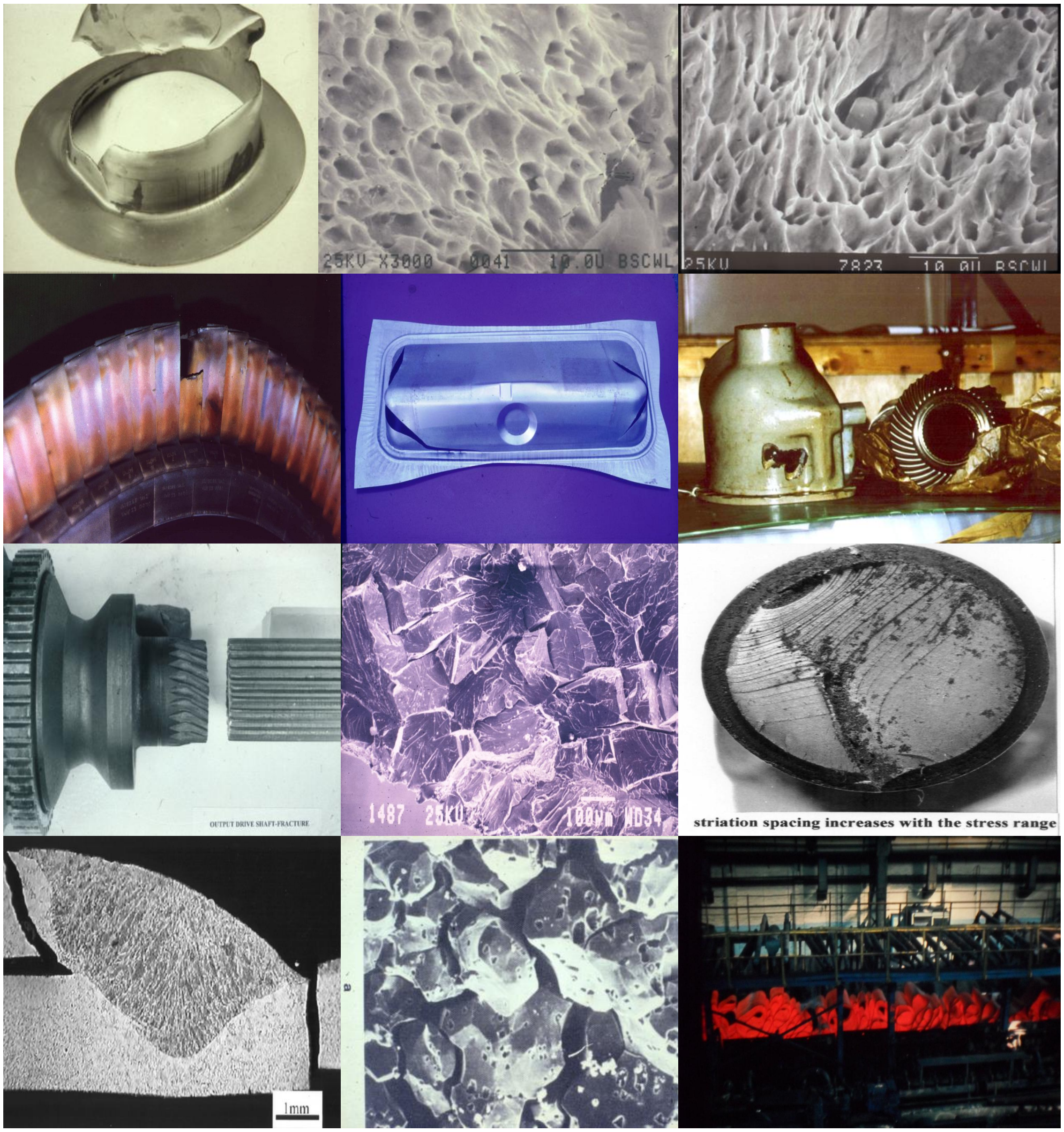
Examples of fractures, failures and rejections in engineering materials and components



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Preface

For over two decades, I have had the good fortune of lecturing to graduate, post-graduate and doctoral students of engineering at different universities within the UK and abroad. Engineering students of various disciplines, civil, mechanical, electrical, metallurgical, materials, aeronautical, etc deal with materials to varying levels of depth, penetration and expertise. Some even learn the basics of predictive failure analysis. Yet, they are not exposed to a broad spectrum of examples of failures, fractures and rejection of materials as well as components.

A civil engineer successfully designed a motorway bridge. Yet, within months after the opening of a new section of a motorway bridge in Melbourne in 1962, there was a collapse of this section in 1963; fortunately, no lives were lost. The reason for the failure was apparently related to the fusion welds that were employed to join the different steel sections. The civil engineer had little awareness of the complex metallurgical issues involved.

It is precisely for these reasons that an attempt is being made in this compilation to provide engineering students as well as those actively engaged in peripheral disciplines in the industry an awareness of the multitude of the issues involved when one studies failures and fractures in engineering components. This compilation covers a broad range of examples where, failures, fractures and rejections have occurred in the engineering and manufacturing sectors. It is hoped that this will prove to be a source of reference and will help to broaden the awareness of the readers and, indeed, enthuse them to probe deeper.

An introduction to this compilation

There are several reasons for failure:-

1. Rejection can be on the grounds of appearance.
2. Rejection can also result from poor surface quality
3. The properties not being uniform/consistent in a batch can lead to rejection
4. There can be premature failure in service
5. There can be failure of critical components that can endanger human lives
6. Failure of components can lead to the threat of litigation
7. Failures, fractures and rejections can lead to a big fall in profitability arising from a loss of business or delivery schedules not being met

Design engineers specify a list of material properties based on the requirements of the component. These properties are developed as a result of the presence of an appropriate microstructure in the material. Parameters such as the grain size, grain shape, precipitate type, size, volume fraction and distribution characterise the microstructure. Two essential factors govern the development of the microstructure-

1 the composition of the material

2.the processing parameters such as, temperature, time at temperature, strain, strain rate, heating as well as cooling rates, etc.
Given that the above two factors are controlled to precise limits and that they are reproducible, the material will develop a microstructure that is appropriate to the properties required.

In practice, however, problems arise due to several reasons; these include
1 properties are not up to specification
2 processing has been incorrect
3 unexpected loss of some key elements in the composition; such loss can occur due to segregation, oxidation or decarburisation during processing
4. incorrect design of components (as in faulty design of castings)
5. the use of incorrect temperatures (as in hot rolling), incorrect pressures (as in press shops that produce automotive panels, etc)
6. a general unawareness of the issues involved as well as a breakdown in communications

It is a combination of such factors that leads to failures, fractures and rejections of engineering components. The following compilation covers a broad range of these examples that have been observed in automotive, aerospace and engineering components produced from metallic as well as composite materials. The failed components used here as examples have been produced by a range of manufacturing processes that include rolling, deep drawing, hydroforming, welding, superplastic forming, protective zinc coating, etc.

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3.1 The stress-strain diagram

- From my experience of marking examination papers, students often fail to write the units of the X and Y axes , N/mm^2 or $Tons/inch^2$. They need to be reminded of the importance of this.
- The elastic modulus , E, influences the stiffness/rigidity in bending. This follows the equation Stiffness S= E.I where I is the moment of inertia. Students need to know why the E for steels is ~210GPa whilst that of aluminium is ~70GPa. For that matter, why is the E for diamond as high as 1050-1200 GPa ?
- The strain rate/ crosshead speed is small as one approaches the yield point; once, this has been recorded, the strain rate is increased so as to complete the test to fracture in a relatively short time.
- Implicit in the construction of the Engineering stress-Engineering strain diagram is the assumption that the cross-sectional area of the test piece remains constant. In reality, this is seldom the case since the area continually decreases with increasing strain. This is, hence, the reason why the True stress-True strain diagram is often more representative.
- Students need to appreciate that the strain beyond the yield point is plastic strain. Also, that the mode of straining here is uniaxial tension. Commercial press forming of sheet materials is often carried out at much higher strain rates; the stress systems are also much more complex than simple uniaxial tension. Hence, the question often arises as to how relevant are the data from such tests in being able to predict the material behaviour of automotive components produced under high speed (high strain rates) and complex stress systems.
- Material properties are affected by the strain rate. A case in point is the behaviour of sheet steels in cars subjected to crash velocities/ strain rates . The strength levels increase with the strain rate. Hence, the information derived from Fig1 bears no relevance to the conditions that prevail at high strain rates. The students need to be aware of this. In fact, the test procedure to determine the properties at high strain rates is more complex.
- Ductility is reflected in the value of the Total Elongation. Softer materials are more ductile. Students may also be invited to consider why face centered cubic metals such as Ni, Cu, Au, Ag, Al and gamma Fe are more ductile than body centered cubic metals such as Cr, Mo, and alpha Fe.

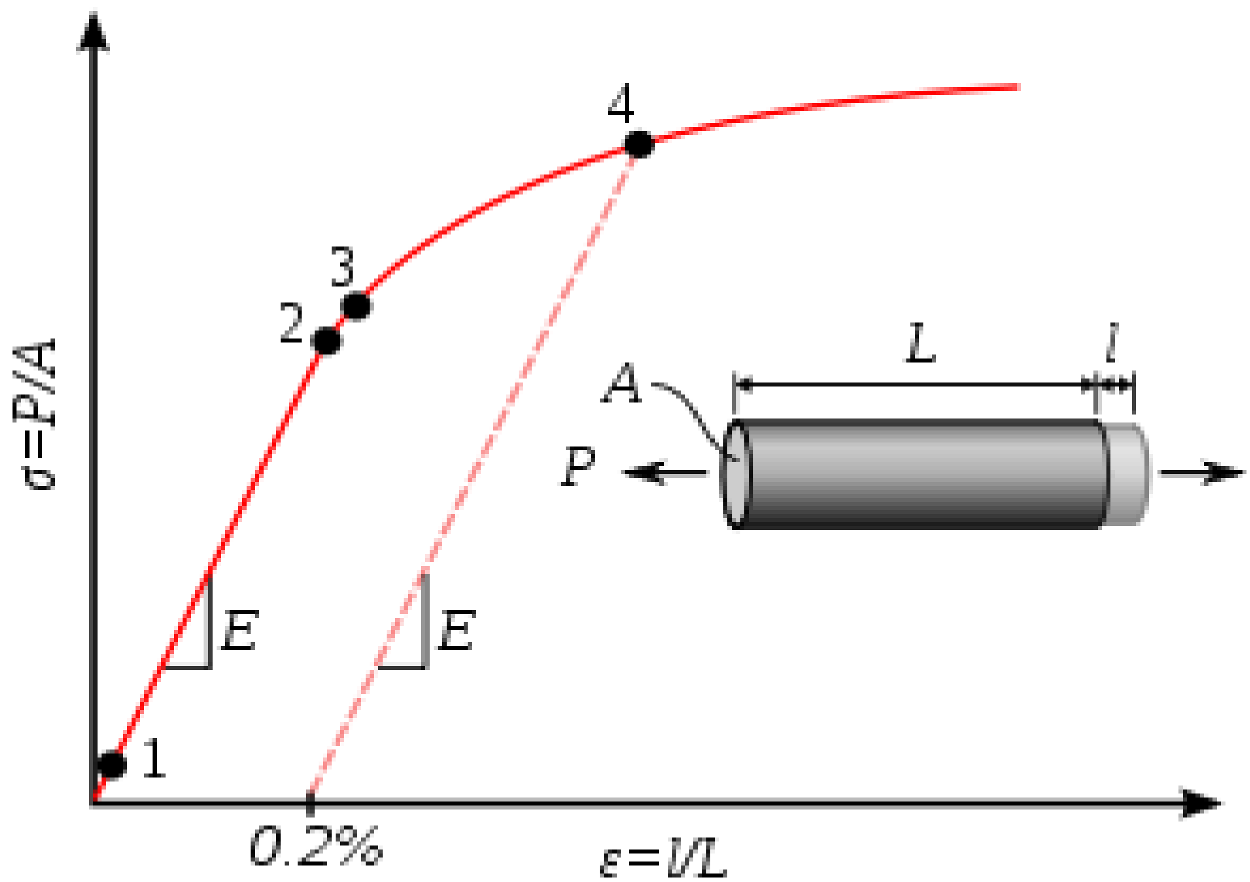


Fig.1 Stress–strain curve showing typical yield behavior for **nonferrous** alloys. Stress (σ) N/mm^2 is shown as a function of strain (ε)
1: True elastic limit
2: Proportionality limit
3: Elastic limit
4. 0.2% off set yield strength, known as proof stress
(data obtained from Internet.Wikipedia)

3.2 Discontinuous yielding and its effects

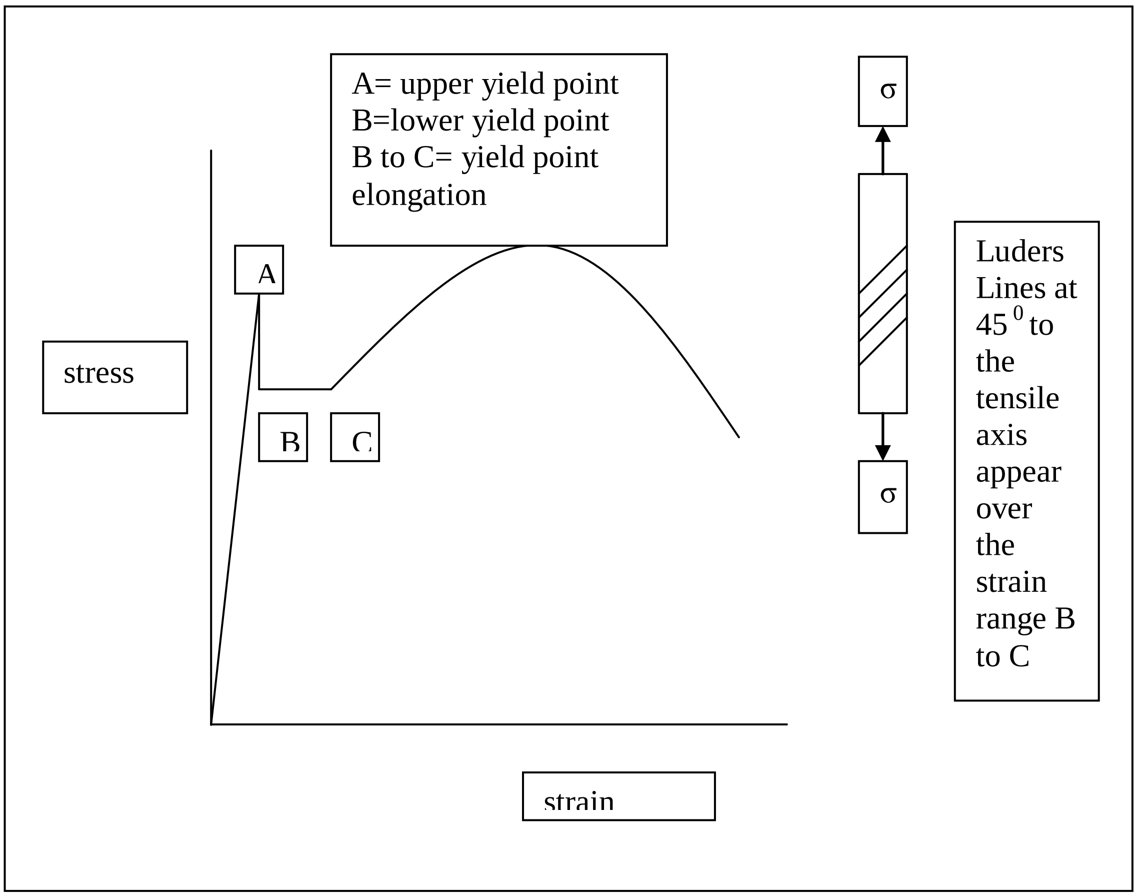
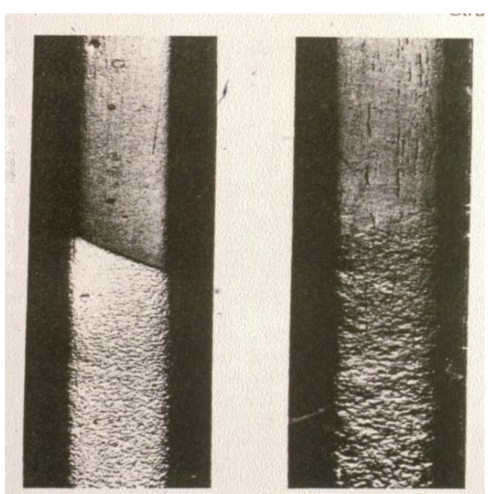


Fig 2 Stress-strain curve for steels

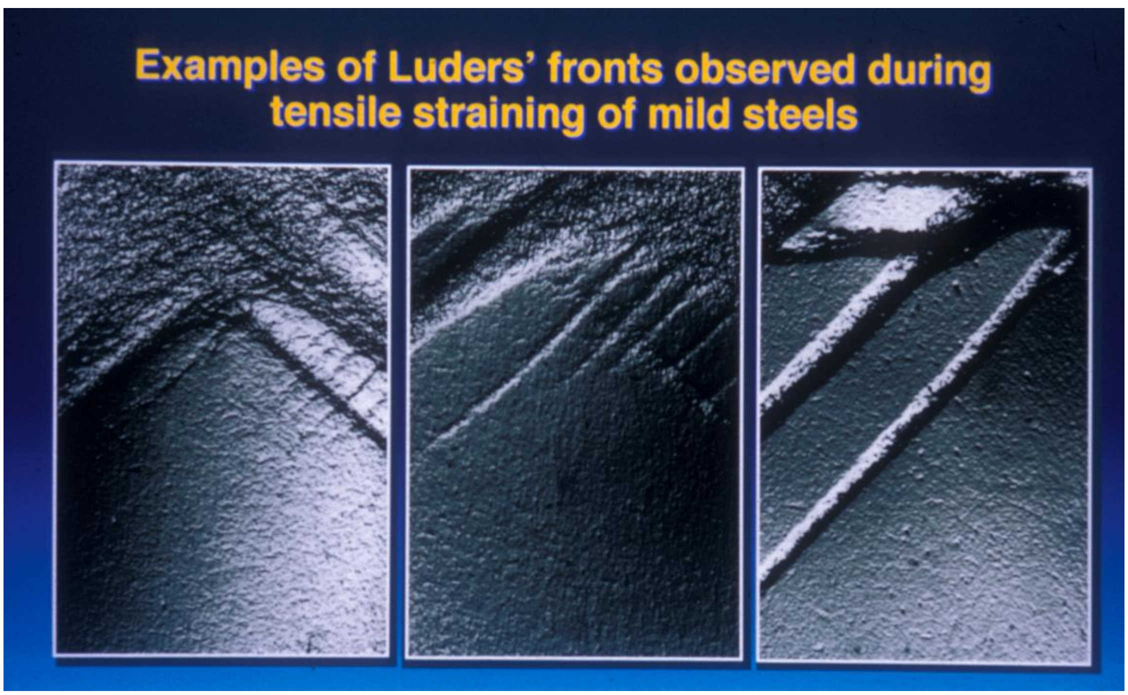
(Stress in N/mm^2)

Fig 2a



- Fig 2 shows discontinuous yielding ie. a sharp upper yield point, A, a lower yield point B and an yield point elongation (YPE)/BC in steels.
- YPE triggers the appearance of Luders bands at 45^0 to the stress axis. (Figs2,2a & 3). Why does this happen at 45^0? This is because the max. critical resolved shear stress is at 45^0 to the principal stress axis
- The students need to be aware of why this phenomenon occurs; that interstitial atoms , C and N are responsible for the pinning of dislocations, thus depleting the availability of mobile dislocations

Fig 3



In commercial pressings where the stress system is not merely uniaxial tension but, in fact , more complex, Luders lines are replaced by Stretcher Strain marks (Figs 4&5) . When sheet steels are used in the manufacture of external autobody components , door , roof, bonnet panels, etc, these Stretcher Stain marks are highly undesirable. In fact, they often lead to the rejection of otherwise sound materials on the grounds of the surface quality being unacceptable.

Fig 4

Fig 5

How is 'discontinous yielding' replaced by 'continuous yielding' in order to avoid the formation of 'Stretcher Strain marks on exterior autobody panels ?

