects of his design and its manufacture into account and, to sharpen his awareness, he usually hears of his mistakes. Defect and Product Support Departments are very closely allied to Design teams in most companies; consequently there is a constant feedback of troubles and the need for expensive rectification. It is often much more difficult to show that, had a part fitted properly or had the treatment been to the required standards, the defect would not have arisen. Nevertheless it is strongly recommended that there should be much more feedback to Production, with respect to service failures, than is the case in most companies today.

There are, of course, problems. Many defects are so significant to the company's image, contractural liability etc. that the defect investigation side is a tightly knit unit working in strict confidence.

Somehow this problem of communication must be overcome, even if there is a delay built into the feedback system to accommodate the security aspects.

It should perhaps be said here once again, to avoid misunderstanding, that, although the problem is complex and a hundred per cent detection will never be achieved, most of the service failures due to stress corrosion could be prevented by the means currently at our disposal. It is a matter of attention to detail - the correct and precise interpretation of the design by the Production Engineer. Somehow this must be brought home to all levels of shop floor Management and Supervision.

It is not pertinent to discuss the relative inspection organisation methods available to monitor this or the advantages of the quality control approach. So much of the manufacturing and processing operations cannot be checked afterwards, by inspection methods at our disposal, that the problem must be tackled with the realisation by the Production Department of their responsibilities in this respect.

This may seem rather over-emphasised after what has been said about the importance of good design, but the difference between Design and Production is that in Design the component or assembly has to be expressed completely on paper and a check can be made whether the proper precautions have been considered; whereas, in Production, once a part is made it is usually impossible to prove what has been done during fabrication.

12. THE PROBLEMS OF COMMUNICATION

12.1 General

In the preceding sections an attempt has been made to review some of the ways by which stress corrosion failures can be avoided and the relevance of the activities of different departments has been accentuated. Many reading this will be feeling that they have read this before and it is not new. This is true and it is not suggested that anything has come out of the survey which was not known to many in industry. It has been said that attention to these details can virtually eliminate stress corrosion failures, yet still they persist. Where is the problem?

The whole aspect of material use, and design and manufacture, has become so complex that it is hardly surprising that aspects of stress corrosion are missed, and that many people actually designing or responsible for making the parts do not know the simple features referred to in this report. The real problem of stress corrosion is therefore one of communication. In most designs the integrity of the structure with respect to static strength and fatigue needs to be proved by tests, whereas these are not of much value with respect to stress corrosion if each part is liable to have different inherent residual stress. (One Government Agency is now requiring this, nevertheless.)

The difference seems to be that fatigue behaviour is accepted as a material property by Design and Production, whereas stress corrosion is considered a disease!

Earlier in the paper it has been suggested that materials used with success by one company have led to disastrous results when used by another. It is believed that this is due to either

(a) the better control and communication of the problem and its solution throughout the one company, usually in the form of standards, or

(b) an inherent know-how which developed, by chance or from feedback, in the use of the particular material within that company.

Referring to (a) it is not the companies with the best research facilities etc. that have necessarily been successful but the companies which have developed and maintained adequate lines of communication. Even having beautifully prepared control specifications is of no value if the system does not ensure their use. While method (b) may seem to be successful, companies reliant on it are very vulnerable, because sudden changes of staff can reduce their know-how to zero.

It is suggested that the only way is to build up an integrated structure of company design rules, standards and manufacturing processes integrated within the company's procedure in such a way that a deviation from the norm upsets the system and the difference has to be examined before production can proceed. It would not be sensible to suggest, in the light of the evidence in this survey, that these features should be developed for stress corrosion considerations alone.

Equally it must be realised that this integrated approach can only be achieved by top management instruction and support. It can only be achieved by the close appreciation and co-operation of all departments of the company. Design Department, Supplies Department, who must appreciate the technical significance of the purchase, Production Department, who must balance the integrity of the structure as part of the cost assessment, and Inspection. Such a system to be effective, must flow out through these departments to semi-finished material suppliers, sub-contract Design Offices, sub-contract Manufacturers etc. A few of the larger companies have complex systems of this sort in operation. A few of these actually work.

It is interesting that a survey of the design requirements of NATO Countries shows that, for instance, in the United Kingdom design requirements for aircraft of the Royal Air Force and Royal Navy have at least thirteen different requirements and advisory notes dealing with stress corrosion and design, and four more dealing with protection; there are a further eighteen references in the complementary inspection document. This is surely enough to deal with the matter, yet clearly it does not suffice. It is suggested that such documents are restrictive and cannot take into account detailed differences of organisation, methods and procedures within each firm. They cannot have an effective feedback system. Recently the problem of the high strength aluminium Zn Mg alloys of the 7075 type was tackled by introducing a *pro forma*, which had to be filled in and returned to the Ministry of Technology, describing the purpose and reasons for use of such an alloy. This has the advantage of ensuring that all the best practices are adopted, and that each design is vetted. Unfortunately it also tends to be restrictive in its approach and, in any event, it is not a practice that can be used for every material. It is proposed that each company can and must solve its problems itself. The survey shows that very few have really attempted to do so.