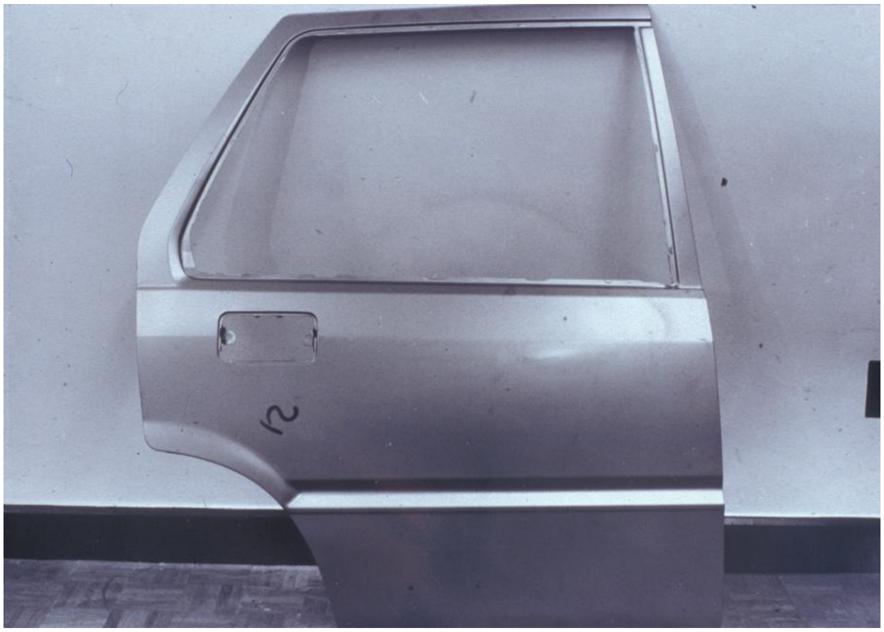
- Skin passing/Temper rolling, a very small amount (~0.8%) cold rolling of annealed sheet steels is the practice normally employed .
- By adding Ti or Nb to the steel; these tie the C and N up as TiCN or NbCN ; the steel thus becomes free of interstitials, C or N.

- The students could consider why this happens; the slight amount of cold rolling , most of which is confined to the skin provides just enough mobile dislocations to facilitate the progress of plastic deformation .In the absence of a well defined yield point, the parameter 0.2% proof stress is used instead (see Fig1)

3.3 Plastic deformation during forming of sheet steel components

We now proceed along the strain axis in Figs 1&2 and apply plastic deformation to produce the example shown in Fig 6

Fig6



This is a car door panel (outer), made from sheet steel, typically about 0.9-1.2 mm thick. The points to note are

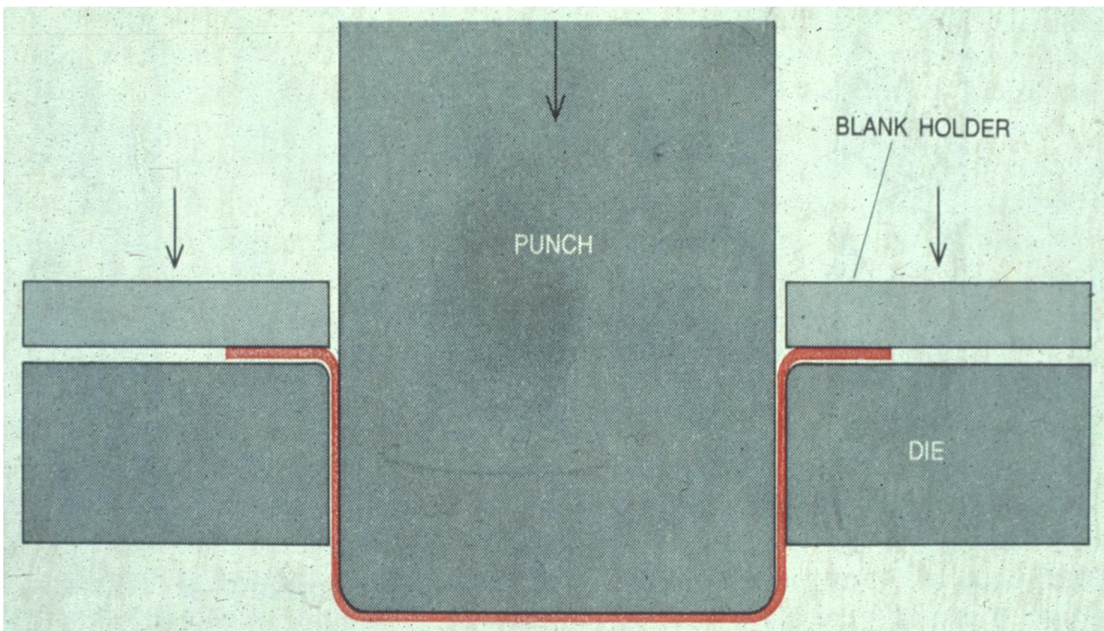
Levels of strain in the panel vary significantly; the students can guess as to the extent of strain gradient within the panel

- Some regions are more strained than others
- How is this strain applied ?
- Essentially, in commercial practice, there are two major modes of forming: deep drawing and stretch forming

3.4 Deep drawing

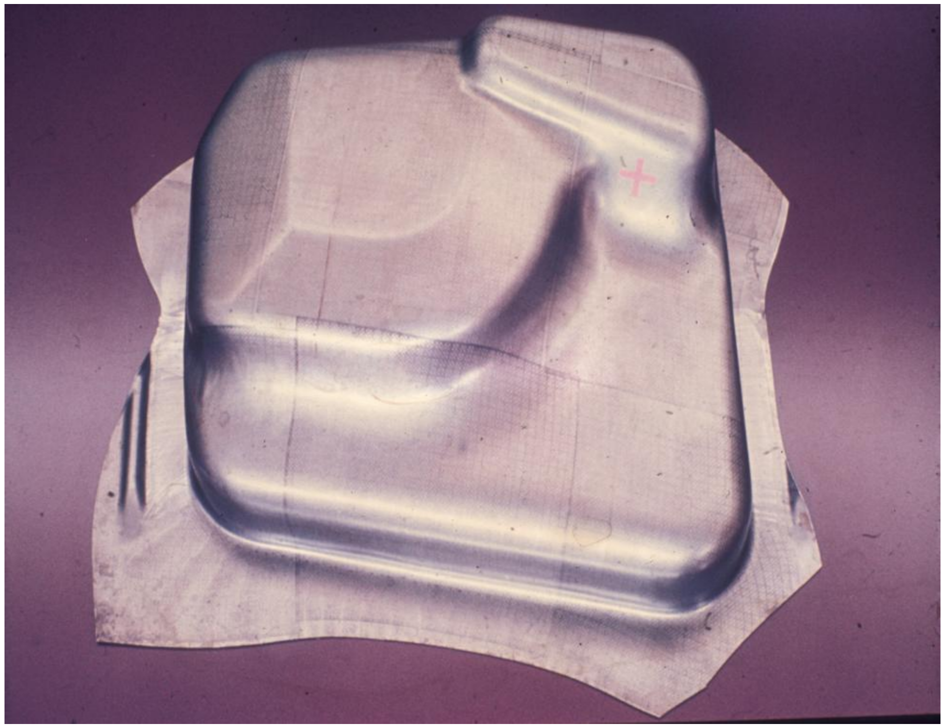
Fig7 The key parameters in deep drawing are

- The force on the punch,
- The rate of punch travel,
- The blank holder pressure



DRAWING, one of the two major modes of forming metal by stamping, is illustrated by the deep drawing of a cylindrical cup. The circular blank is drawn into the cup-shaped die by the flat-headed punch. The wall of the cup supports the major part of the load and tends to undergo thinning. Best material for drawing is therefore a material that is resistant to thinning.

Fig 8



- Fig 8 is a sheet steel (thickness ~ 0.9mm) pressing / an oil sump in a car
- The major mode of plastic straining is via a deep draw
- Deep drawability is assessed by the plastic strain ratio ie, the ratio of the width strain to the thickness strain in a tensile test piece/ Lankford parameter , R or r
- The corners exhibit ''ears'', this is because of anisotropy
- Anisotropy implies that the properties are different in the three directions ie. along ,across and at 45^0 to the direction in which the sheet was originally rolled in the mill
- The mean plastic anisotropy, R_m or r_m is $(R_0 + 2R_{45} + R_{90}) \div 4$
- Rolled sheet materials exhibit planar anisotropy
- Following the draw, all the ''ears'' are trimmed away from the main pressing

Fig 9

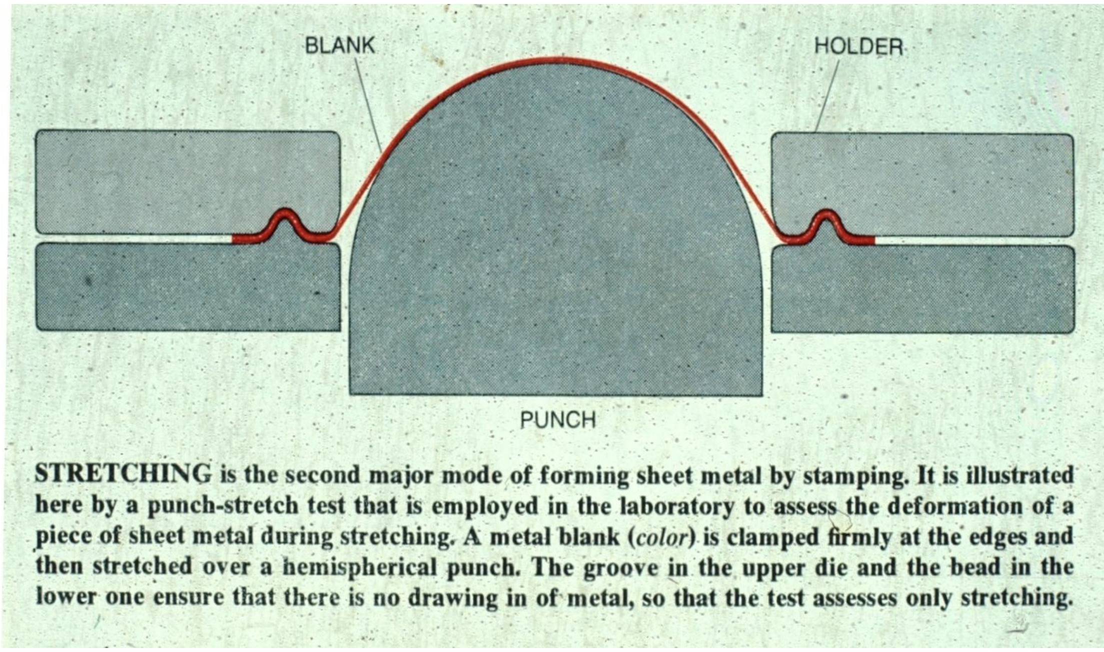
- This is from a sheet steel about 1.4-1.6mm thick
- This is an example of a failed draw
- The mean plastic strain ratio, R_m, calculated from the 0^0, 90^0

and at 45^0 to the rolling direction was relatively low

- Significant thinning is evident as the wall thickness strain rose to a high level. Also evident are the score marks on the wall; this may suggest that the tooling was not set correctly or that the level of lubrication was poor .

3.5 Stretch forming

Fig 10



- Stretching (Fig 10) is the second major mode of forming components from sheet
- Deformation around the radii of a bath or a kitchen sink is based on stretching/ for eg. the failure around the radii in the bath (Fig 11)
- The parameter, work hardening index, n, derived from the slope of the log.true stress log/true strain relationship, reflects the stretchability
- Components can fail when the 'n' value is low

Fig 11

Fig 12

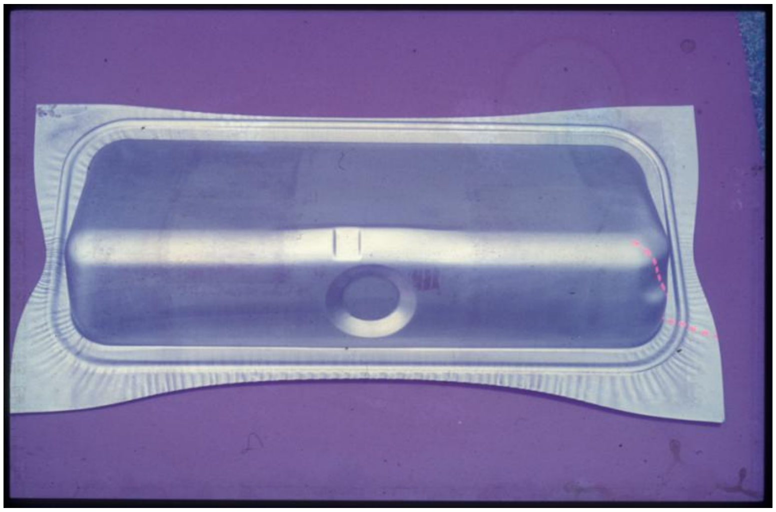
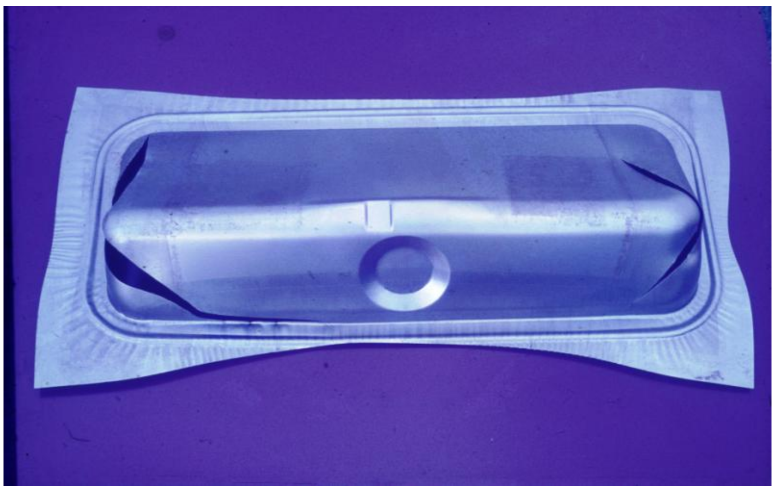


Fig 13



- Fig 12 shows a successful pressing based on a steel with good stretchability ie. a high ‘n’ value
- Fig 13 shows the failure around the radii of the component in a steel with a poor ‘ n’ value
- Other than this difference in the ‘n’values, both materials showed comparable deep drawaibity ie. their R_m values were similar
- Also to be noticed in both figures is the pronounced earing arising from anisotropy
- Clear evidence of wrinkling can be seen on the ears; this arises from inadequate blank holder pressure exerted during forming

3.6 Anisotropy and earing behaviour

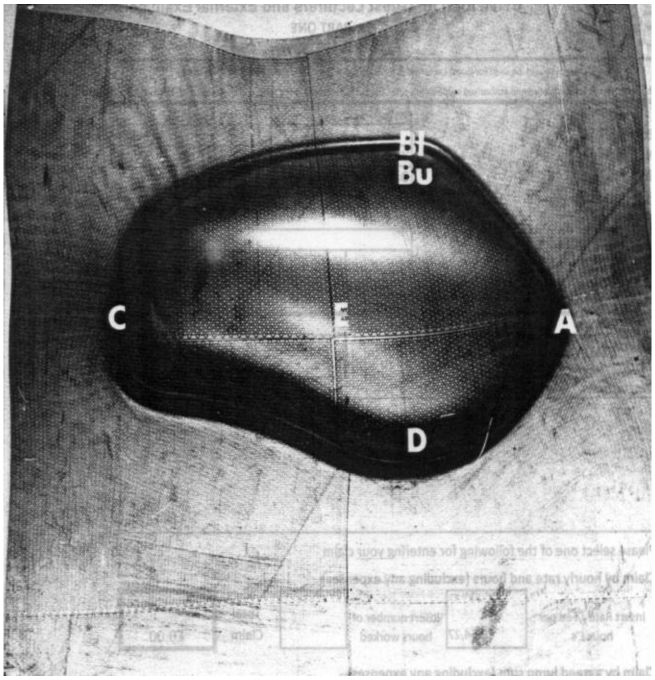
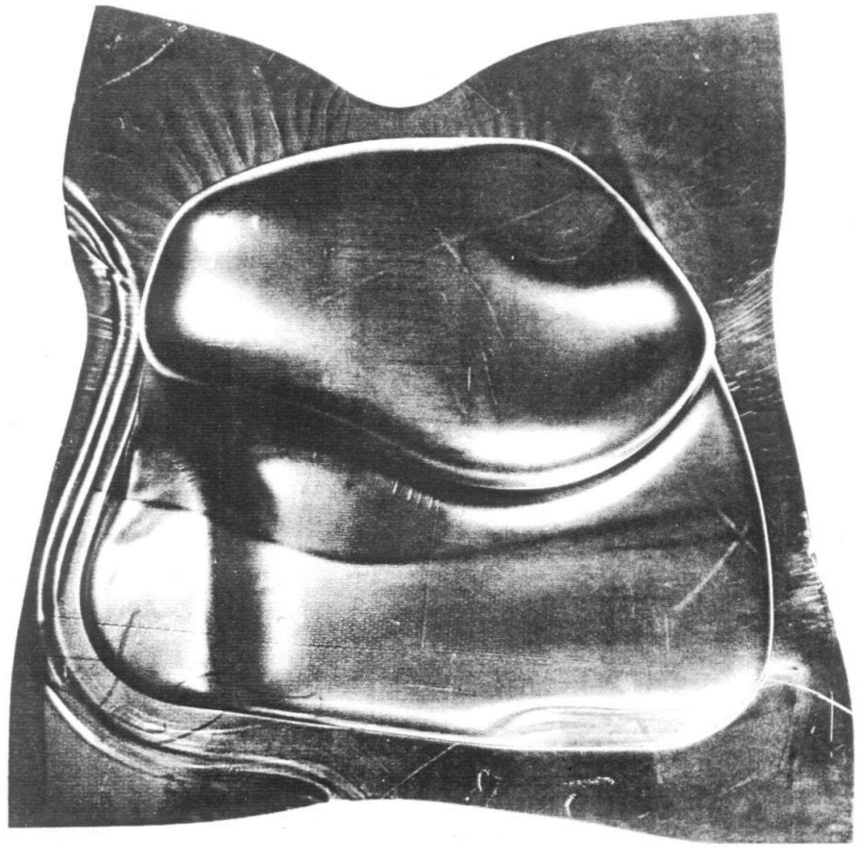


Fig 14a

Fig 14b ↗



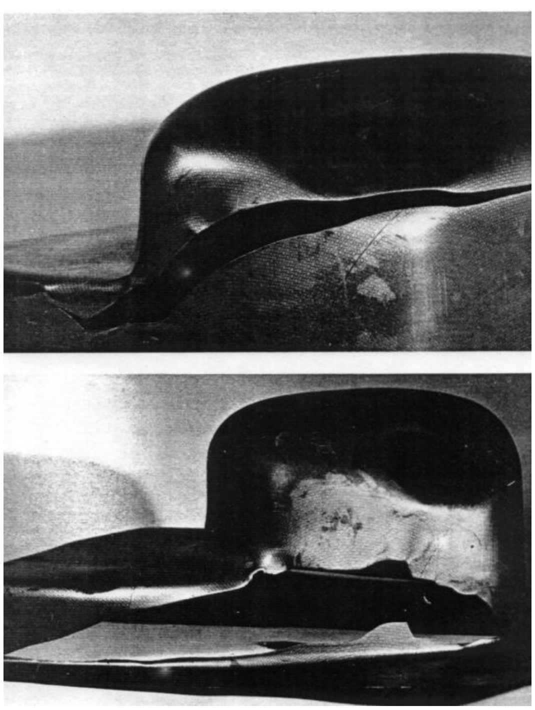


Fig 14a is the first stage pressing. Note the onset of earing. Fig 14b is the final pressing. Fig 14c shows the tearing that has led to the failure . A combination of poor deep drawabilty and stretchabilty has led to the failure.

Also evident are

a. pronounced earing due to anisotropy of the steel sheet
(seen in Fig 14b)

b. clear evidence of wrinkling ; evidently, the correct blank holder pressure may not have been used.