12.2 The Formation of a Specification System

It would seem to the author that the important feature of any communication system is that, although different sorts of instructions are required for people of different disciplines, they must all be thoroughly integrated and thus must stem from a central source. This does not mean that the Department that writes and issues the information or instructions is responsible for company policy, or even technically responsible for the choice of material or method. But they must be technically capable of disseminating the decisions taken by the company and fed to them for implementation. They must be adequately alive to appreciate the impact of a change in one instruction upon another.

It is suggested that two main avenues of information should be set up. The instructions to the Drawing Office and the instructions to Production. (Inspection proves that these have been carried out.)

It is further suggested that, to make the system practicable, it must be simple. This sometimes means that action or control has to be based on broad generalities. The company is more likely to react to a general rule in a consistent fashion. Obviously such "rules" will not be strictly accurate, or the "ideal" for any given case. The aim, however, is not to produce a few isolated specific parts of high quality, but to raise the whole output to a better standard than before, and at the same time to control the company activity in such a way that will stop the really bad cases from leaving the factory.

There is much to be said in educating every member of the staff in the technical aspects of the various problems, but in the author's opinion this is unlikely to succeed; it is too great a task . A degree of confidence must be built up between specialist persons or departments who can then agree a set of rules without necessarily understanding all the other Departments' reasons.

Finally, it is necessary for Management strongly to support the system and for as many Departments and people as possible to have a say in the preparation of the system, so that it can be truly said that it is their system and not one imposed upon them by a nebulous hierarchy.

For the people responsible for implementing such instructions and issuing the various documents this path is fraught with frustration, delay, and a feeling that it will never be actioned. Nevertheless the preparation of a new Drawing Office instruction or specification for the Shops must be accepted as a slow process. Once the system is accepted and well established, the confidence and success it then has will be worth all the frustration. To have clear-cut rules issued from an isolated authority without the democratic process of preparation may produce very good instructions written by an expert but the shop and everyone else will delight in seeking loopholes and dodging the intentions all to frequently. It is unlikely that the specification or instruction can be so precise yet adequately all-embracing that it will meet all possible cases strictly to the letter. It is only the good will of the people who have helped to build the system that can make it work.

The manner is which this is done will obviously vary from company to company, depending upon the company organisation, size etc. One company, newly integrated, set up a series of committees for each of the fields described, each person on the respective committee (not necessarily a very senior member of the company, but one recognised as an authority within the unit) being chosen from each part of the Company. The Chairman of each committee, usually selected by Management, was made responsible for the output of the particular committee and furthermore was responsible for integrating with the chairmen of the other committees. They were further welded together by forming the chairmen into a main standards committee responsible for defining company policy towards the different problems. This main committee was chaired and directed by a member of the Board of Directors. It was the responsibility of each committee to obtain the views and advice of any specialists and sometimes to promote research or test work to substantiate the instructions being developed.

Once this sort of organisation has been set up and working it will be found that instructions for any special feature such as stress corrosion are not likely to be issued, but that all aspects will be watched in the various standards wherever they arise. Thus:

(i) Instructions regarding material properties will be given in the Design Handbook, with comments upon selection. This will usually be a selected short list in the interests of standardisation and economy of stocking, heat treatment etc. The list should be devised by consultation between design, structures and materials people on the requirements of the particular project and monitored by Buying Departments, Inspection Departments etc. to confirm the choice.

(ii) A policy should be prepared on the procedure for the supply of forgings, castings etc. Guide lines for selection, heat treatment, machine requirements etc. should be given to Designers and procedures issued to Buying, Inspection and Production, quoting in detail how the Drawing Office decisions are to be implemented. Rigid procedural systems should be included so that, for instance, a forging could not get into production without the grain flow, the residual stress etc. being checked. One way to do this is to organise the order-supply procedure so that "first-offs" are obtained by Buying Departments, and fed to Inspection Laboratories and the Stress Office; not until all three have signed a form of agreement can a drawing be raised in issue to the production standard. Only then can Buying Department purchase production quantities.

(iii) Every aspect of the need to reduce residual stress is involved in such a way that material must have been supplied and made to one or other of the procedures which will achieve this, i.e. slow cooling rate, cold-compression, controlled stretch etc.

(iv) A policy on protection should be formulated and clear-cut instructions given, i.e. cadmium plating, anodising etc. followed by painting of a standard type. The manner of control of each process should be issued to Shops and Inspection.

(v) The policy to shot-peen or shrink-fit, and the accepted tolerances, should be formulated and implemented.

(vi) The policy on minimum bend radii should be given to the Drawing Office.

(vii) Methods and procedures for dealing with distortion and its correction should be introduced.

Soon, when such a system is operating and the rules known, suppliers, sub-contractors and everyone will be feeding back information, noting differences from the rules and checking whether these are intentional or a mistake. A Company policy will have been established. In fact, not many will know why certain things are done, but the door must always be open for them to ask. In the main, if confidence can be induced they will happily operate to the rules laid down. This partnership of goodwill towards the system is vital. It would be ridiculous to suppose that every instruction was correct or always covered every aspect intended. The feedback from experience will surely hammer the system into a very sound working tool. A lot of money can be saved in this way, and almost all the service failures said to be due to stress corrosion could be prevented.