Fig 14c

3.7 Wrinkling during forming

Fig 15 shows the importance of the optimum blank holder pressure to be applied.(see also Figs 7 &10)

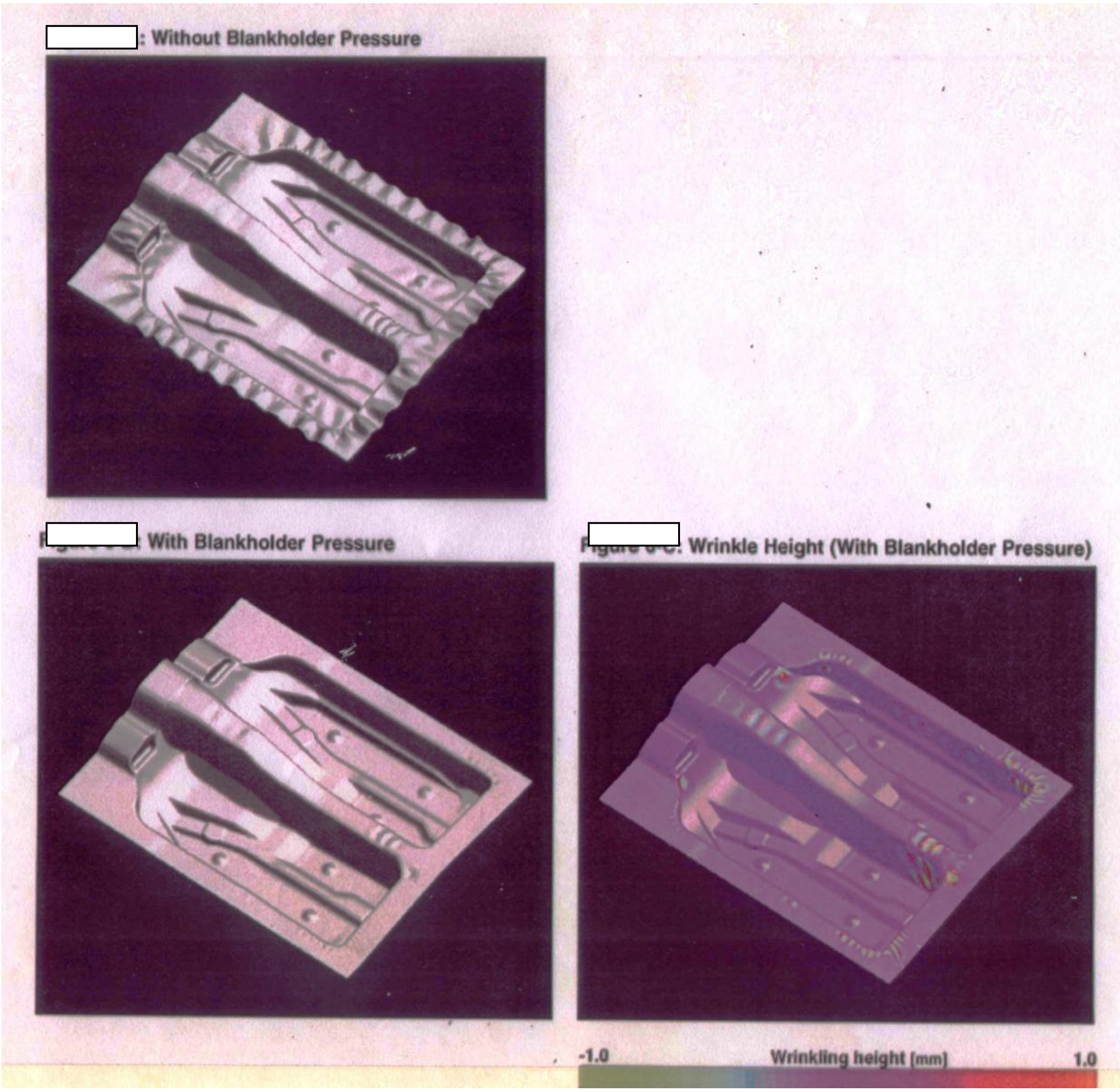
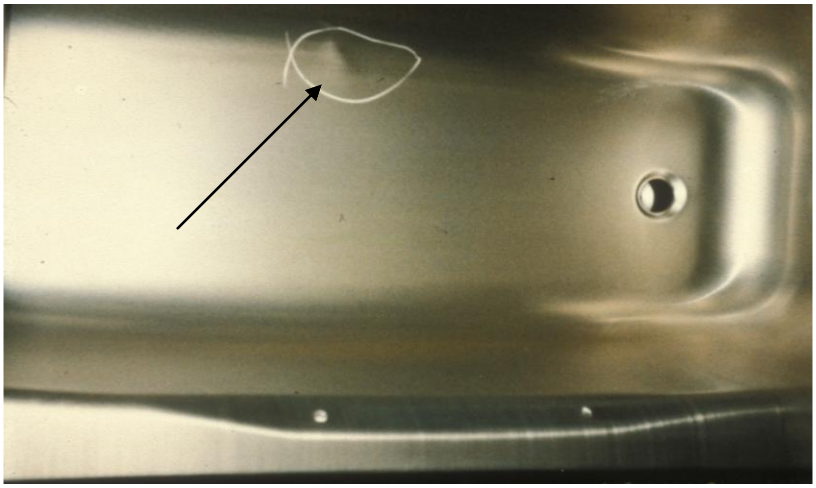


Fig 15

3.8 Rejection of formed components due to other reasons

Internal defects such as non-metallic inclusions (to be described in detail later) can result in failures in otherwise sound pressings. An example is seen in Fig 16.

Fig16



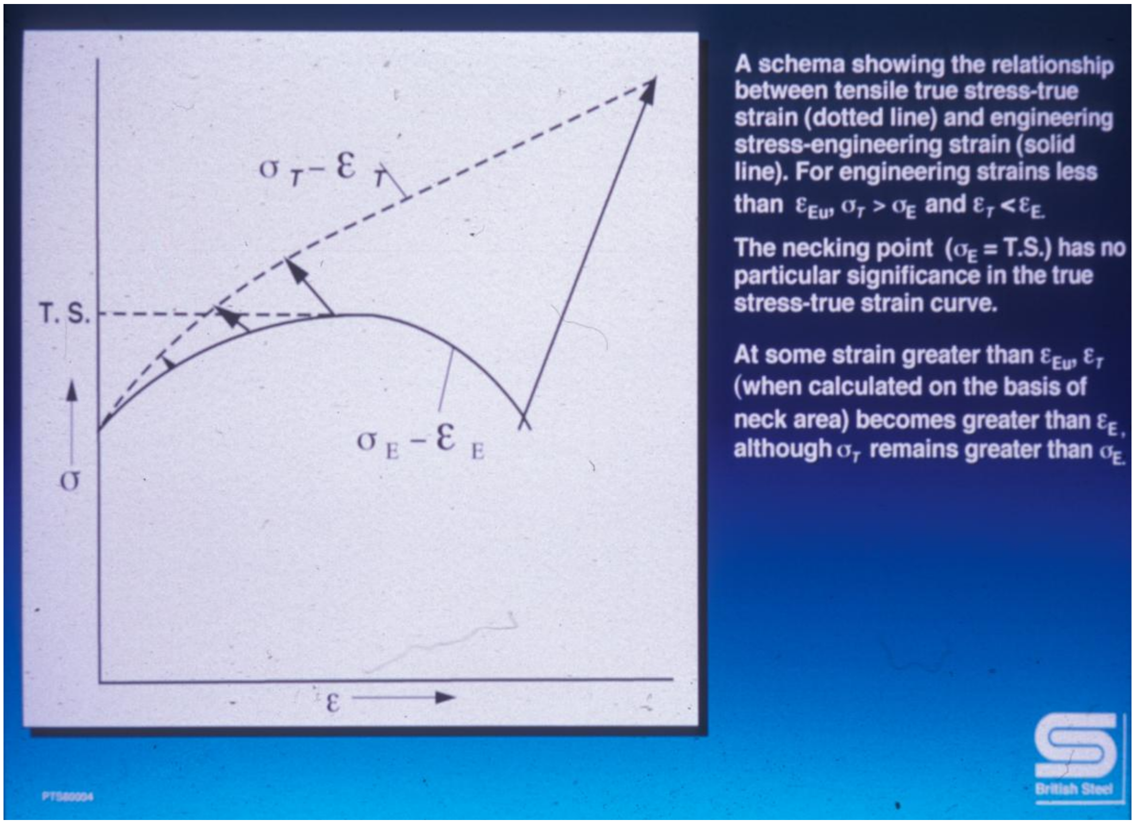
The settings in the press can have very significant effects on the operation. Material that is entirely satisfactory can be rendered useless by incorrect press parameters, such as the rate of punch travel, force applied on the punch, blank holder pressure, die clearance , level of lubrication, etc. (Fig17).

Fig17

3.9 True stress-True strain curve

Fig.18 shows the difference between the Eng. stress/Engineering strain curve and the True stress/True strain curve. With the former, it is assumed that the cross sectional area remains unchanged whilst with the latter, the cross sectional area changes steadily with increasing strain.

Fig 18



As the level of strain increases, we approach the point of plastic instability; in ductile samples, a typical necking failure is the outcome (Figs 19 &20).

3.10 Ductile fractures and effect of non-metallic inclusions on ductility

Fig 19 Ductile fracture in a rod sample   Fig 20 Ductile fracture in a sheet sample

Ductile materials exhibit significant total elongation prior to fracture. Typically, with a well annealed sheet steel (mild steel), the total elongation over a 50mm gauge length can exceed about 40%.Fig 21 shows a scanning electron micrograph of a typical ductile fracture; the fibrous nature of the fracture is clearly evident.

In industrial applications , there are many occasions when a seemingly ductile material fails prematurely. This is because of the presence within the material of non-metallic inclusions (NMIs); these are metallic oxides, sulphides and silicates that get entrapped during solidification. Particles of entrapped slag or eroded refractories used in the tundish whilst teeming get worked within the material during forging or extrusion or hot rolling, cold rolling etc. These NMIs are sub-microscopic particles that often escape detection by conventional tests. However, when the material is used to produce components, these particles act as stress raisers and lead to the fracture or splitting during forming. The particles create voids around them, adjacent voids coalesce thereby creating large discontinuities within the material. These are shown in Figs 22-25.

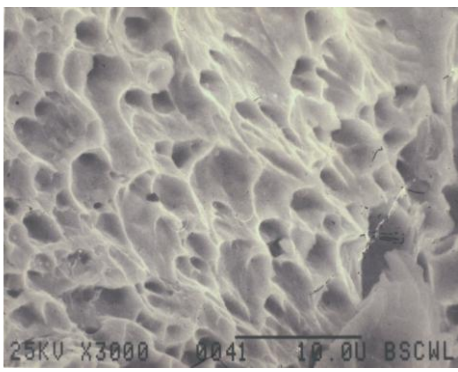


Fig 21 Ductile fracture

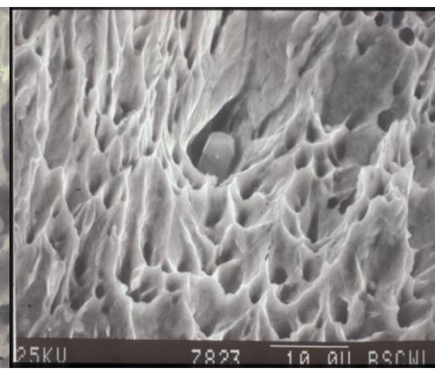


Fig 22 Ductile fracture showing a NMI & a void around it

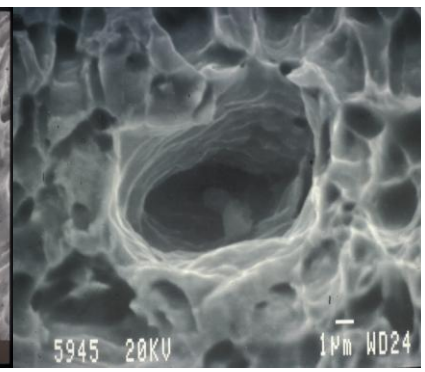


Fig 23 Ductile fracture & an enlarged void with a NMI within

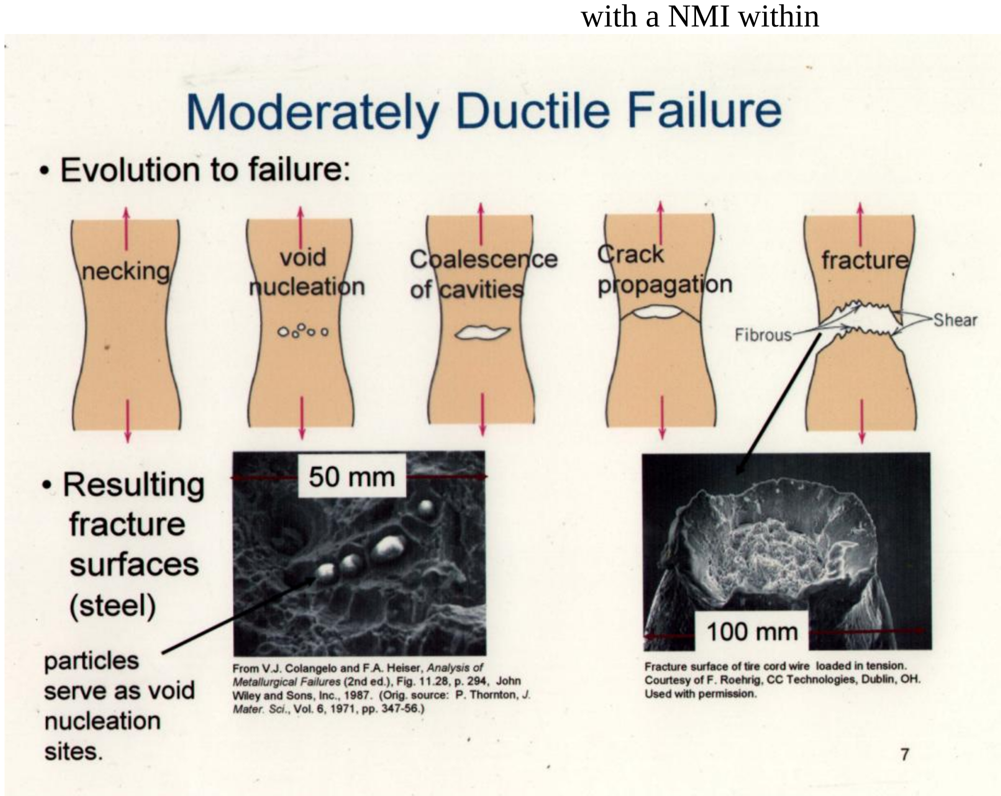


Fig 24 Effect of NMIs (from Roehrig, CCtechnologies, Dublin/ obtained from the Internet)

Due to poor production practices, commercial materials can, at times, suffer from a higher than normal level of contamination from NMIs. Fig 25 is an example. Components produced from such a material will fail either during the production stage or after a very short time in service.

Fig25

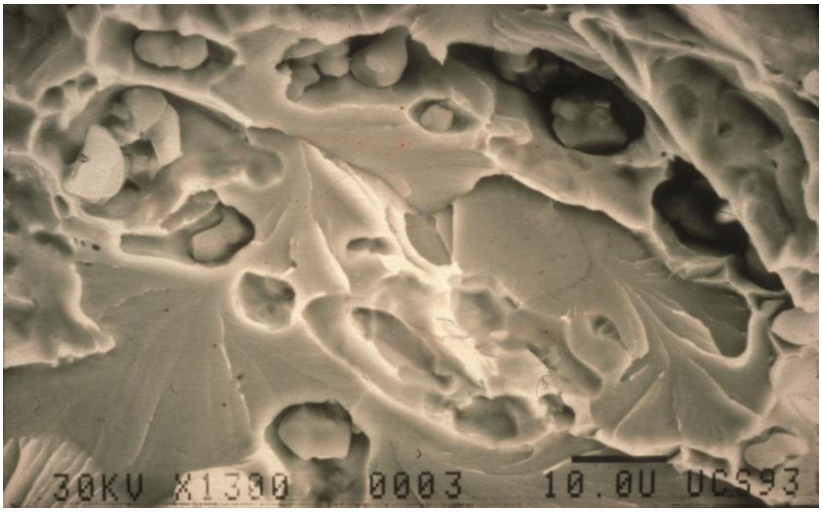


Fig26

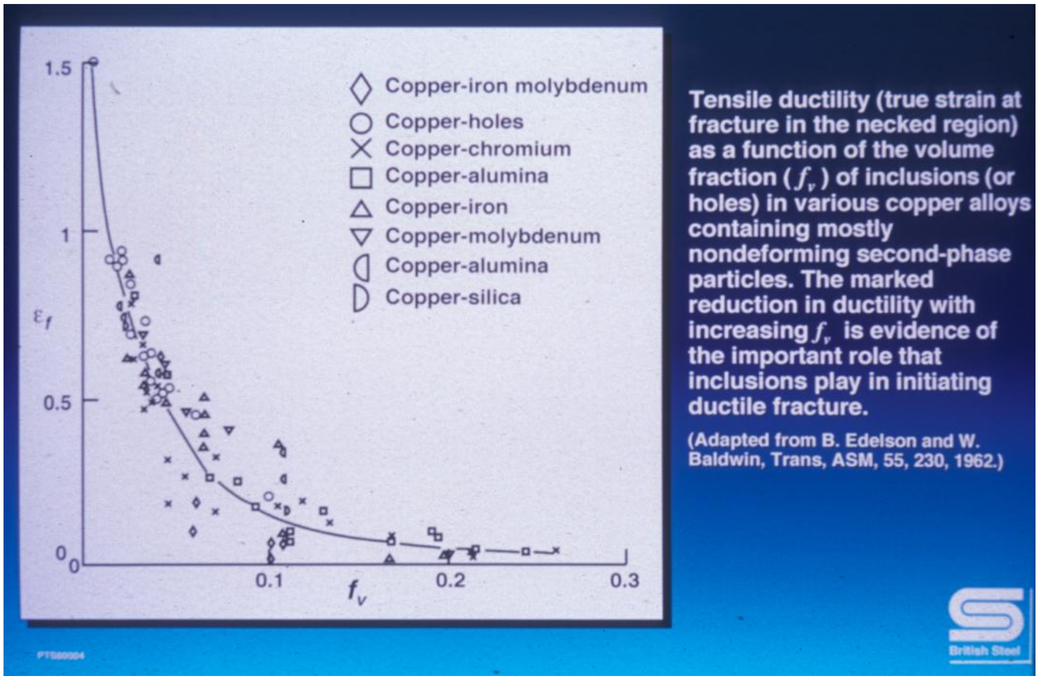


Fig 26 clearly shows that production practices need to be very carefully controlled in order to drastically reduce the NMI count. This is particularly important in the case of critical aircraft components such as turbine discs and blades. The level of inspection must be such that freedom from NMIs down to an agreed size is ensured in the material supplied to the customer.

3.11 When and why do materials fail in a brittle manner ?

Fig 27

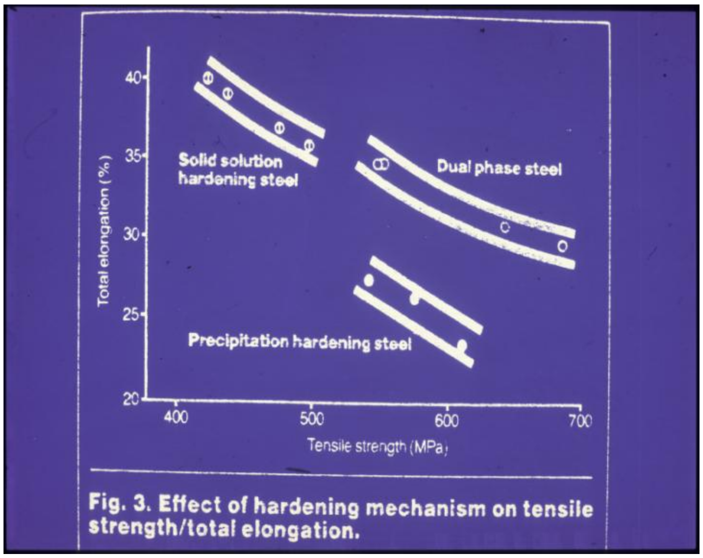
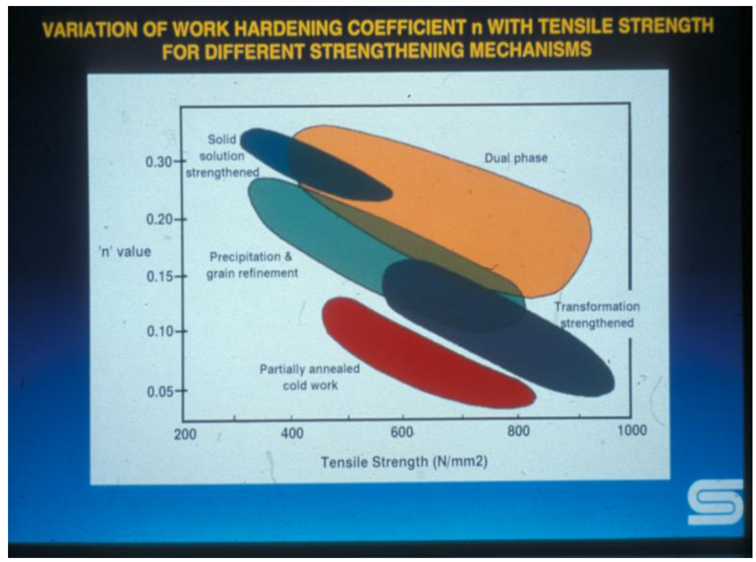


Fig 28



It is clear from Figs 27 and 28 that the ductility (as measured by the 'total elongation to fracture') and the stretchabilty (as measured by 'n', the work hardening index / see also Fig 10) decrease as the tensile strength increases.
Martensitic steels are typical examples. Heavy cold working , for example, by cold rolling, wire drawing or extruding, also leaves the materials with very low ductility. In these instances the materials fail in a brittle manner.