The Turin Conference on Stress Corrosion formed an introduction to the problem. Work in the universities, research institutes and company laboratories will lead to better materials and better protection, but at present the onus of responsibility must lie with reasonable standards of design and proper manufacturing and assembly methods.

It is hoped that this survey will contribute to a better integration of effort by all parts of every aerospace company. The means of reducing the problem of stress corrosion would seem to be in our hands now. We must build up our lines of communication to see that the practices are more faithfully implemented.

A symposium dealing with all aspects of this survey will give the opportunity for specialists in each field discussed to develop the features in more detail than this paper can do. It is hoped that this will set the pace for the necessary practices to be introduced.

13. CONCLUSIONS

A review of some of the aspects of the prevention of stress corrosion may be of value.

13.1 Reduction of Residual Stress in Die Forgings

It has been advocated in this paper that reduced cooling rates are advantageous. It is argued by many that this

(a) does not always prevent high internal stresses,

(b) is liable to produce intercrystalline corrosion sensitivity,

(c) causes a reduction of tensile strength due to certain effects with some alloys.

It is possible that each and everyone of the points will not be met without difficulty.

However, there is little doubt that the Al Zn Mg alloys of 7075 type, chromium free, can be produced with very slow cooling rates on adequately thick sections and it is not often that serious residual stresses result. In any event the approval forging should have been metallurgically examined before production and a change of technique introduced if there had been trouble. The mechanical properties will be adequately maintained and it is not too important what happens to the intercrystalline corrosion resistance. This can be looked after by protective methods. The fact that the stress corrosion will not be improved does not matter too much either. The part will not fail if the stress component of the environment is absent.

It would seem that the T 73 type treatment, or even similar ones, can also lead to low residual stresses. This would seem to be as important as the improvement of actual stress corrosion behaviour shown by testing in the laboratory. These treatments also reduce the mechanical properties.

13.2. Reduction of Residual Stress by Stretching

It is necessary to control the stretch applied. It has been shown that large longitudinal plastic deformation, although leading to improved longitudinal properties, may cause a reduction of the properties in the other directions and the compression strength in the longitudinal direction may be reduced also.

Thus, controlled stretching should always be adopted. This is commonly set at 1½% to 2½%. Increasing the stretch increases the proof stress and reduces the proof/ultimate ratio. In reply to questions during the survey some people felt that the fracture toughness, and perhaps the dynamic crack propagation, was reduced by doing this.

From the design viewpoint, bearing in mind all aspects of fabrication, it is necessary to establish whether the behaviour of solution-treated, stretched and aged Al Cu Mg Si (BS L64), so worked that it has proof and tensile strengths equal to the precipitated condition, also has the same fracture toughness behaviour, and whether the stress corrosion resistance differs as well.

13.3 Shot-Peening

Everyone everywhere believes that shot-peening is the best preventative to crack initiation in any alloy. It is important to know why this is so. If it is because of residual stress, then how significant is the influence of relaxation induced by the service dynamic loading of the part. In the case of main undercarriages, which are usually designed with static factors approaching unity, will a heavy loading lead to stress relaxation and hence susceptibility to crack initiation? Indeed, the whole question of the design usage of surface compressive methods is dependent upon the answer to this problem.

It would seem that the residual stress *per se* is not the real cause of the improvement of behaviour, but the influence of the changed metallurgical structure. The whole outlook on surface finishing might be changed if this could be demonstrated. Nevertheless, the evidence at this stage seems so overwhelming that such treatments are beneficial in virtually all the practical cases, that it would seem that they can be applied without too much worry as to these precise answers at this time. This would also seem to be true despite the simple laboratory demonstration that the fatigue behaviour of a plain specimen tested in axial tension is reduced by shot-peening.

Presumably, in practice all parts are so complex in shape or stress pattern that the pure case never arises.

13.4 Protective Treatments

The survey shows the marked value of protective metallic coatings. Although aluminium alloys in sheet and plate form have been used with Alclad for many years, there is now a tendency to forego this to obtain improved dry-air fatigue performance. In the interests of stress corrosion and corrosion in general this could well be reviewed. Some comparative tests incorporating modern paint systems as well, would be interesting.

In the 1939-45 war the German industry produced clad extrusions for stringers etc. Should this be reviewed in the light of modern technology?

Nearly all researchers have shown that metal spray such as zinc or aluminium is beneficial and, when applied to a blasted surface, as is usual, does not cause a reduction of fatigue performance. There are problems of adhesion and limits and fits, but these should not be insoluble.

Most high strength steels still seem to be cadmium plated, though zinc spray has been shown to be very effective. Perhaps aluminium spray would be better overall, although slightly poorer from the aspect of adhesion. The United States Air Force Materials Laboratory are developing a method of treating bolts etc. with aluminium, which may have marked advantages.