Materials that are otherwise ductile at ambient temperatures and above can fail in a brittle manner when exposed to sub-zero temperatures. This is known as the 'ductile to brittle transition' behaviour, typical of Body Centered Cubic (BCC) materials such as Fe (steels), Cr and Mo. Plate or structural steels that are used in oil rig installations, platform decks, jacket legs secured to the sea bed are examples where the steels are alloyed with nickel to ensure that the components do not fail on impact in a brittle manner when exposed to temperatures of around -40 to -80^{0}C.

Figs 29- 31 are examples of heat treated steel components that failed in a brittle manner.

Fig 29

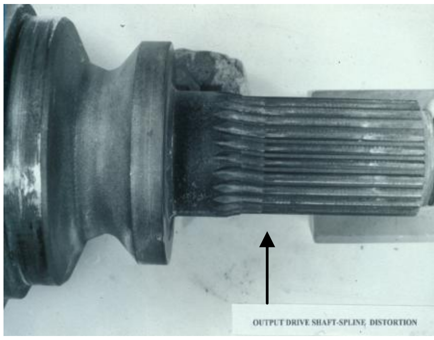


Fig 30

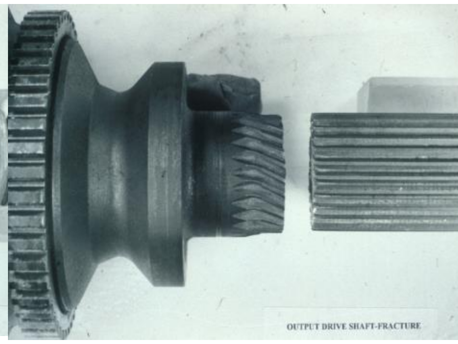


Fig 31

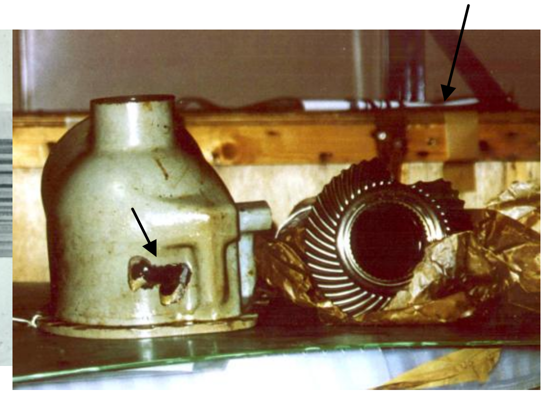
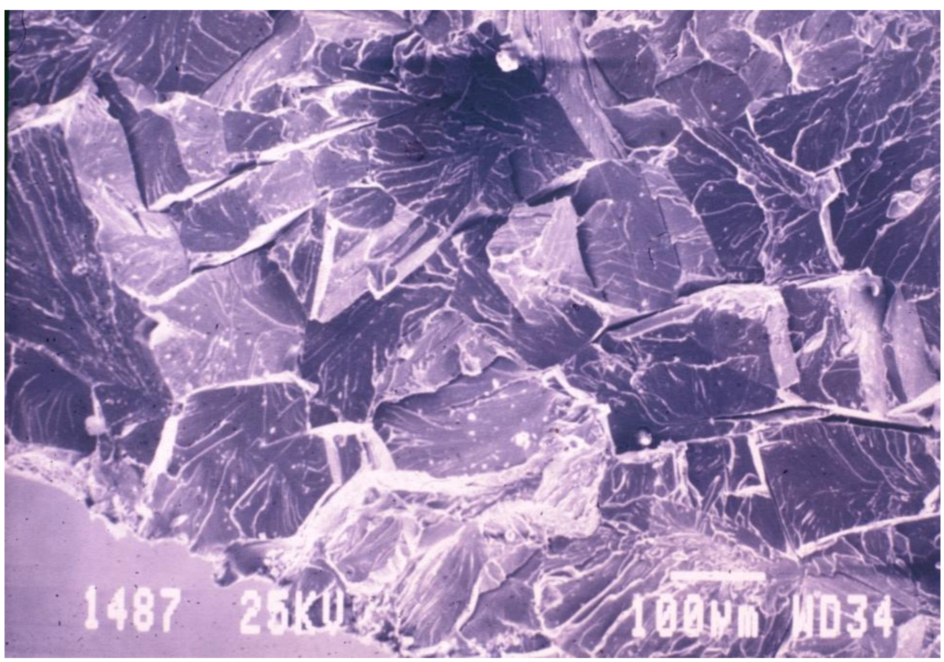


Fig 31 is a part of the drive shaft (shown in the right of the figure), a broken fragment of which impacted the wall of the magnesium casting oil sump (shown in the left of the figure) within which the drive shaft is located. The impacting broken fragment tore a hole through the casting(shown with an arrow) and led to a total loss of the oil within the sump.

Fig 32 is an example of a typical brittle fracture , also known as a clevage fracture.

Fig 32



3.12 Fatigue failures

Fatigue fractures similar to those in Figs 33 (a bolt) & 34 (a pulley) show features, often described in books as clam shell markings or beach markings.

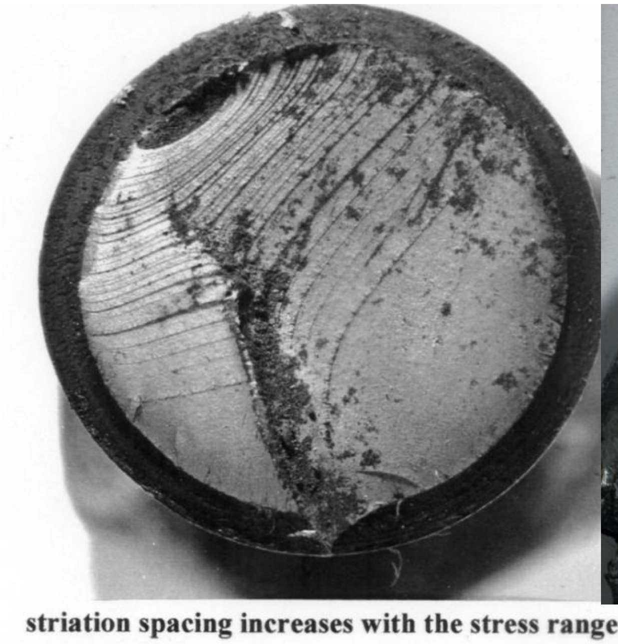


Fig 33

Fig 34

In the electron microscope, these striations appear as in Fig 35. Fig 36 explains the manner in which these striations appear on the fracture surfaces.

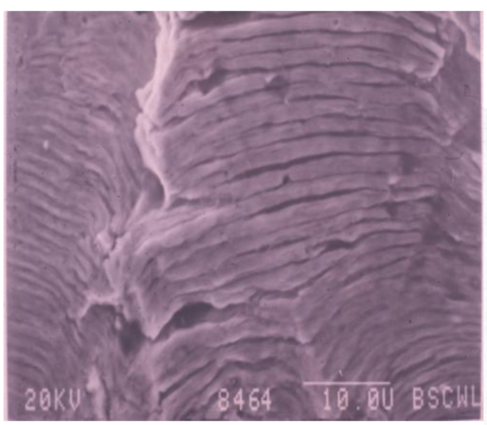


Fig 35

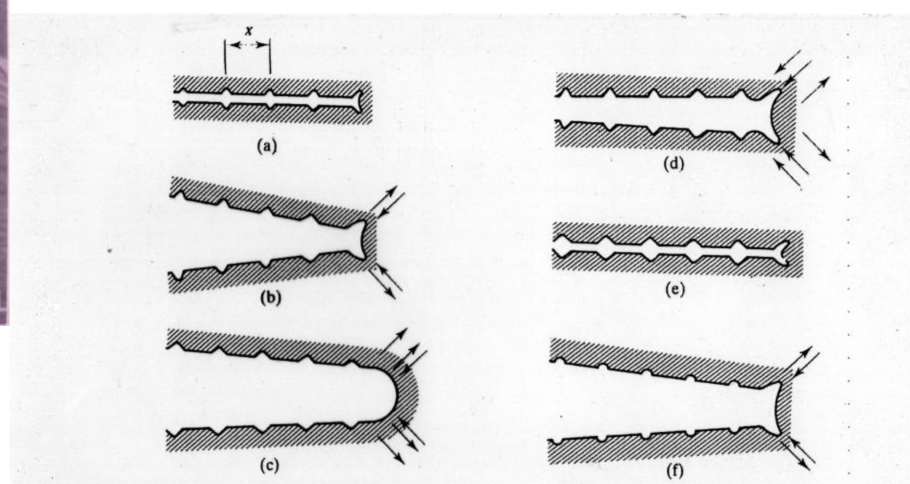


Fig 36 →

Schematic mechanism of fatigue striation formation.

(a) A fatigue crack with characteristic striae spacing, x. As the tensile stress is increased, the crack opens (b), and plastic deformation blunts the crack (c). On stress reversal, the blunting i removed (d), and the crack has advanced by the characteristic distance x. The process is ther repeated (e, f). (Note; the stressaxis is vertical.)

(Adapted from C. M. Laird, ASTM STP415, Philadelphia, Pa. 130, 1966.)

Fig 37 shows an example of a valve spring (info. supplied from Ford/Dunton) that had failed in fatigue prematurely. Examination of the fracture surface showed that the cracks that led to the failure of the spring had nucleated from a NMI that was embedded within the steel. This is seen if Figs 38&39. The role of the NMIs is also seen in Figs.21-26.

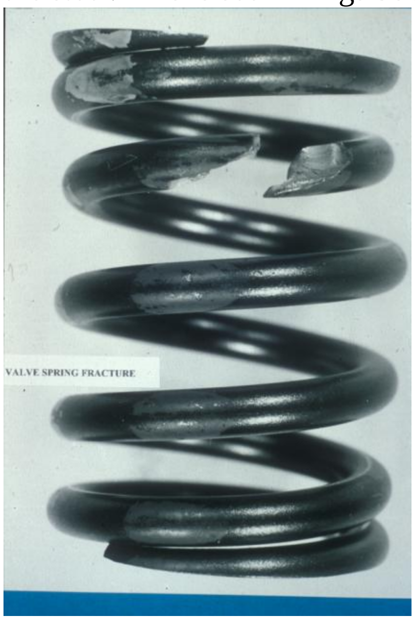


Fig 37

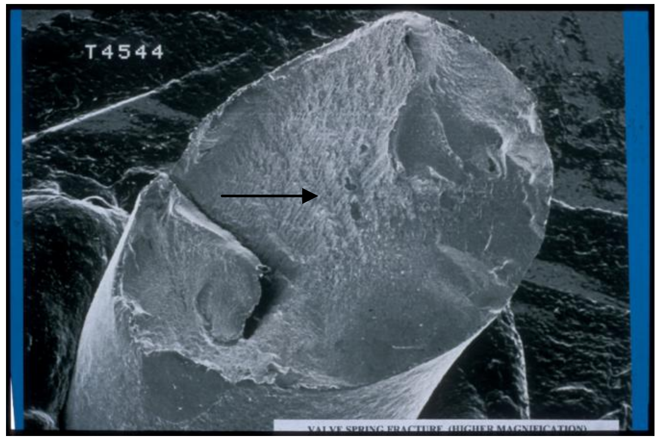
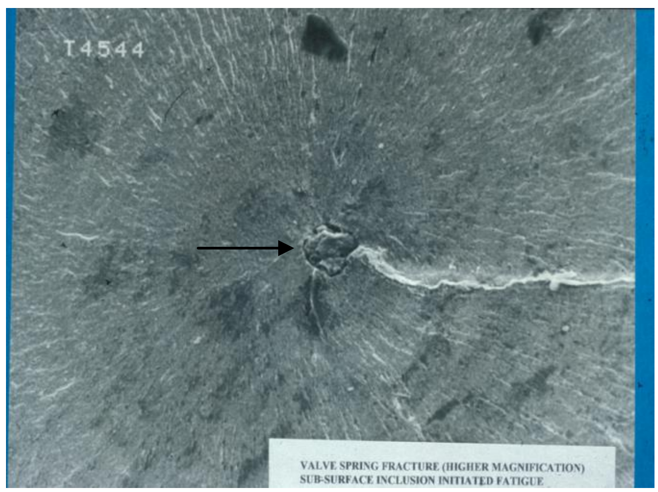


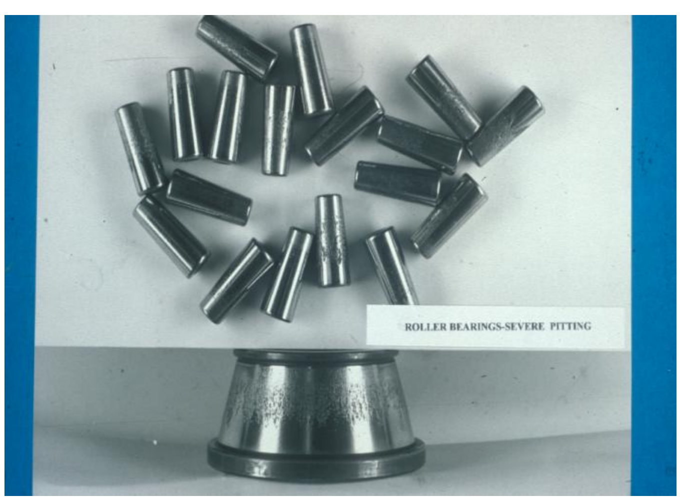
Fig 38

Fig 39 →



Other issues in this context are examples of abrasion of components subjected to fatigue loading . Fig.40 shows the pitting/ abrasion and wear on the roller bearings and the cage.

Fig 40



3.13 Failures in welded structures

Fig 41

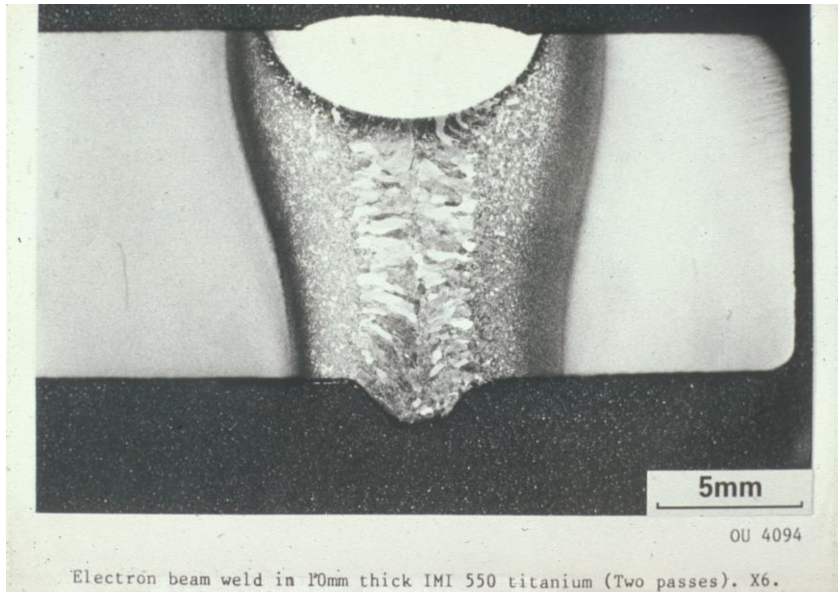


Fig 42

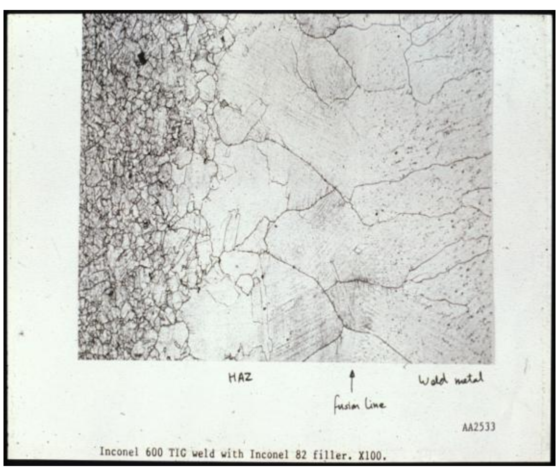


Fig 43

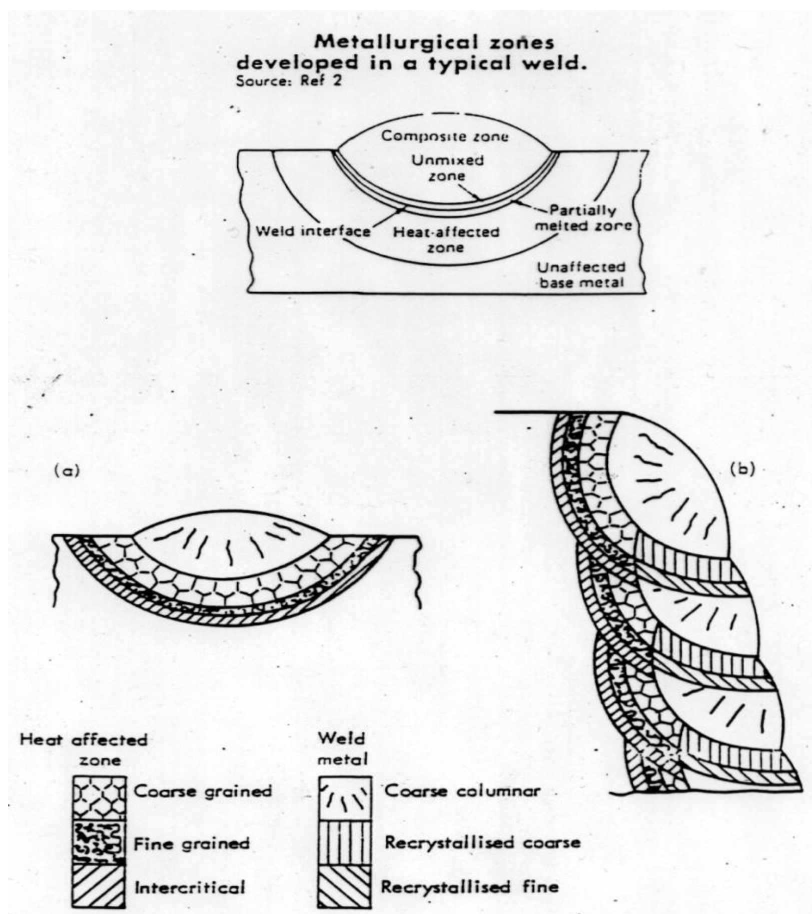


Fig 44

Examples of the 'Heat Affected Zone ' HAZ, are seen in Figs 41-44. Potentially, this area is most prone to failure for a number of reasons.

1. The weld metal solidifies , there is a change from the liquid to solid state with accompanying volume changes.
2. The weld metal may often exhibit porosity as well as large dendritic crystals, similar , in principle , to as- cast structures.
3. Rapid cooling as the heat source is removed can lead to the formation of martensite that is hard and brittle
4. Rapid solidification can also lead to residual stresses in the HAZ.

Fig 45

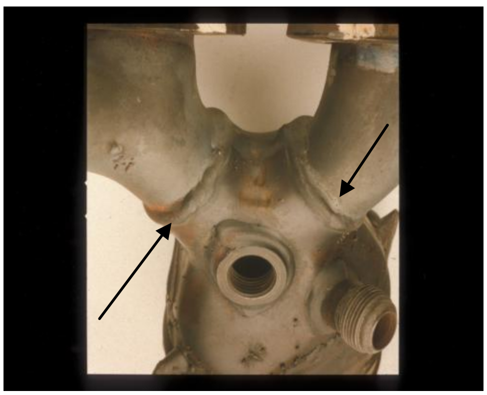


Fig 46

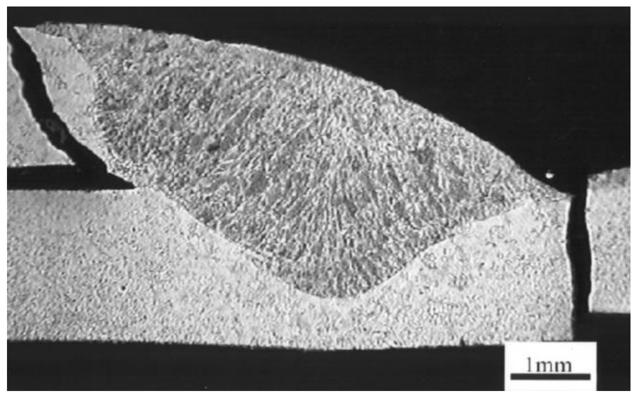


Fig 47

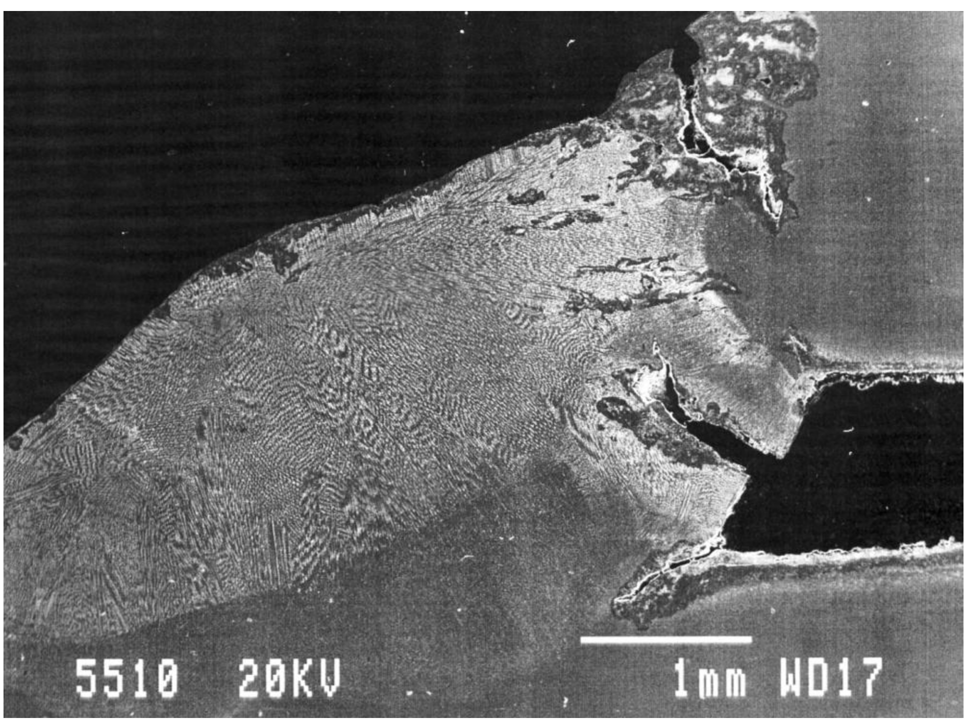
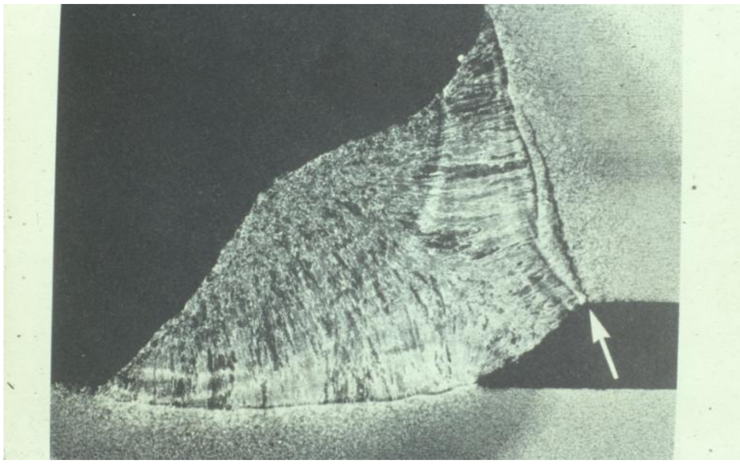


Fig45 shows the fusion welds in an automotive component made from an austenitic stainless steel. On cooling from the weld heat as the electrode is removed, certain areas in the immediate vicinity of the weld transform to martensite. Potentially, this leads to brittleness in the HAZ. Figs 46 & 47 clearly show the failure in the HAZ. It is interesting to note in Fig 47 that the weld area exhibits a ‘ herring bone’ appearance, typical of as – cast structures.

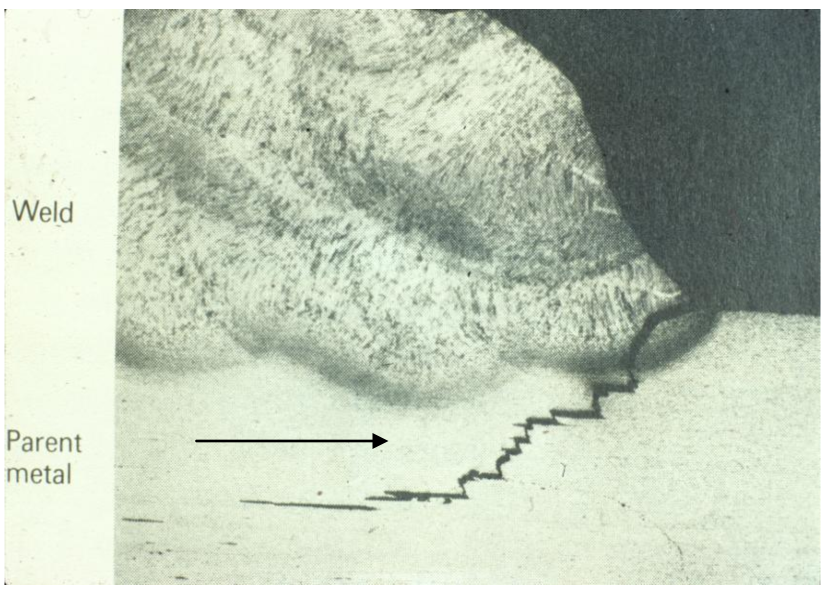
Damp electrodes can often be responsible for the entrapment of hydrogen which leads to the weld cracking in the vicinity of the HAZ. An example is shown in Fig 48.

Fig 48



The role of the NMIs has already been shown in several examples of failures in Figs 22-26 and Figs 37-39 . NMIs that remain relatively soft at hot rolling temperatures such as ~1200 ^{0} C get deformed and are strung out along the rolling direction; they remain undetected within the hot rolled product. When components produced from such materials are welded and put into service, they fail in a manner similar to that seen in Fig 49.

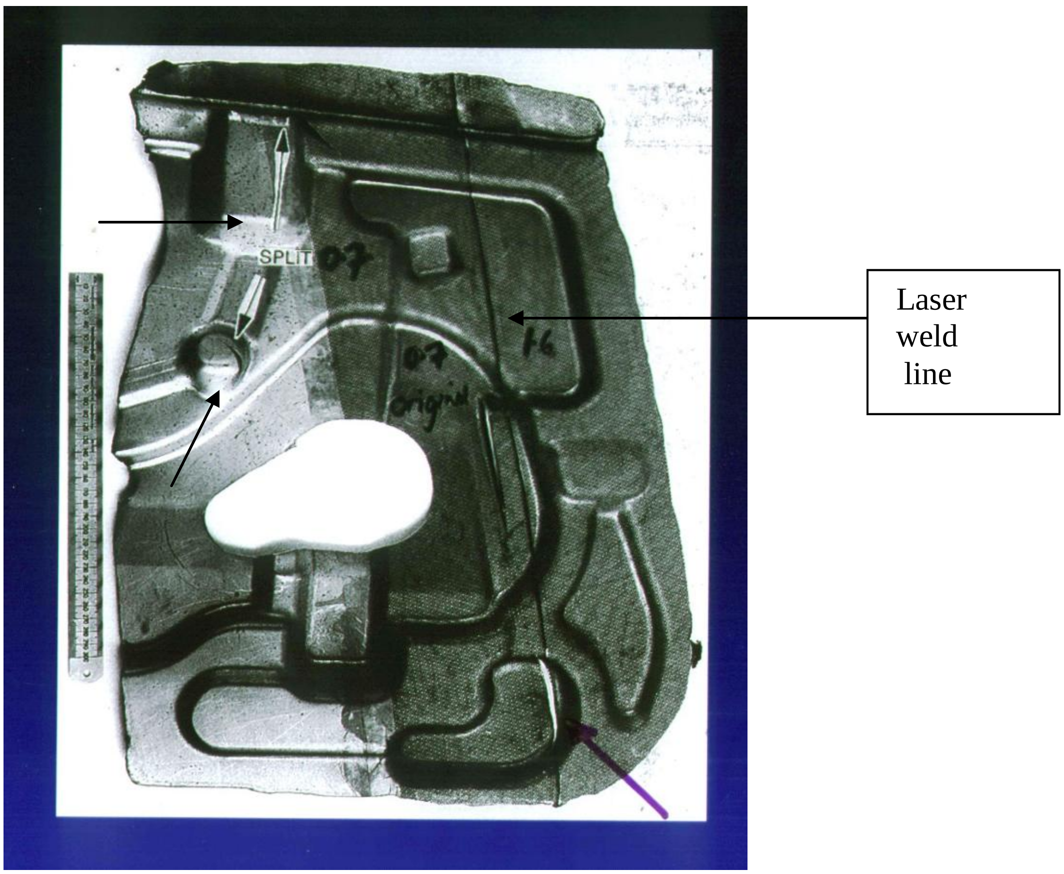
Fig 49



The strong directionality of the almost parallel cracks indicates that the cracking has taken the line of least resistance ie. along the directionally strung out NMIs within the material.

Laser welding is widely used in autobody manufacture, the main advantage being that materials of different strength levels and thicknesses can be joined together in order to reduce the weight of the vehicle. Problems often occur in laser welded assemblies because of the differential stresses being set up during the forming operations. The example shows a pressing made up steel sheets of two thicknesses (0.7mm and 1;6mm).Fig 50.

Fig 50



The thinner (0.7mm) steel has split in the vicinity of a deep draw.

3.14 Failures in castings

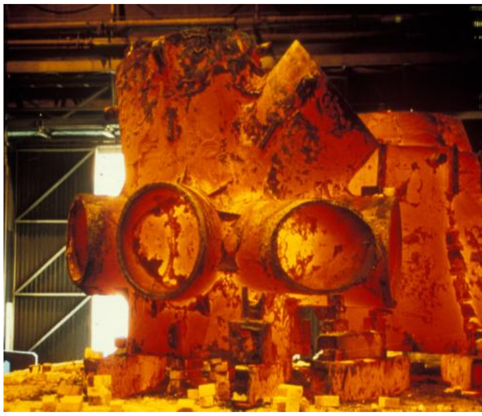


Fig 51 Fig 52 Fig 53

Figs 51-53 are examples of massive steel castings (about 75 -100 Tonnes in weight) produced by the River Don works , Sheffield .These are used as nodes to secure the jacket legs that are fixed in the sea bed. These stabilise the platform decks in the off-shore oil industries. (photos/ courtesy of Dr. Roger Richardson)

An important point to appreciate whilst dealing with castings relates to the dendrites that form as the casting solidifies. After the formation of the chill /equiaxed crystals immediately adjacent to the mould surface, large dendritic crystals (shown by an arrow in Fig 54) form and grow in the direction of the temperature gradient. The bigger the casting, the slower the cooling rate and larger is the size of the dendrites.

The Tables below show how the size and the manner of castings affect the cooling rates and, hence, the size of the dendrites.

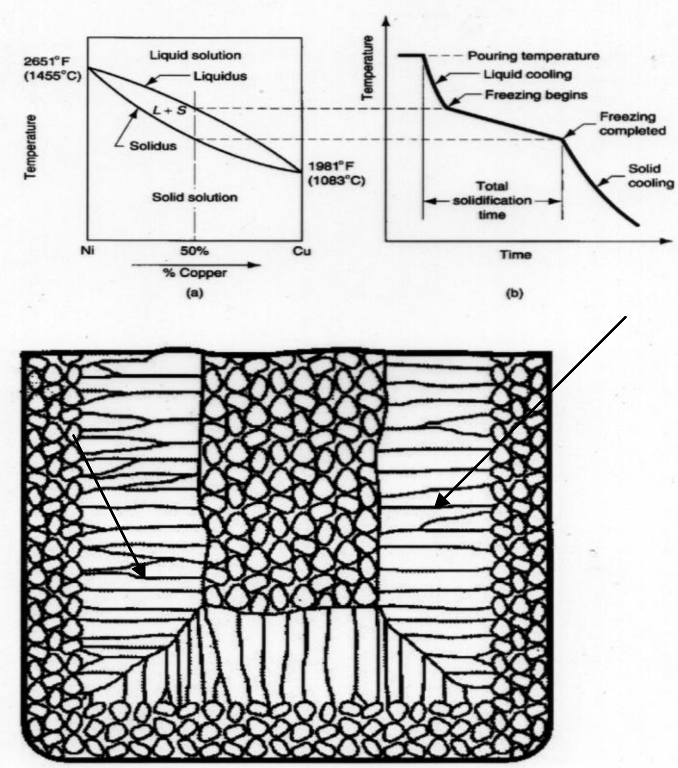


Fig 54

Range of cooling rate Ks^{-1}	Designation of cooling rate	Production processes	Dendrite arm (µm)
10^{-4} to 10^{-2}	slow	Large castings & ingots	5000 to 200
10^{-2} to 1	medium	Small sand castings & ingots, Billets & bar continuous castings	200-50
1 to 10^{3}	Near-rapid	Strip casting, die casting, coarse powder atomization, spray casting, semi -solid forming, metal-matrix composite casting	50-5
10^{3} to 10^{9}	Rapid	Melt spinning, fine powder atomization, thin strip casting, electron beam or laser surface melting	5-0.05

Example	Surface Cooling rate (Ks^{-1})	Surface Dendrite Arm Spacing DAS,µm	Centre Cooling rate (Ks^{-1})	Centre DAS, µm
100 mm thick sand casting	0.02	184	0.02	184
100mm thick chilled casting	3.2	35	1.2	47
3mm thick die casting	3.6×10^{3}	3.3	1.3×10^{3}	5
100 µm thick splat – cooled droplet	3.2×10^{6}	0.35	1.2×10^{6}	0.5

Top Table- Range of cooling rates in solidification processes Bottom Table- Cooling rates & Dendrite Arm Spacings (DAS) in an Al-Cu alloy

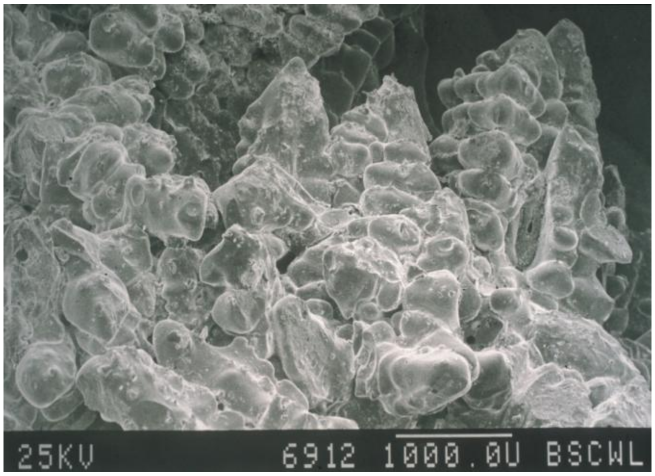


Fig 55

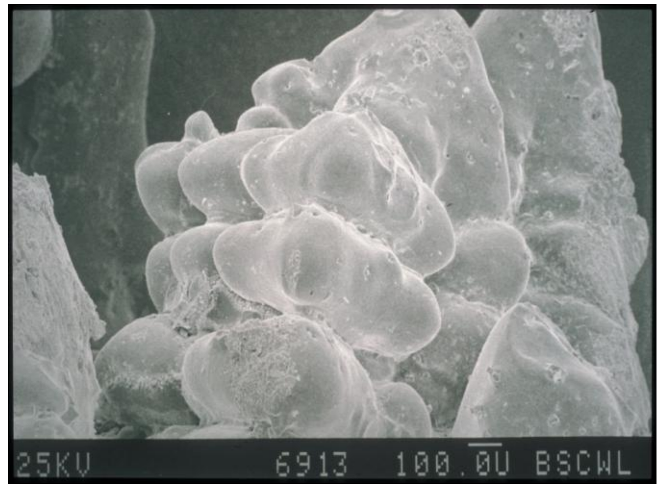


Fig 56

Examples of the dendrites are shown in Figs 55 & 56. The effect of the dendrite size on the properties and, hence, on the success or failure of an industrial component is shown in the example given below.

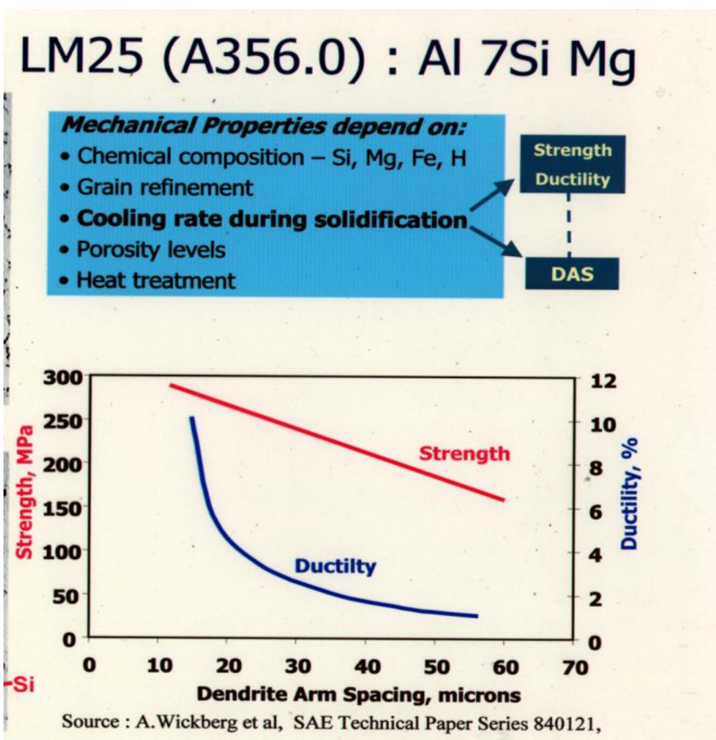


Fig 57

Fig 57 shows the adverse effects of large dendrite arm spacing (DAS) on the strength and , in particular, on the ductility in the case of a cast Al-Si-Mg alloy.

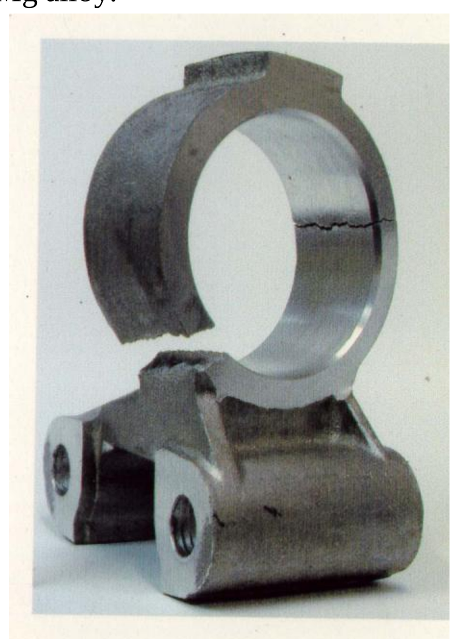


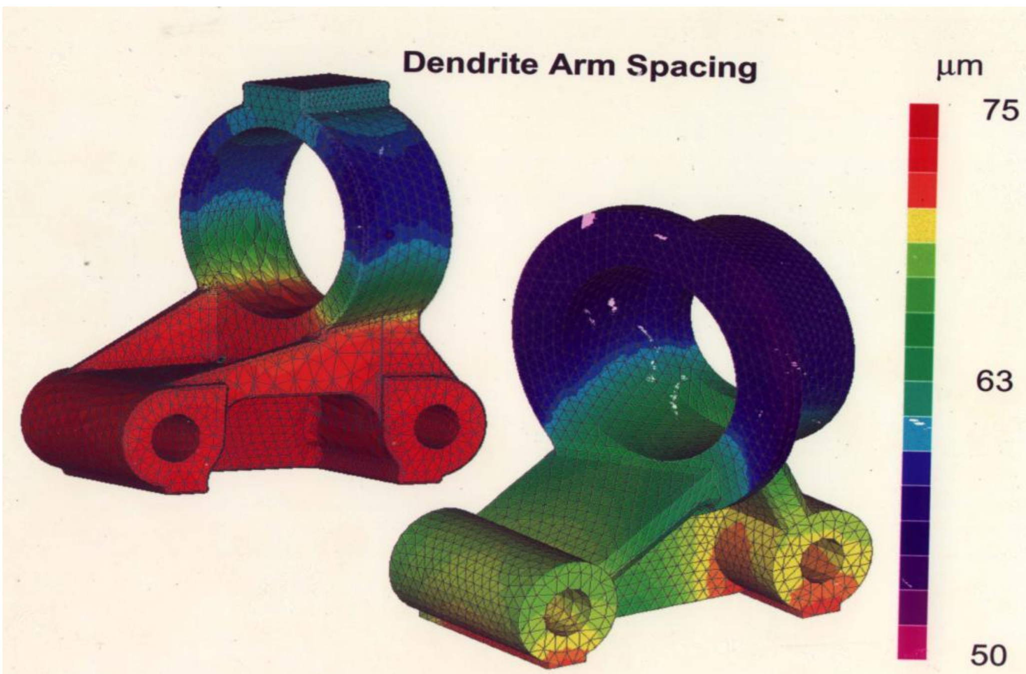
Fig 58.

Jonathan James et al of the Univ. of Wales, Swansea examined the reasons behind the frequent failure of an automotive component made from an Al.alloy casting ,Fig 58.