There have been significant advances in paint technology. It would seem that properly constituted paints may help with respect to stress corrosion but may need larger quantities of available chromates than for ordinary corrosion protection. Paints are only good if their adhesion is excellent. Thus, the surface preparation is important:

(i) Anodising does not seem to improve the stress corrosion resistance of aluminium alloys. Anodising should not be sealed before bonding; therefore, is it the best preparation for painting and, if so, should it not be left unsealed before painting?

(ii) It is said to be necessary to passivate electro-plated cadmium and zinc surfaces before painting (unless etch primers are used). For epoxy paints it is necessary to pre-treat aluminium alloys to obtain adequate water resistance. Should we not passivate or pre-treat sprayed zinc or aluminium coatings before painting?

(iii) At present nearly all paint films are resinous and rather brittle. All are permeable to moisture. It has been shown that impermeable butyl films can cause specimens in wet laboratory tests to behave as if tested in dry air. Should we not press for paint technologists to pursue this aspect more persistently so that an impermeable elastomer paint becomes the order of the day? It is said that this is not wise because, if the paint were damaged, failures would arise. The paint will always become damaged somewhere. Such remarks always assume that parts should be designed beyond the material's threshold stress and can then rely on the paint. Very few people, apart from considering the short transverse direction, actually alter their design values to take stress corrosion into account so we can only be better off than at present, not worse, by using protectives developed along these lines.

ACKNOWLEDGEMENTS

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The author is employed as Materials Engineer to Hawker Siddeley Aviation Limited, Hatfield, England, and would particularly like to thank the Directors of that company for their tolerance and support of these activities and his many colleagues, who have assisted in a variety of ways.

APPENDIX I

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APPENDIX II

THE FOLLOWING HAVE KINDLY ASSISTED WITH AND CONTRIBUTED TO THE SURVEY:

Europe

Dr Grayham	BAC Operating, Weybridge	United Kingdom
Mr J.Boraston	BAC Operating, Filton	
Mr J.Fielding	Hawker Siddeley Aviation, Manchester	
Mr N.Imrie	Dowty Rotol, Gloucester	
Mr H.G.Coles	Ministry of Technology	
Dr Mullins	Ministry of Technology	
M. A.Guilhaudis	Centre de Recherches, Péchiney	France
M. M.Sertour	Sud-Aviation	
M. M.Apert	Centre d'Essais des Propulseurs	
Prof.R.Mazet	Office National d'Etudes et de Recherches Aerospatiales, ONERA, Chatillon	
M. J.Herenguel	Trefimetaux, Argenteuil	
M. M.Renouard	Director Cegedur Sp Issoire	
Brigadier General D.Kanellopoulos	202 MD Athens	Greece
Prof.Dr Ing F.Bollenrath	Aachen	Germany
Dr T.Gayman	Münich	
Dr Gay	Industrieanlagen Betriebsgesellschaft	
Dr Ing.Schaffer	Entiwicklungsring Süd, GmbH, Münich	
Mr H.Kjøllesdal	Oslo	Norway
Dr R.J.Schekelman	Royal Netherlands Aircraft Factory	Netherlands
Mr H.P.Van Leeuwen	National Aerospace Laboratories (NLR), Amsterdam	
Col A.Parot	Forces Armées, Brussels	Belgium
Prof.Frithof Niordson	The Technological University of Denmark, Copenhagen	Denmark
Col A.Griselli	Ministero della Difesa Aeronautica	Italy

United States of America

Mr Ward Minkler	Titanium Metal Corporation, New York
Dr Wrulk	
Mr M.C.Woodward	ALCOA, Pittsburgh and ALCOA, New Kensington
Mr March	
Mr Mayer	
Dr Brandt	
Mr D.O.Sprowls	
Mr Spuhler	
Mr Nordmark	

Mr George Hosne	ALCOA, Cleveland
Mr L.Faure	
Mr R.Botterman	
Mr Gardiner	
Mr G.H.Rothgeny	Cleveland Pneumatic, Cleveland
Mr Toole	
Mr R.Unger	
Mr Steigerwald	TRW, Cleveland
Mr Langenfeld	Monsanto, St.Louis
Dr Hatton	
Dr F.Whitney	
Prof.Sulbransen	
Dr Lovelace	Air Force Materials Laboratories, Wright-Patterson Air Force Base, Dayton, Ohio
Mr Teres	
Mr Zeoller	
Mr George Loder	
Dr Staehle	Ohio State University Columbus, Ohio
Dr Beker	
Mr Punte	North American Aviation, Columbus, Ohio
Mr P.Maynard	
Mr Warner	
Dr Lucas	NASA, Huntsville, Alabama
Mr J.Kingsbury	
Mr James Seorfe	Lockheed Aircraft, Burbank, California
Mr W.J.Chrichlow	
Mr M.Tinkinsley	
Dr K.Webber and others	Lockheed Aircraft, Rye Canyon, California
Dr Piper	Boeing Aircraft, Seattle
Mr B.Thierry	
Mr H.Zahn	
Dr Bethune	
Mr W.S.Hamilton	
Mr D.R.Goehler	

Canada

Mr A.H.Hall	NRC, Ottawa
Dr G.J.Biefer	Corrosion Section, Mines Branch, Department of Engineering, Mines and Resources, Ottawa
Dr A.J.W.Melson	Accident Investigation Department, CIU Aviation Branch, Department of Transport, Ottawa
Mr T.W.Heaslip	
Mr J.B.Shah	
Mr J.A.Dunsby	

To assist the present project, Mr A.H.Hall made a separative survey of 10 aircraft users and manufacturers in Canada. The results are included in this report.