Mathematical models of the cooling rate and, hence, the size of the dendrites showed that the design had to be altered in order to accelerate the cooling rate, thereby reducing the size of the dendrite and , thus making the casting less prone to failure. Their results are shown in Figs. 59-60.

Fig59

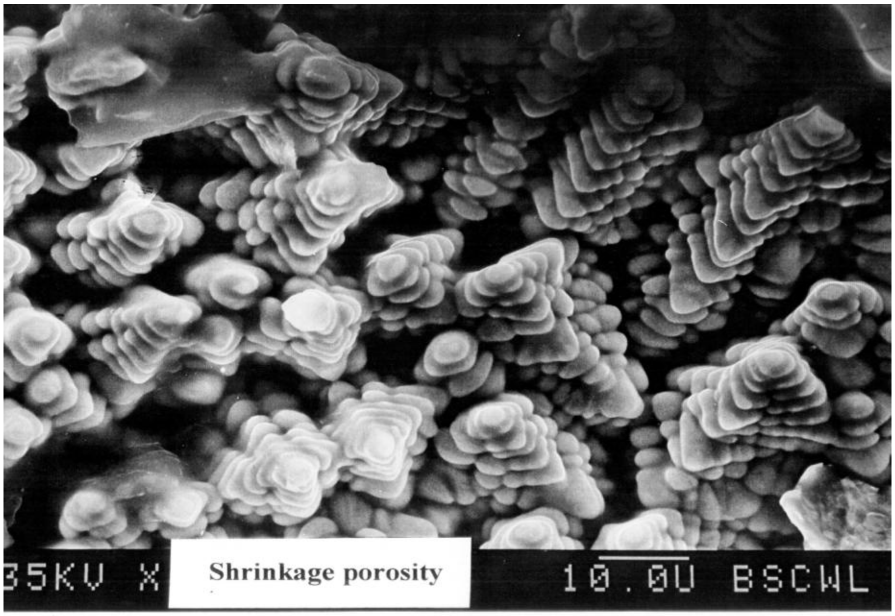
Fig60



The modified design is shown in the right of Figs 59 & 60. Apparently, the new design proved more satisfactory to the customer and the incidence of failure was drastically reduced. The example shows how important it is to control the cooling rate so as to limit the size of the dendrite and thus reduce the risk of a failure of the casting.

Castings can also fail because of the problems of volume changes that occur on solidification; these , in turn, lead to shrinkage porosity. Fig 61. The dendritic columns

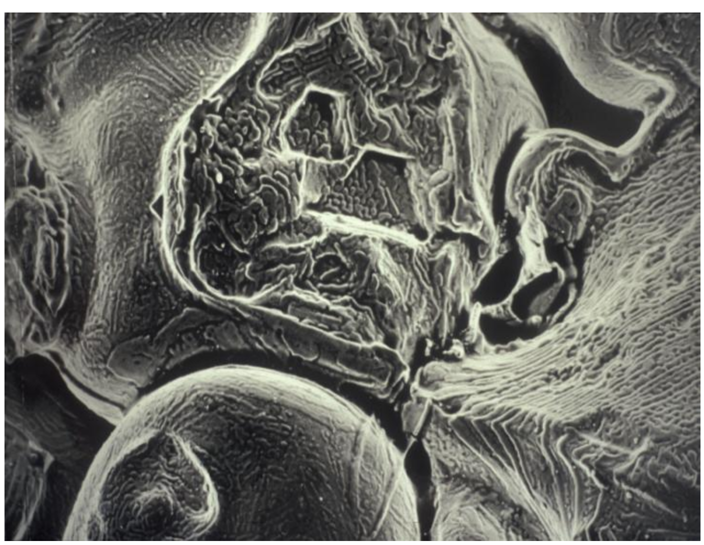
Fig 61



and the space between them (porosity) can be seen clearly in the figure.

Gases entrapped on solidification of castings can also lead to porosity , an example of which is seen in Fig 62. Porosity of either sort can lead to the failure of castings in service.

Fig 62



3.15 Hydroforming

Conventional forming methods based on deep drawing and stretch forming have already been discussed with reference to Figs. 6-17. Over the past decade or so, hydroforming has been employed with great success. With tubular automotive components such as side roof rails, exhaust manifolds and exhaust systems, engine cradles, etc, the benefits are significant in that the operation can be completed in one step. This is in contrast to conventional forming, where several components are formed individually and joined together by spot welding. The operations involved in hydroforming are shown in Figs 63 & 64.

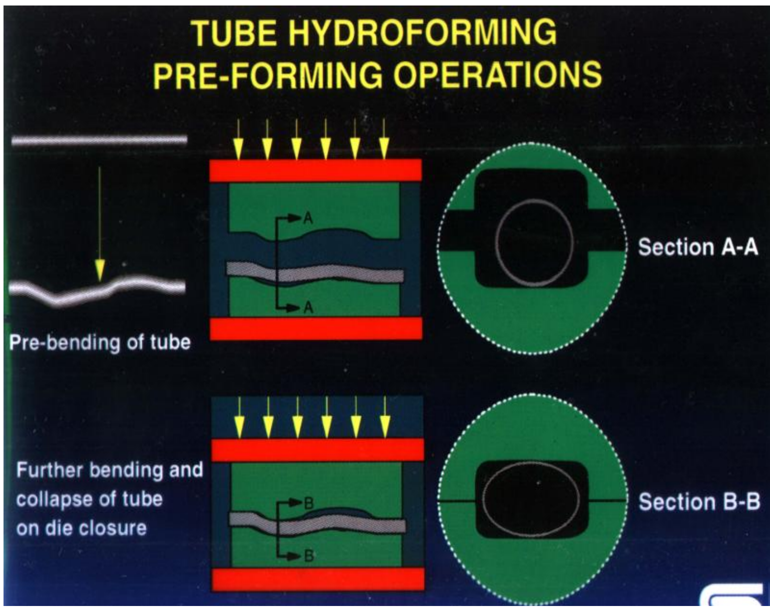


Fig 63

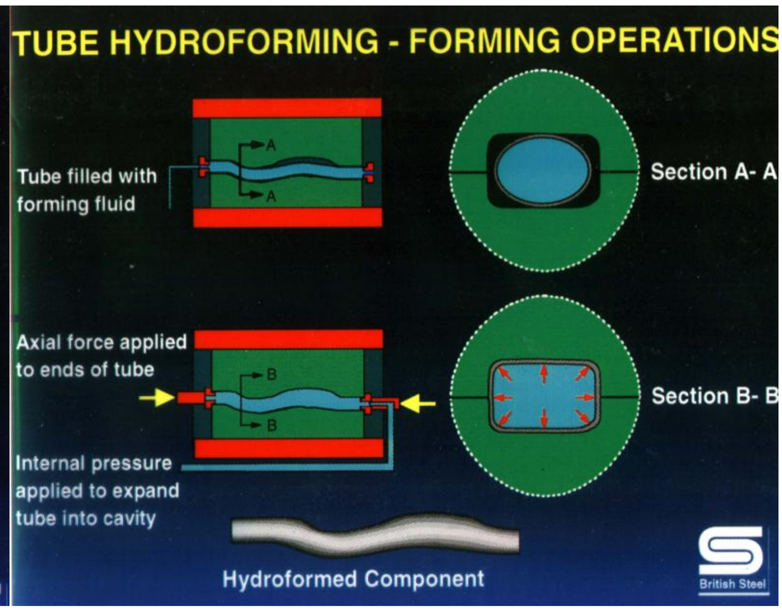


Fig 64

The pre-bending of the tube follows the design imported from the CAD file relating to the component. When the ends are sealed and the tube filled with the fluid and axial force is applied, the pressures reach in excess of 600 bar. Hydraulic pressure is used to expand the tube to follow the contours of the die cavity.

Trial and error help to optimise the pressure and the axial force applied during forming. Fig 65 illustrates how critical it is to avoid failures such as those shown in Figs 66 & 67.

Fig 65

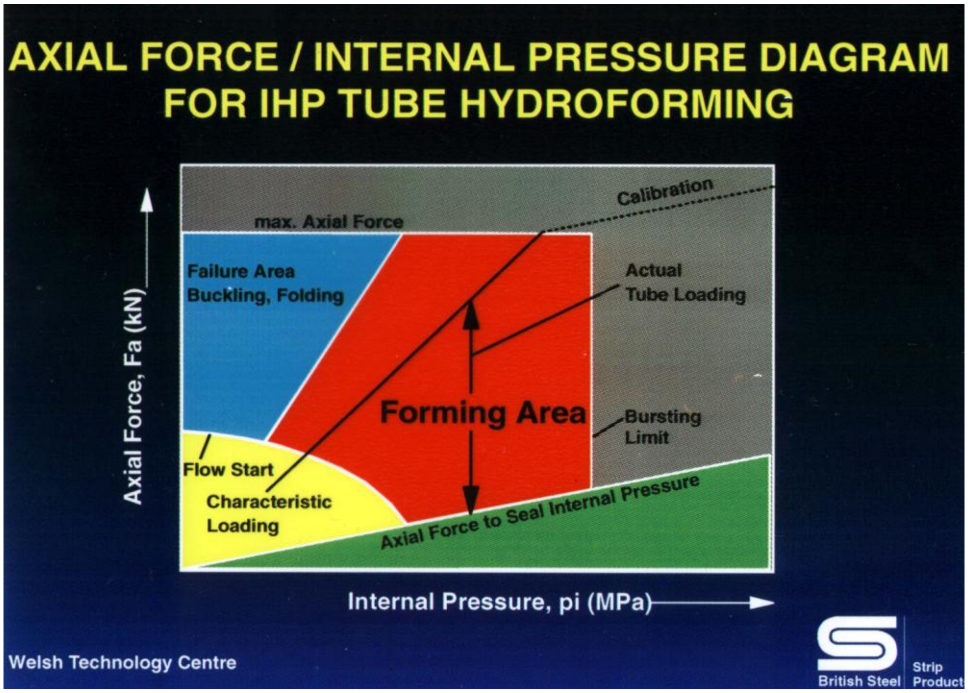


Fig 66 / Buckling

Fig 67/ A split due to high pressure &/ incorrect tooling

(Figs 63-67 are from the Welsh Technology Centre/ CORUS)

3.16 Superplastic forming (SPF)

The total elongation values of ductile materials such as mild steels , typically, are about 40% as measured over a test piece of 50mm gauge length. (see Figs 2,19 & 20). These exhibit the typical ‘necking’ failures. In contrast to these figures, as far back as about 1934, Pearson discovered the phenomenon of superplasticity; given the correct test temperatures and strain rates, he was able to obtain total elongation values of 1950 % ! It is this feature that has ,over the past two decades, been commercially exploited with certain aluminium, titanium and nickel alloys.

Conventional forming systems discussed with reference to Figs.6-17 and Figs.63-67, have high tooling costs, involve high strain rates, leave the components with problems such as ‘ spring back’ and are used for high volume, mass produced parts. In contrast, SPF entails minimal tooling costs and slow strain rates; it is , hence, not ideal for high volume, mass produced parts and leaves the components in a relatively strain-free condition. However, SPF involves operating at relatively high temperatures ie. when the materials behave superplastically. The aerospace industry has benefitted significantly from the SPF methods.

Essentially, the strip is heated to a high temperature, relatively close to the melting point ; it is about 510 ^{0} C with aluminium alloys and > 900 ^{0} C with titanium alloys. The heated strip is placed in the die chamber where gas (inert) pressure is used to force the sheet to follow the contours of the die (female forming) or to drape over the tool (drape forming) or male forming..The strain rate involved is slow. Often, more than one sheet is used, sometimes with separators or spacers in between. After SPF, the components still remain at the SPF temperature and the gas pressure is raised to bring about homogenisation of the microstructure. This is called diffusion bonding and can last a few hours. Examples of SPF procedures are given in Figs. 68 & 69.

In comparison to the automotive industry, the aerospace industry entails a relatively low volume production. SPF has proved highly beneficial to the production of aerospace components. SPF is widely employed in the manufacture of the fan blades in commercial and military aircraft(Figs 70-73).

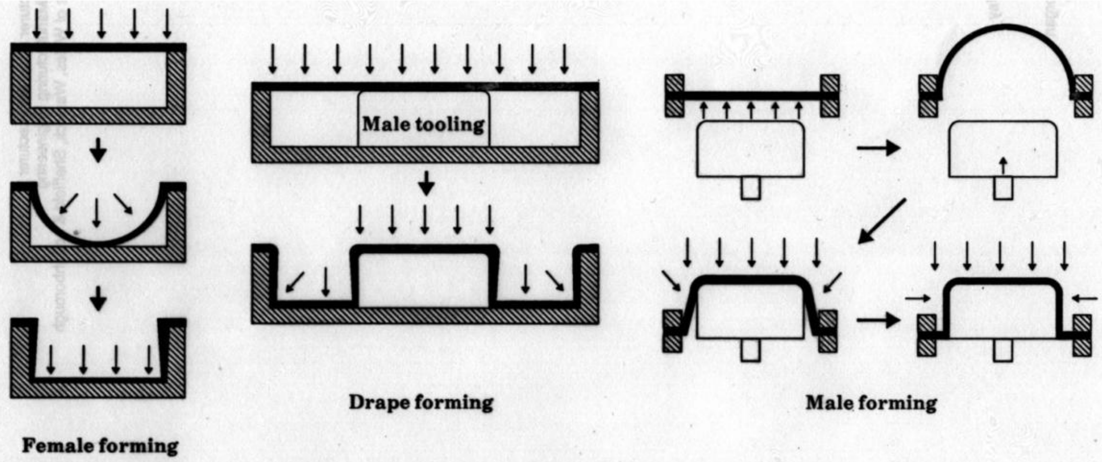


Fig 68

(PM/CD/F17)

THE SIMPLEST SPF PROCESS IS THE SINGLE - SHEET METHOD, WHICH IS FURTHER SUBDIVIDED ACCORDING TO THE TYPE OF TOOLING USED. FEMALE FORMING AND DRAPE FORMING OVER A MALE TOOL ARE THE MOST COMMON SPF METHODS

SP Forming of structure using gas pressure

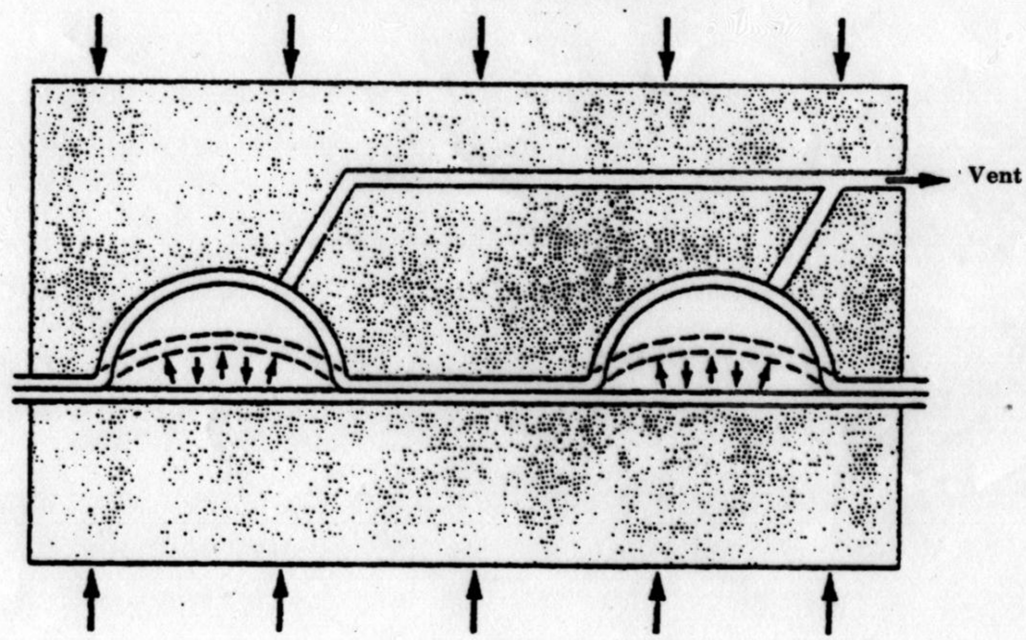


Fig69

TW) - SHEET SPF / DB

The information in Figs 70-73 has been given to me during my visit to the Rolls- Royce (RR) Plant at Barnoldswyck in Lancashire on the 25th of Feb.1999.