APPENDIX III

FORM OF A TYPICAL CONTROL PROCEDURE

HAWKER SIDDELEY AVIATION

PROCESS SPECIFICATION

S.26.4515
Page 1 of 12

SUPPLY PROCEDURE FOR CLASS 1, 2 AND 3 FORGINGS

CONTENTS

RELATED DOCUMENTS

British Standard Specification L.100, 3S.100.
Standard S.25

HSA.Spec.No.S.29.4	Test piece requirements for heat treatment control
" " " S.26.2503	Ultrasonic inspection
" " " S.26.4518	Inspection of aluminium alloy forgings
" " " S.26.2002	Vacu-blasting
" " " S.26.2004	Vapour Blasting
" " " S.26.4519	Inspection of titanium alloy forgings
" " " S.29.56	Pickling of titanium
" " " S.29.38	Temporary corrosion preventatives

See also Av.P.4089. D.408 and 465.
A.R.B. Civil inspection procedure BL/4-6 and BL/4-7.

SCOPE

To define the supply requirements applicable to Class 1, 2 and 3 Forgings.

This Specification supersedes DHA 85.

COMPILED BY

Hawker Siddeley Aviation Limited, Hatfield, Herts.

This Specification is private and confidential and may not be copied or communicated without the permission of Hawker Siddeley Aviation Limited.

APPROVED BY :

Issue 3
Amdt. -

1. INTRODUCTION

1.1. This specification details the ordering and supply procedure to be followed to ensure that all supplies of Class 1, 2 and 3 forgings meet Hawker Siddeley Aviation Limited, design requirements.

NOTE : For definition of Class 1, 2 and 3 refer to Av.P.970 Chapter 400/2 or British Civil Airworthiness Requirements Chapter D.1-2 Para. 4.10.

1.2. The forging approval procedure required by this specification shall be invoked for all Class 1 and Class 2 forgings in the following circumstances :

1. New design
2. To replace parts previously machined from bar or plate
3. On change of material specification
4. New source of supply
5. Change of forging technique

The full approval procedure detailed in Clause 4. shall be applied when a die-forging is produced for a part previously supplied as a hand forging.

NOTE : The requirement for re-approval of forgings on change of Material Specification may be waived, on written authorisation by the Stress Office, where it is agreed that the change will not invalidate the existing approval tests.

2. LIAISON AT DESIGN STAGE

2.1. A technical representative of the Supplier is to discuss the requirements of all major structural forgings with the Drawing Office and Production Planning Engineers at the design stage, prior to the issue of the forging drawing. It is recommended in the interest of production economy that this liaison is maintained for all forgings.

2.2. At this stage additional consideration shall be given to the general forging contour with the object of eliminating lap defects.

3. PRELIMINARY DRAWING ISSUE PROCEDURE. CLASS 1 AND 2 ONLY

3.1. The requirements of each new forging will be indicated on a preliminary forging drawing which is to be forwarded to the Supplier by the Buying Office.

Integral test samples as a check on overheating of steel forgings may be required. The provision of these test samples shall be decided by the Design Authority in consultation with the Supplier.

The location must be shown on the Preliminary Issue Forging Drawing. If they are not required the forging drawing or order shall be annotated accordingly.

This drawing will bear the note :-

"PRELIMINARY ISSUE. FORGING TECHNIQUE NOT FINALISED".

3. PRELIMINARY DRAWING ISSUE PROCEDURE - continued

3.2. The Supplier is to prepare and submit for approval his forging drawing indicating grain flow, die line, location of tensile test pieces, extension pieces, integral test samples (where specified for steel forgings) and extension pieces on titanium forgings (where provided) confirming their ability to produce forgings in accordance with the preliminary issue drawing with mechanical properties not less than the values specified in Appendix 1 for the appropriate material at the location indicated.

3.2.1. The Supplier's drawings for aluminium alloy, titanium alloy and steel forgings are to include an appropriate allowance for metal removed during surface preparation to Clause 5.1.6. and Clauses 5.3.5. and 8.3.1. as relevant.

3.2.2. In the event of the Supplier being in doubt as to his ability to meet these requirements in full, a further discussion shall be arranged with his Technical Representative and the Design Authority concerned.

3.2.3. The Supplier's drawings are to be distributed by the Purchaser's Buying Office to :-

(a) The Design Authority concerned
(b) The Stress Office
(c) The Process Engineer's Office
(d) The Tool Drawing Office

3.2.4. The recipients will immediately notify the Buying Office concerned of their approval or alternatively of any modification which may be desired.

3.3. Following agreement with the Supplier that the forging requirements can be fully met, the Note :- "PRELIMINARY ISSUE, FORGING TECHNIQUE NOT FINALISED" shall be deleted from the drawing which shall be brought up to date and raised to the appropriate issue thus authorising production to proceed.

4. INITIAL ORDERING AND SUPPLY PROCEDURE. CLASS 1 AND 2 ONLY

4.1. All initial orders, on all sources of supply for forgings to this specification shall be endorsed as follows :-

"Sample forgings in accordance with the requirements of S.26.4515, clause 4 are to be submitted for approval together with two copies of the Supplier's Laboratory Test Report, quoting details of grain flow and mechanical properties".

4.2. Each Supplier, after production techniques have been established, must produce at least two sample forgings from the initial batch, i.e. one or more as necessary for his Laboratory Test Programme and one for confirmation of Supplier's dimensional check by the Purchaser's Inspection Department.

4.3. The Supplier must submit two copies of his Laboratory Test Report giving details of grain flow, grain size, surface defects and physical properties at the locations called for.

4. INITIAL ORDERING AND SUPPLY PROCEDURE - *continued*

4.4. The Supplier shall submit macro samples from the cut up forging to facilitate examination of the required grain flow.

The position shall be chosen while marking out, prior to cutting up the forging at the tensile test piece locations. If this is not possible two forgings must be taken.

Macro specimens shall be submitted in preference to photomacrographs.

4.5. For handed forgings, test reports and macro specimens shall be submitted in respect of both right- and left-handed forgings.

4.6. All tensile test pieces shall be cut from the forgings only after the full heat treatment cycle has been applied.

Forgings which are to be part machined before heat treatment shall be so machined.

4.7. The sample forging must comply with the appropriate supply requirements detailed in Clause 5.

4.8. Laboratory Test Reports, sample forgings and macro samples shall be forwarded to the Purchaser's Buying Office.

NOTE : For the subsequent procedure (after delivery) refer to Clause 6.

4.9. Where the initial order of hand forgings is small and subsequent production orders are to be die-forgings; it may be possible, subject to agreement between Supplier and Purchaser, to take the test material for grain flow and mechanical properties from the material excess to mechanical dimensions on a forging rather than cut up a separately prepared forging especially for the purpose.

5. SUPPLY REQUIREMENTS

5.1. Aluminium alloy forgings

5.1.1. The appropriate inspection requirements detailed in British Standard L.100 shall be complied with.

5.1.2. All identification markings shall conform to Standard S.25.

5.1.3. When called for on the forging drawing, ultrasonic inspection to S.26.2503 shall be carried out on the forging billet.

5.1.4. Every precaution shall be taken by the Supplier at all stages in production to ensure freedom from forging defects and the Supplier shall if necessary, introduce extra moulding dies at intermediate stages.

5. SUPPLY REQUIREMENTS - continued

5.1.5. Detailed inspection shall be applied at each forging stage to ensure freedom from defects and to remove such defects as might be introduced before proceeding with the next operation.

5.1.6. The Supplier will be responsible for carrying out the full surface preparation and inspection requirements of S.26.4518 on all Class 1 and 2 forgings before despatch and the Supplier's Release Note shall certify that all such forgings have been so prepared and inspected and that the forgings are being released as free from surface defects.

It is most important that surface examination is included to prevent forgings of coarse grain being released.

The requirements of S.26.4518 need not be carried out on hand forgings providing sufficient material is to be removed all over to meet mechanical dimensions and the final surface quality from machining is sufficient, to ensure removal and inspection for all surface defects during the normal manufacturing operation.

5.1.7. In exceptional circumstances arrangements may have to be made with the Purchaser's Production Department for the surface preparation and inspection to be carried out by the Purchaser, e.g. delay in delivery greater than the Purchaser's production programme will allow, due to the surface preparation and inspection requirements detailed in Clause 5.1.6. Where this procedure is adopted the Purchaser's Buying Office shall endorse the order to the effect that the forgings are to be supplied to the procedure detailed in S.26.4515 less the surface preparation and inspection requirements to Specification S.26.4518 and shall also notify the Works Inspection Department that the order has been so endorsed.

5.1.8. Forgings must be protected before delivery with an approved temporary corrosion preventative complying with S.29.38.

5.2. Steel forgings

5.2.1. The appropriate inspection requirements detailed in British Standard Specification 3.S.100 shall be complied with.

5.2.2. The checking of integral test samples to the terms of British Standard Specification 3.S.100 Section 6 Clause 9 shall be carried out to the satisfaction of the Supplier's Chief Inspector.

5.2.3. All identification markings shall conform to Standard S.25.

5.2.4. All bars and billets to British Standard Specifications S.28, S.98 and S.99 shall be subjected to ultrasonic examination prior to forging (D. Mat. M.O.Av. Memo. No.5. refers).

5. SUPPLY REQUIREMENTS - continued

5.2.5. When called for on drawings for Class 1 high tensile steel forgings, ultrasonic examination shall be carried out on the bar or billet prior to forging.