Fig 70

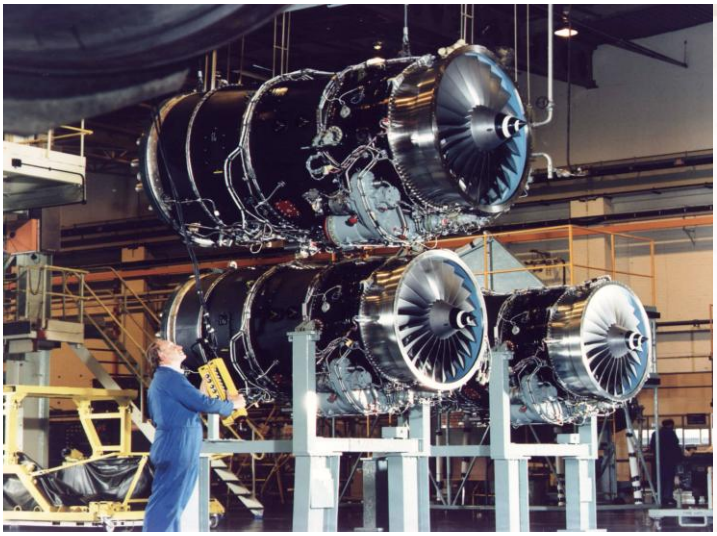


Fig 71

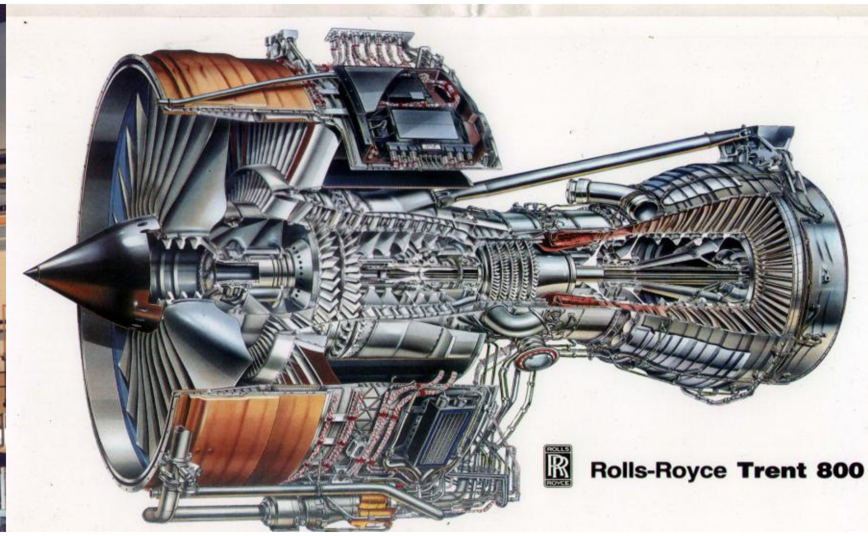


Fig 72

Fig 73

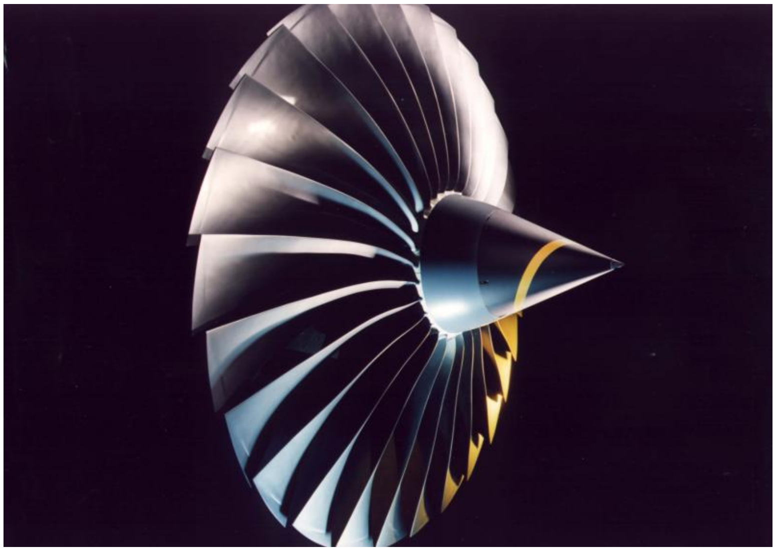


Fig 72

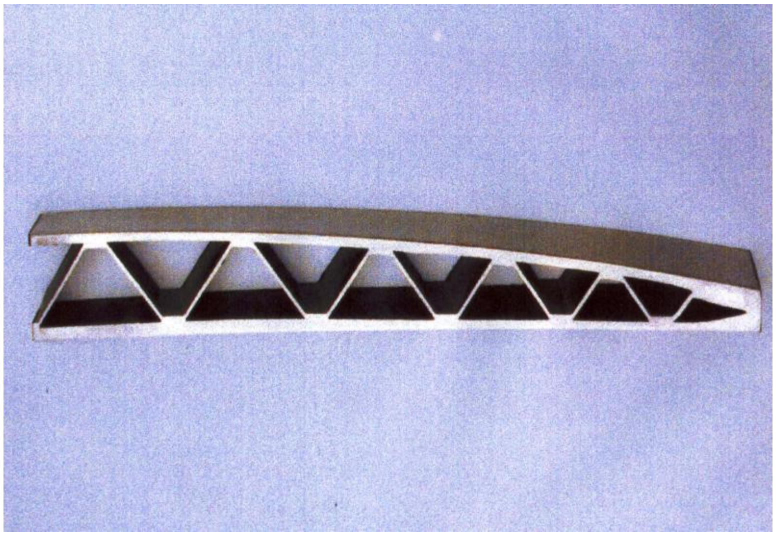
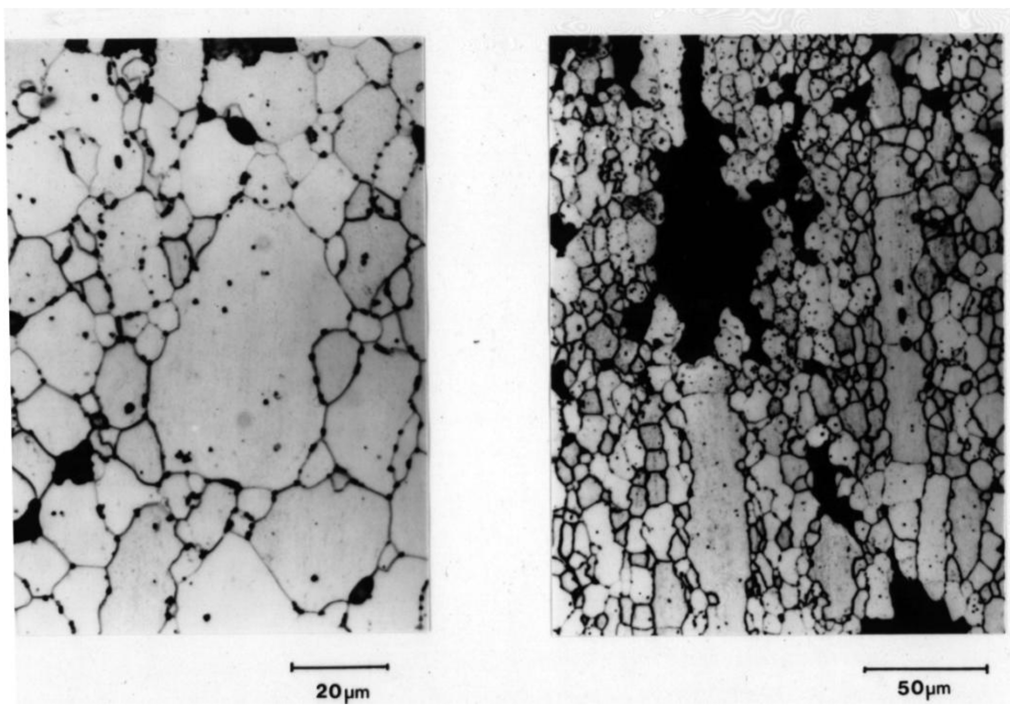


Fig 73

Fan blades (Fig 72) have to withstand the force of the air being sucked into the engine during take-off. In addition, they have to be strong enough to withstand the impact of projectiles, runway debris and bird strikes. They should not break or fragment since the broken segments could endanger the engine components.They must not be prone to low cycle or high cycle fatigue failure . The blades made by RR are based on a three-sheet process with a titanium alloy. For reasons of confidentiality, the processes details are not given here. Fig 73 shows a cross-section of the blade ; the top and bottom faces are from a~10mm thick sheet whilst the reinforcing membrane within is ~1mm thick. The membrane is shaped in the form a' Warren' girder; it helps to stiffen the blade . SPF is carried out at > 900 ^{0} C under a protective gas atmosphere. The gas pressure is increased during the diffusion bonding (DB) process that follows.

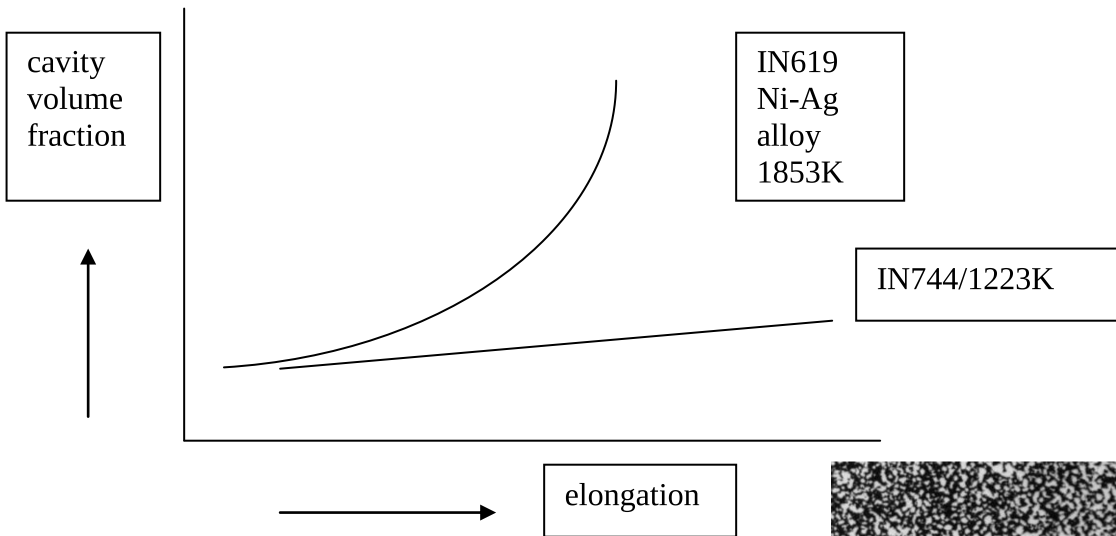
Failures arise during and after SPF due to a number of reasons. A first requirement is that the material employed shows a very fine grained microstructure that is uniform through the thickness and along the length and width of the sheet. The temperature of the sheet, the strain rate employed, the gas pressure used and the conditions of the DB process are important. The examples in Figs 74 &75 shows that cavitation can lead to a sharp fall in the elongation.

Fig 74



Grain growth
and associated cavitation in SPF 8090 aluminum alloy(Info.from ALCAN)
T=515 ^{0} C, 500% elongation

Fig 75



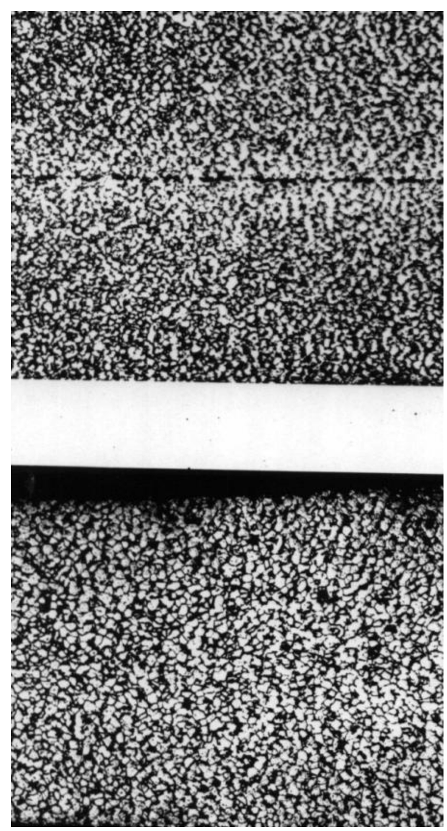


Fig 76 shows the effect of incorrect DB. The top photo shows a band of non-uniform microstructure. The bottom shows that the defect has been eliminated by the correct choice of the DB heat treatment parameters.

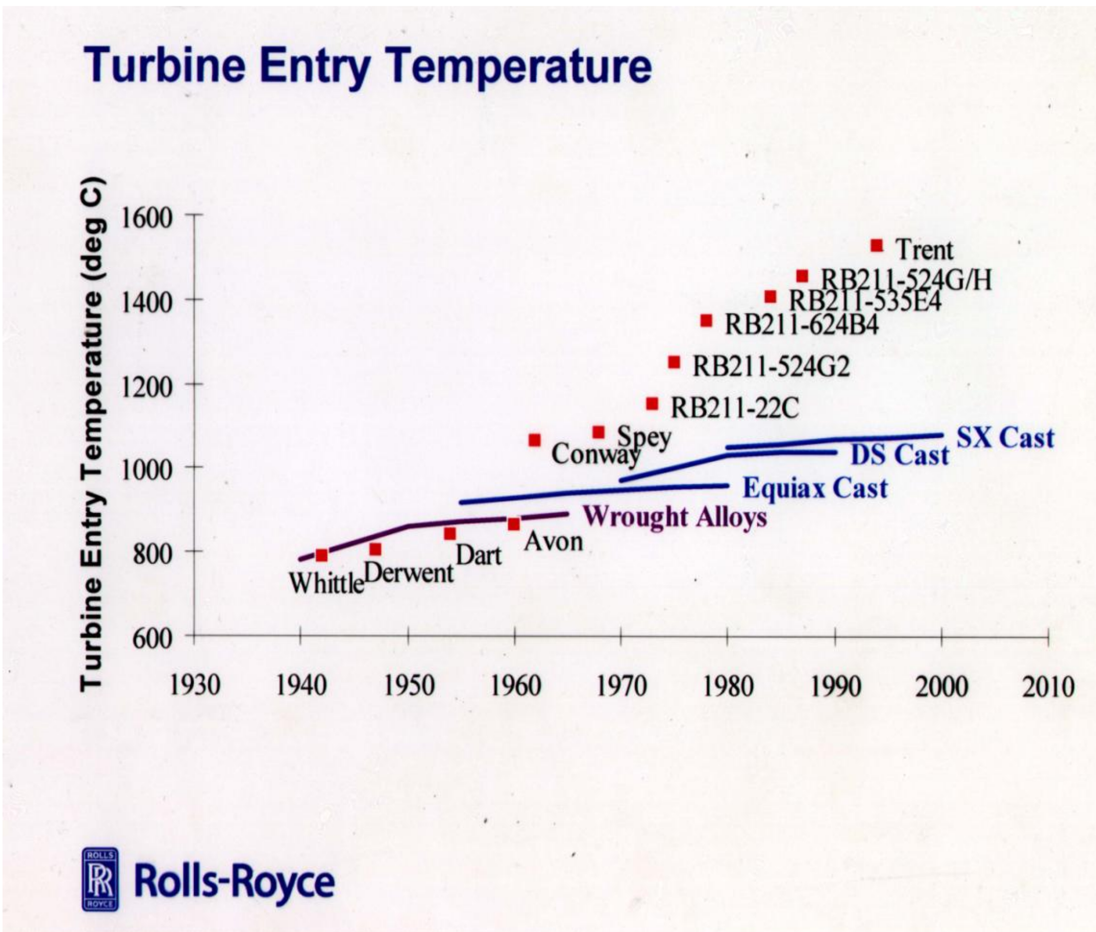
Fan blade failures can also arise from the non-metallic inclusions/ NMIs in the Ti alloys used. (see Fig 21-26). Residual stresses caused by machining can result in failures in the root sections of the blades.

Fig 76

3.17 Engine component failures due to a combination of high temperatures and stress levels

Figs 70 & 71 show examples of the R-R engines . With increase in long haul flights and higher pay-loads (a Boeing 747 fully laden on take-off weighs about 400 Tonnes), bigger, better engines with higher thrust levels(exceeding 115,000lbs) are constantly being developed. Fig 77 shows the rise in the turbine entry temperatures.

Fig 77



With entry temperatures approaching ~ 1600^0 C, the demands placed on the turbine discs and blades are very severe. The materials chosen must be free of NMIs, must withstand high temperature oxidation, must have adequate yield and fatigue strength at these temperatures. In general, a complex alloy mix of Ni, V, Mo, W, Cr is employed to meet the severe conditions within the engine. The turbine blades used in the high pressure section of the engine are produced by an investment –type of casting to produce single crystals, from which the blades are machined out. Fig 78 shows a blade cut at the base to reveal the channels within to provide air cooling. The examples shown below have been given to me during visit to the Turbine Blade Division of R-R at Bristol.

Fig 78

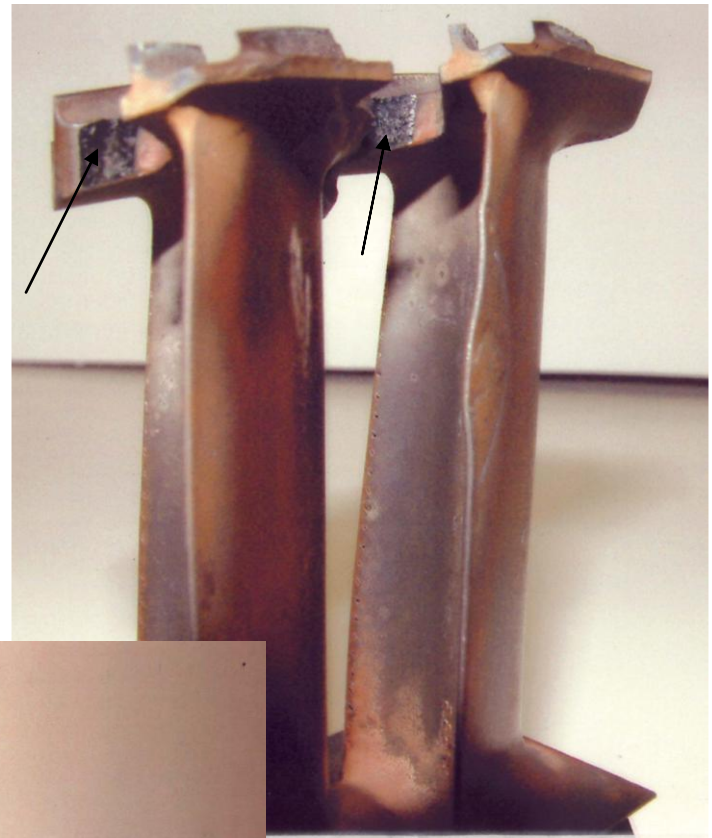


Fig 79

Fig 80

The root of the blade is shaped like a fir tree and slots within the turbine disc

Fig 79 & 80 are examples of damage to the high pressure turbine blades. Continued exposure to a combination of high stress levels and temperatures has led to the shape distortion to the blade as well as to the breakage at the tips . Fig 81 is an example of failure within the vents in the intermediate section of the engine . This is primary damage; secondary damage occurs as the broken fragment spins away with a high centrifugal velocity and force and impacts and ricochets elsewhere within the engine .

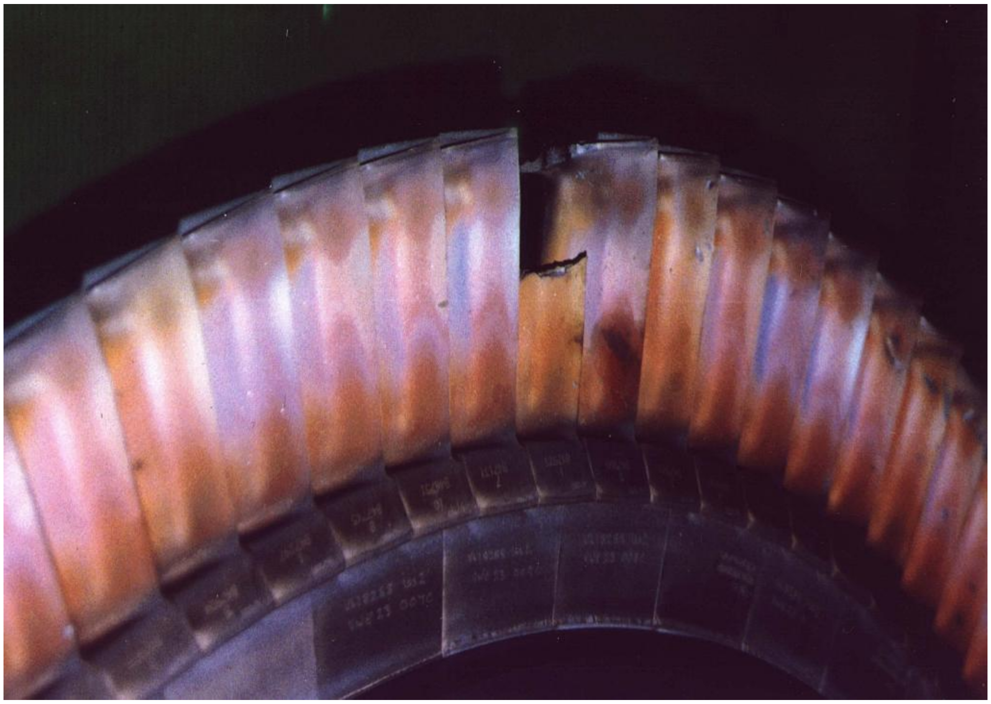


Fig 81

Engine components subjected to a combination of stress and high operating temperatures fail due to reasons that include- weakened grain boundaries ,excessive grain growth brought about by the gradual disappearance of the precipitate particles that normally restrict grain boundary migration and grain growth.

Fig 82 shows the denuded grain boundaries, known as 'precipitate-free zones', PFZ. The precipitates seen on the boundaries have grown in size during service at the expense of those that were, at the outset, uniformly distributed on either side of the boundaries. As a consequence, the boundaries are weakened. Potentially, failure can occur in service.