5.2.6. All forgings delivered in the finally heat treated condition shall be hardness tested at a sufficient number of positions on each forging from end to end to demonstrate the uniformity of properties.

5.2.7. The material from which S.99 and D.T.D.730 forgings are manufactured shall be checked for cleanliness as follows :-

(a) A sample shall be taken from the top end of the last cropped ingot teemed in the batch

(b) This sample shall be forged down to 2 inches diameter and examined

(c) The cleanliness shall be such that the amount of inclusion does not exceed 60 on the FOX inclusion chart

5.2.8. Alternative methods of determination of the cleanliness of the forged bar such as magnetic particle inspection may be used, providing the equivalent standard to 60 FOX is established.

5.2.9. Before delivery, forgings shall be de-scaled to the requirements of British Standard Specification 3.S.100 Section 1 Clause 6 and the Supplier shall carry out such inspection as will satisfy him that the forgings are free from surface cracks or other harmful defects.

5.2.10. Forgings shall be protected before delivery with an approved temporary corrosion preventative complying with S.29.38.

5.3. Titanium forgings

5.3.1. An extension approx. $\frac{1}{2}$ in. x $\frac{1}{2}$ in. shall be provided on each forging for test purposes. Two such test pieces shall be provided per batch, per part No. per cast :-

(a) One for microscopic examination for surface contamination.

(b) One for hydrogen and nitrogen analysis.

Alternatively, if more economical :-

One forging per batch, per part No. per cast shall be taken for this purpose.

The same forging (if large enough) may be used to provide a mechanical test sample to meet the test requirements of the Material Specification. The minimum properties of this test piece shall conform to the requirements of Appendix 1 to this Specification.

5. SUPPLY REQUIREMENTS - continued

Where it is decided to use the extension test piece above for control, then each batch of forgings from the same ingot shall be represented by a forged tensile test piece made from the same ingot and heat treated with the batch of forgings it represents.

The size of the forged test piece shall be such that it represents the maximum ruling section of the forging and shall be subjected to the same amount of "work" as the corresponding section of the forging. The test sample shall not be mechanically worked after heat treatment. If an extension piece is provided for contamination check, its position shall be indicated on the Supplier's drawing submitted for approval in accordance with S.26.4515. procedure.

5.3.2. All identification markings shall comply with Standard S.25.

5.3.3. All forgings shall be hardness tested at a sufficient number of positions to demonstrate their uniformity before despatch and the hardness range recorded on the Release Note.

5.3.4. All forgings shall be delivered in the finally heat treated condition unless otherwise specified on the order.

5.3.5. All forgings shall be delivered in the fully de-scaled condition, unless otherwise agreed. The final de-scaling process shall be by grit-blasting to S.26.2002 followed by pickling to S.29.56 to remove 0.005 in., thus ensuring the removal of gas contaminated material. The pickling treatment also serves to reveal the grain of the forging.

5.3.6. A dimensional check shall be carried out to confirm that 0.005 in. has been removed in pickling.

The dimensional check shall be by actual measurements made on some portion of the forging itself or on a small sample de-scaled and pickled with the forging.

6. FORGING APPROVAL PROCEDURE AFTER DELIVERY OF SAMPLE FORGINGS, CLASS 1 AND 2 ONLY

On receipt of the sample forging, macro samples and test reports, the Buying Office shall distribute them as follows :-

(a) The sample forging to the Works Inspection Department for visual inspection and confirmation of the Supplier's dimensional check.

(b) One copy of the Supplier's Laboratory Test Report and the macro samples to the appropriate HSA Laboratory.

(c) One copy of the Supplier's Laboratory Test Report to the Stress Office responsible for stress clearance of the drawing.

6. FORGING APPROVAL PROCEDURE AFTER DELIVERY OF SAMPLE FORGINGS - continued

6.2. A micro examination shall be carried out by the Laboratory of every first off delivery of titanium forgings to prove that all surface contamination has been removed.

This shall be carried out on the macro test samples submitted by the forging supplier.

6.3. A photograph of the accepted grain size for titanium forgings shall be taken by the Laboratory and a copy issued to the HSA Chief Inspector to illustrate the so far agreed acceptance standard.

6.4. Any decision by the Purchaser to make further tests on sample forgings is to be made at the discretion of the Laboratory in collaboration with the Stress Office.

6.5. Supplies of forgings shall not be released for use until the Stress Office in conjunction with the Design Office and the Laboratory have issued to the Buying Office and the Works Inspection Department, approval of the Supplier's report.

7. ORDERING AND SUPPLY PROCEDURE FOR APPROVED FORGINGS

7.1. Subsequent orders for Class 1 and 2 forgings which have been initially approved to the requirements of this Specification shall be endorsed as follows :-

"These forgings to be covered by the Supplier's undertaking that they were produced to the same forging technique as laid down and recorded for the initially approved forgings of the same pattern."

7.2. The Manufacturing Process Layout shall specify the number of test samples necessary to meet the requirements of S.29.4 where forgings are to be delivered in other than the finally heat treated condition.

7.2.1. The order shall state and the Manufacturer shall supply, the number of test samples necessary to enable the requirements of the appropriate testing procedure to be met.

7.3. All supplies of forgings shall comply with the appropriate supply requirements detailed in Clause 5.

8. PROCEDURE AFTER DELIVERY OF PRODUCTION FORGINGS

8.1. Approval of machining class 1 and 2 only

8.1.1. One of the initial batch of forgings (this includes forgings which have been sub-contracted for pre-production machining) shall be finish machined but left in the un-painted condition. An approved temporary protective shall be applied.

8. PROCEDURE AFTER DELIVERY OF PRODUCTION FORGINGS - continued

8.1.2. This fully machined sample shall be submitted to the Chief Inspector who will arrange for it to be approved by the Chief Structural Engineer in conjunction with the Designer-in-charge of the unit concerned.

8.1.3. The machined sample shall be retained by the Inspection Department as the standard to which all other forgings shall be finished until such times as the production technique is established.

8.1.4. The Works Inspection Department shall maintain a register giving the location of these sample forgings.

8.2. Requirements applicable to aluminium alloy forgings Class 1 and 2 only

8.2.1. Visual inspection after delivery of aluminium alloy forgings which have been certified as meeting the requirements of Clause 5.1.6. shall be at the discretion of the Chief Inspector.

8.2.2. Where the special arrangements detailed in Clause 5.1.7. are adopted in exceptional circumstances the Works Inspection Department shall ensure that the requirements of S.26.4518 are complied with after the delivery of the forgings.

8.3. Requirements applicable to titanium forgings

8.3.1. The Works Inspection Department shall ensure on receipt of titanium forgings that the forgings and the contamination test pieces are de-scaled, further pickled to remove 0.005 in. and inspected in accordance with S.26.4519.

Appendix 1 overleaf

APPENDIX 1

AGREED PROPERTIES FOR STEEL, ALUMINIUM ALLOY AND TITANIUM ALLOY FORGINGS

Specification	Material	U.T.S. tonf/sq.in.		Yield Stress tonf/sq.in.	Elongation % $4\sqrt{SO}$	
		Longitudinal and transverse		Longitudinal and transverse	Longitudinal	Transverse
		Min.	Max.	Min.	Min.	Min.
S.129 S.130	L.T.S. Stainless	35	45	13	30	10
S.80	H.T.S. Stainless	55	65	40	15	7
S.82	H.T.S.	85	95	50	12	7
S.92	Mild Steel	40	55	31	20	8
S.93	Mild Steel	35	45	20	20	8
S.96	H.T.S.	55	65	43	18	7
S.97	H.T.S.	65	75	54	Up to 4 inches	
					16	7
					Over 4 inches	
					14	7
S.98	H.T.S.	75	85	65	Up to 4 inches	
					14	7
					Over 4 inches	
					12	7

Continued on page 11

APPENDIX 1 (Continued)

Specification	Material	U.T.S. tonf/sq.in.		Yield Stress tonf/sq.in.	Elongation % $4\sqrt{SO}$	
		Longitudinal and transverse		Longitudinal and transverse	Longitudinal	Transverse
		Min.	Max.	Min.	Min.	Min.
S.99	H.T.S.	80	90	70	12	7
DTD.730	H.T.S.	85	95	70	12	7

Specification	Material	U.T.S. tonf/sq.in.		Yield Stress tonf/sq.in.		Elongation % $4\sqrt{SO}$	
		Longitudinal	All Transverse Directions	Longitudinal	All Transverse Directions	Longitudinal	All Transverse Directions
		Min.	Min.	Min.	Min.	Min.	Min.
L.76	Aluminium alloy	24	23	13.5	13	12	8
S.07.1001	Aluminium alloy	27	26	22	22	6	4
DTD.5024	Aluminium alloy - Non chromium bearing.	31	29	27	25	8	4 *
DTD.5034	Aluminium alloy - chromium bearing	31	29	27	25	8	4 *

Continued overleaf

APPENDIX 1 (Continued)

Specification	Material	U.T.S. tonf/sq.in.		Yield Stress tonf/sq.in.		Elongation % $4\sqrt{SO}$	
		Longitudinal	All Transverse Directions	Longitudinal	All Transverse Directions	Longitudinal	All Transverse Directions
		Min.	Min.	Min.	Min.	Min.	Min.
L.85	Aluminium alloy	24	24	20	18	8	* 6
DTD.731	Aluminium alloy	27	26	21	20	6	4
L.77	Aluminium alloy	29	26	25	23	6	* 4
DTD.5153	Titanium alloy	70	70	58	58	10	10
DTD.5143	Titanium alloy	62	62	57	57	15	15

* $2\frac{1}{2}$% in the short transverse direction for these materials.

NOTE :- The figures given in tables on Sheets 10, 11 and 12 are specification properties, or properties which have been agreed between the Purchaser and the Supplier and which can be guaranteed on forgings of all sizes, at locations specified on the forging drawing.
Where it is not dimensionally possible to use British Standard test pieces, B.S. sub-standard tensometer test pieces may be used.

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