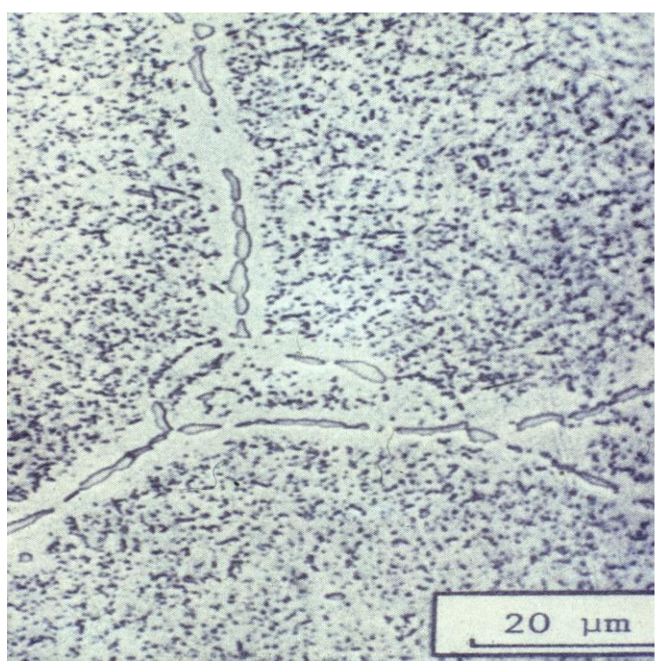


Fig 82

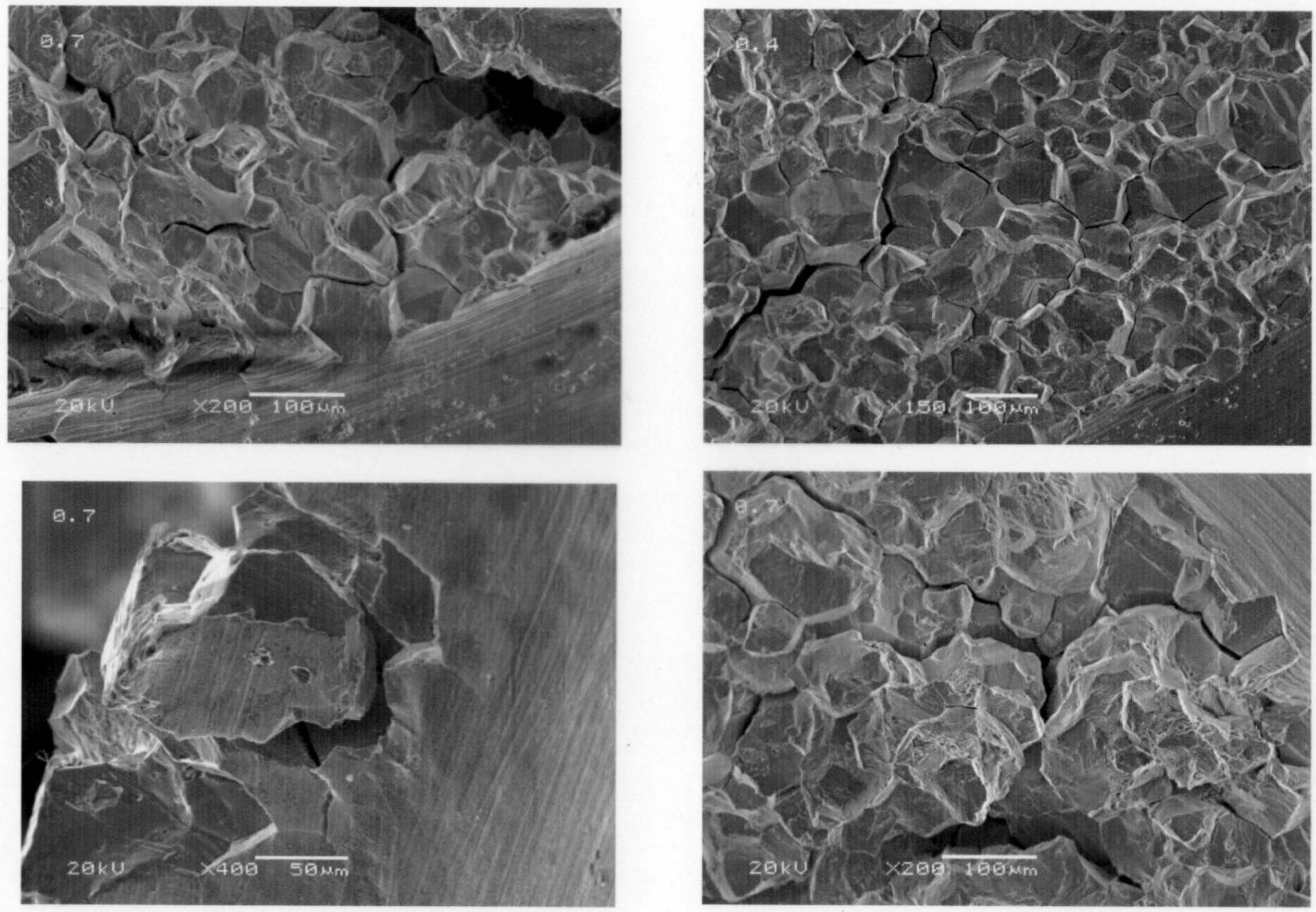
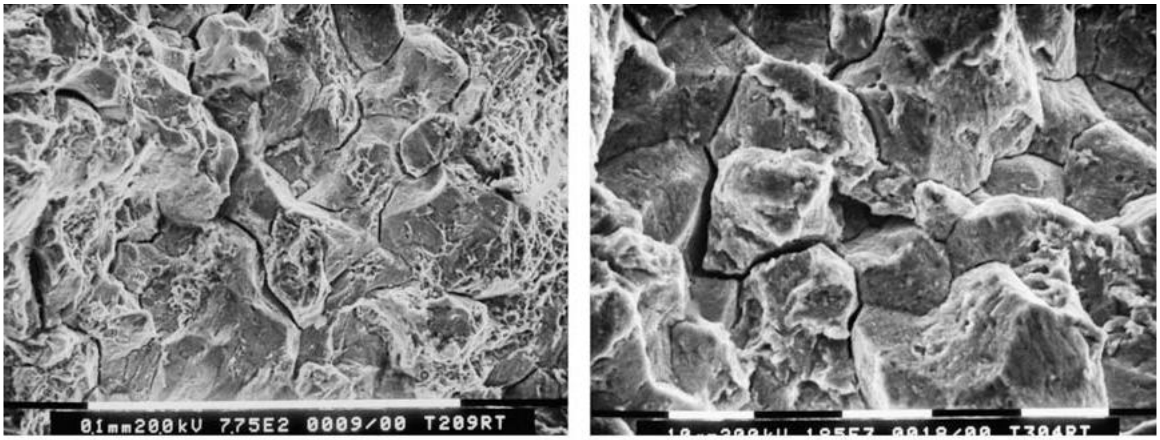


Fig 83 (sourced from the Internet)

The extent of microstructural damage seen at the grain boundaries in Fig 83 is a typical example of the reasons behind the failure of components as a result of creep . Softening, shape distortion and eventual fragmenting seen in Figs.79-81 are often attributed to failure under creep.

3.18 Stress corrosion cracking SCC

A combination of stress and a corrosive environment can lead to SCC. Steel structural components, reinforcements, turbine rotors, automobile bimetal bearings based on alpha plus beta type brasses,, high strength aluminium alloys of the 2000 and 7000 series are examples of materials known to exhibit SCC . Several studies have shown that SCC takes the form of intergranular cracking. Examples of SCC are shown in Figs 84-86.



0.002 MPa.s^{-1} 0.00034 MPa.s^{-1}

Fig 84 . SCC in rotor steels at two applied stress rates /exposed to water at 30 ^{0} C (after Ramamurthy & Atrens Corrosion Science,52 /2010, Pp1042-1051)

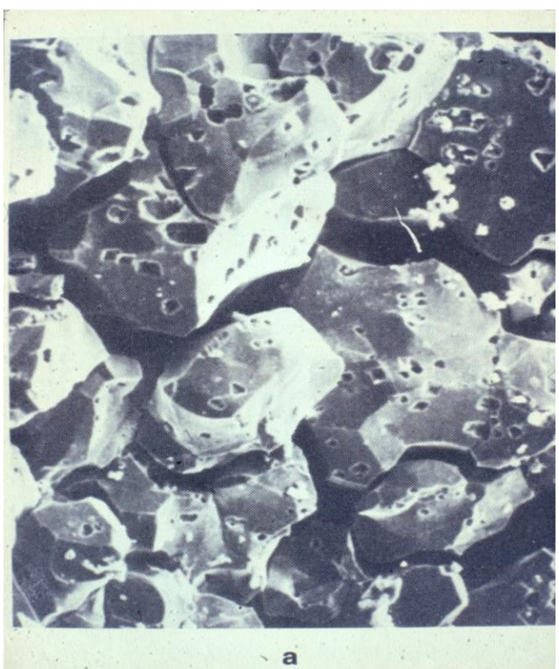


Fig 85 Failure at the grainboundaries & severe pitting on the grain surfaces.

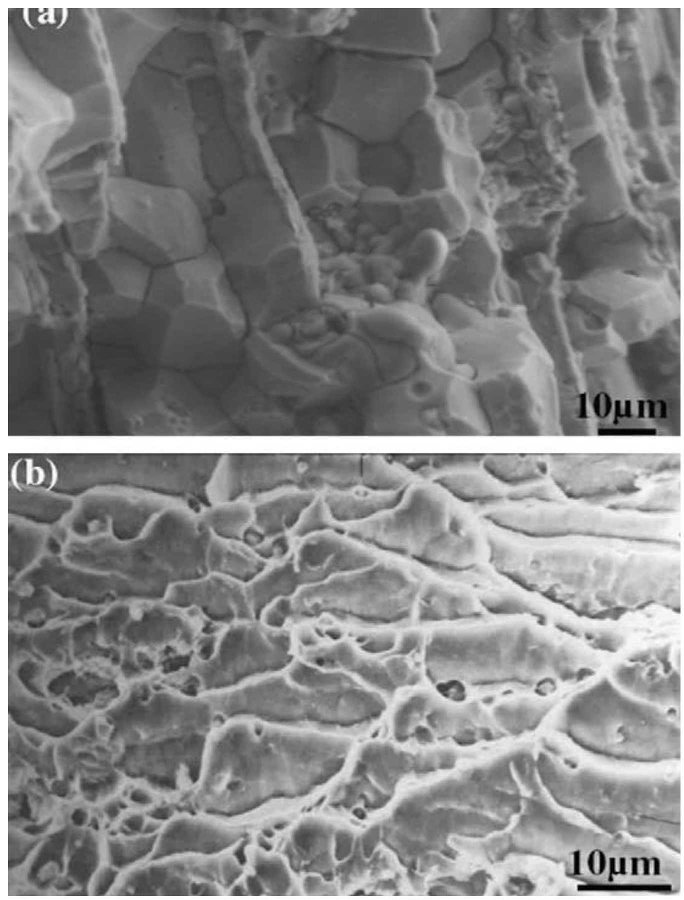


Fig 86 .a. base alloy/Al-Zn-Mg-Cu-Zr showing SCC. b. same alloy with Sc addition showing a ductile fracture (Bobby Kannan & Raja,Eng. Fracture Mechanics,77/2010)P249-256

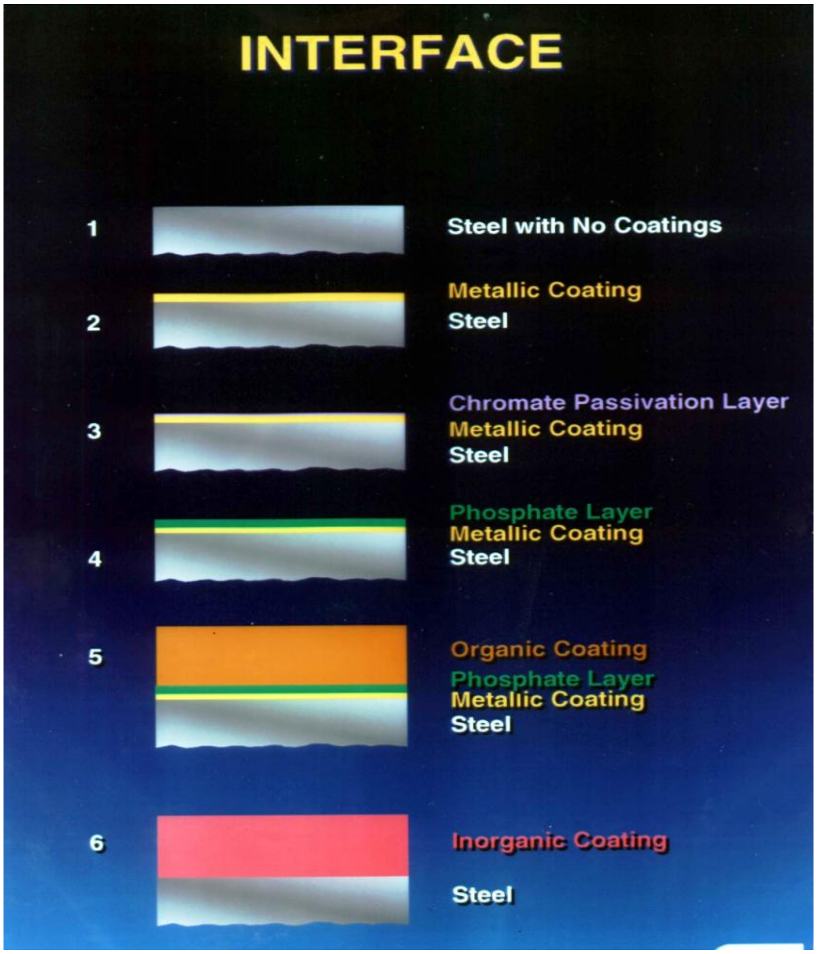
SCC involves slow, environmentally induced crack propagation which may be assisted by a combination of mechanical and chemical forces. The stresses required are tensile and relatively small, usually below the yield strength. Given a corrosive environment, externally applied stresses or residual stresses promote SCC. Cracks nucleate and propagate at a slow rate; according to R.H.Jones & R.E.Ricker , the rates are $\sim 10^{-9}$ to 10^{-6} m/s. Pre-existing defects such as NMIs (discussed in Figs 21-26) can often help to nucleate the cracks.

It is evident from fig 84 that SCC occurs at all stress rates. Ramamurthy &Atrens note that the fracture stress decreased slightly with a falling applied stress rate until 0.02 MPa/sec and then decreased significantly with a further fall in the applied stress rate. They note that SCC velocity is affected by the applied stress rate and the crack tip strain rate. Preventive measures suggested include a decrease in the magnitude of the stress by a decrease in the external load or by an increase in the cross-sectional area perpendicular to the applied stress. A heat treatment to anneal out residual stresses is also recommended.

Fig 86a (Bobby Kannan & Raja /2010) shows severe intergranular attack in an Al-Zn-Mg-Cu-Zr alloy. They found that resistance to SCC can be enhanced by additions of Sc which help to inhibit recrystallisation . This is shown in Fig 86 b which reveals an essentially ductile fracture.

3.19 Corrosion in the absence of stress; failures in zinc coated sheet steel components

Sheet steels are protected against corrosion by means of coatings, based essentially on zinc. In place of the steel substrate, the zinc layer undergoes sacrificial corrosion, often producing a deposit, known as white rust (zinc oxide). There are different products, examples of which are given in Fig 87. →

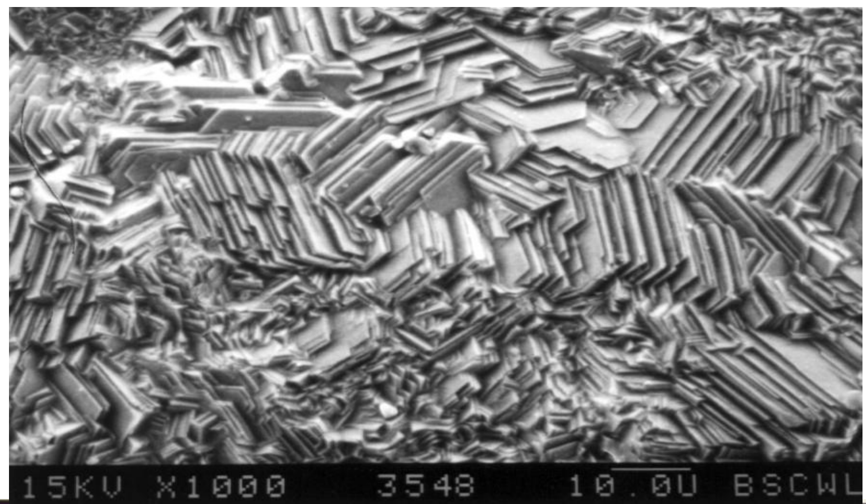


The most widely used metallic coating, shown in Fig 87 , is zinc. Depending on the nature and severity of the application, the coating is covered by a further layer of corrosion inhibitors.

Zinc coatings on sheet steels are applied either by hot dip galvanising (this process has many variations) or by electrodeposition involving a soluble zinc anode , an electrolytic cell and the sheet steel being the cathode). The most widely used hot dip galvanised product can be seen on the guard rails of roadside bridges, motorway crash barriers, farm buildings, grain silos, new metal dustbins, etc. The characteristic ‘spangle’ appearance of the zinc crystals on such products can be seen with the naked eye (Fig.88).

Fig 88

Relatively smoother zinc coating by electrodeposition has until recently been widely used for automotive skin planels. When seen under the electron microscope , platelets of zinc are clearly visible.
Fig 89. →



A product that is widely used in the roofs and interiors of buildings, office furniture and similar applications is known as COLORCOAT. Cut edges of sheets of this product often suffer from corrosion. An example is shown in Figs 90a&b

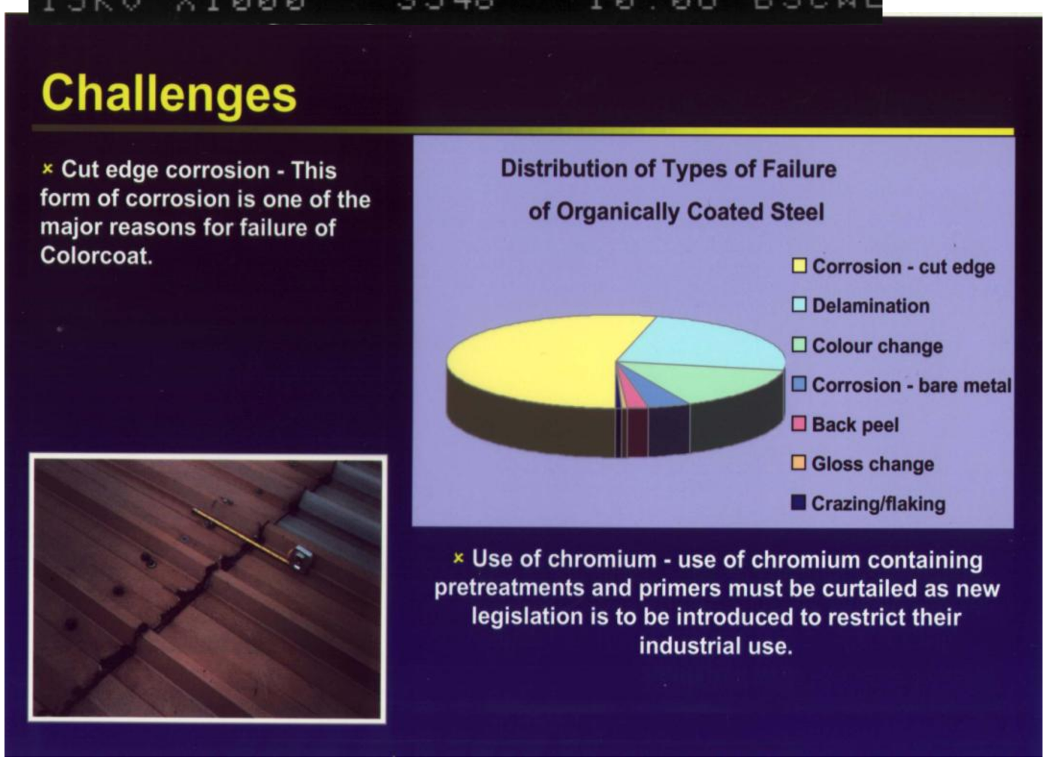


Fig 90a

(from The Welsh TechnologyCentre Centre/ex CORUS)

Sheet steels used in the manufacture of autobodies need to meet exacting demands since cars are exposed to a range of severe conditions. The coating must have a good bond with the steel substrate; this is especially important during the forming of door, wing, bonnet and roof panels in the press shops. At times, the adhesion of the coating is poor and defects such as those in Fig 91&92 appear on the surface . The reasons for such failures can be seen from Fig 93.

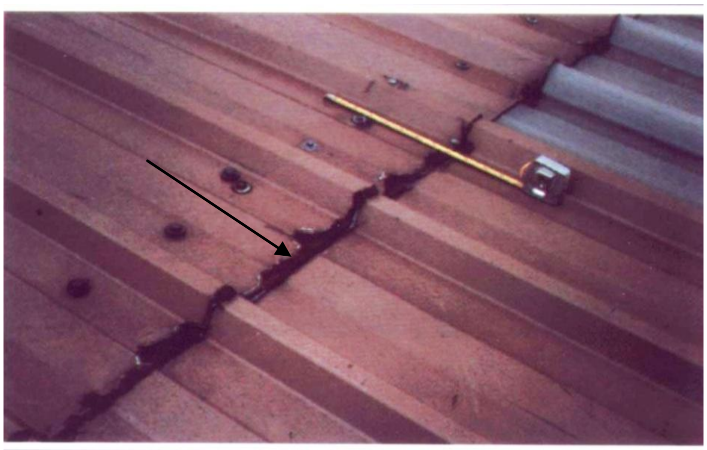


Fig 90b

Fig 91

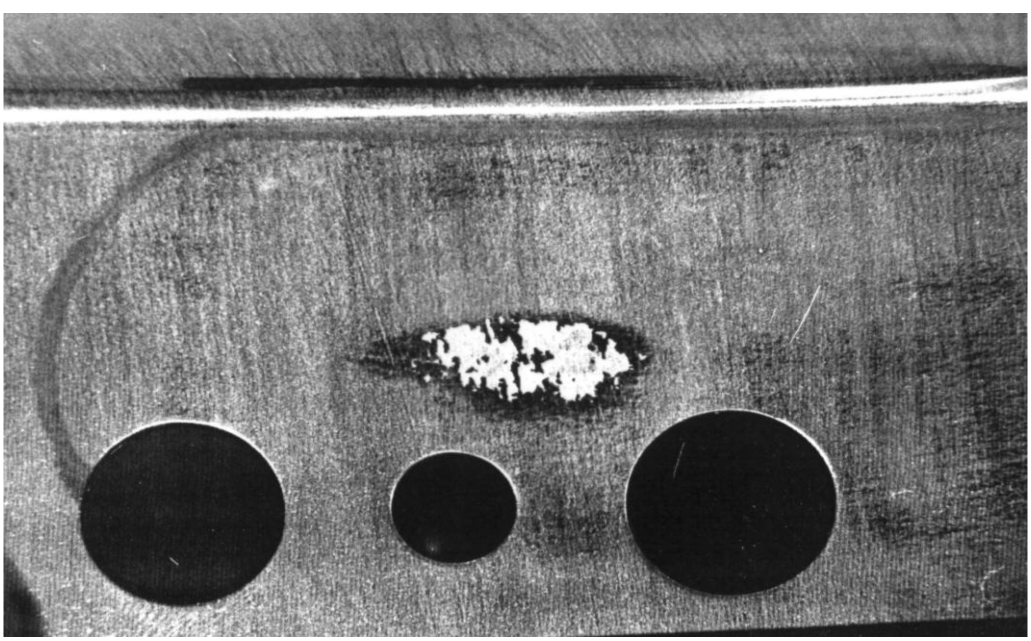
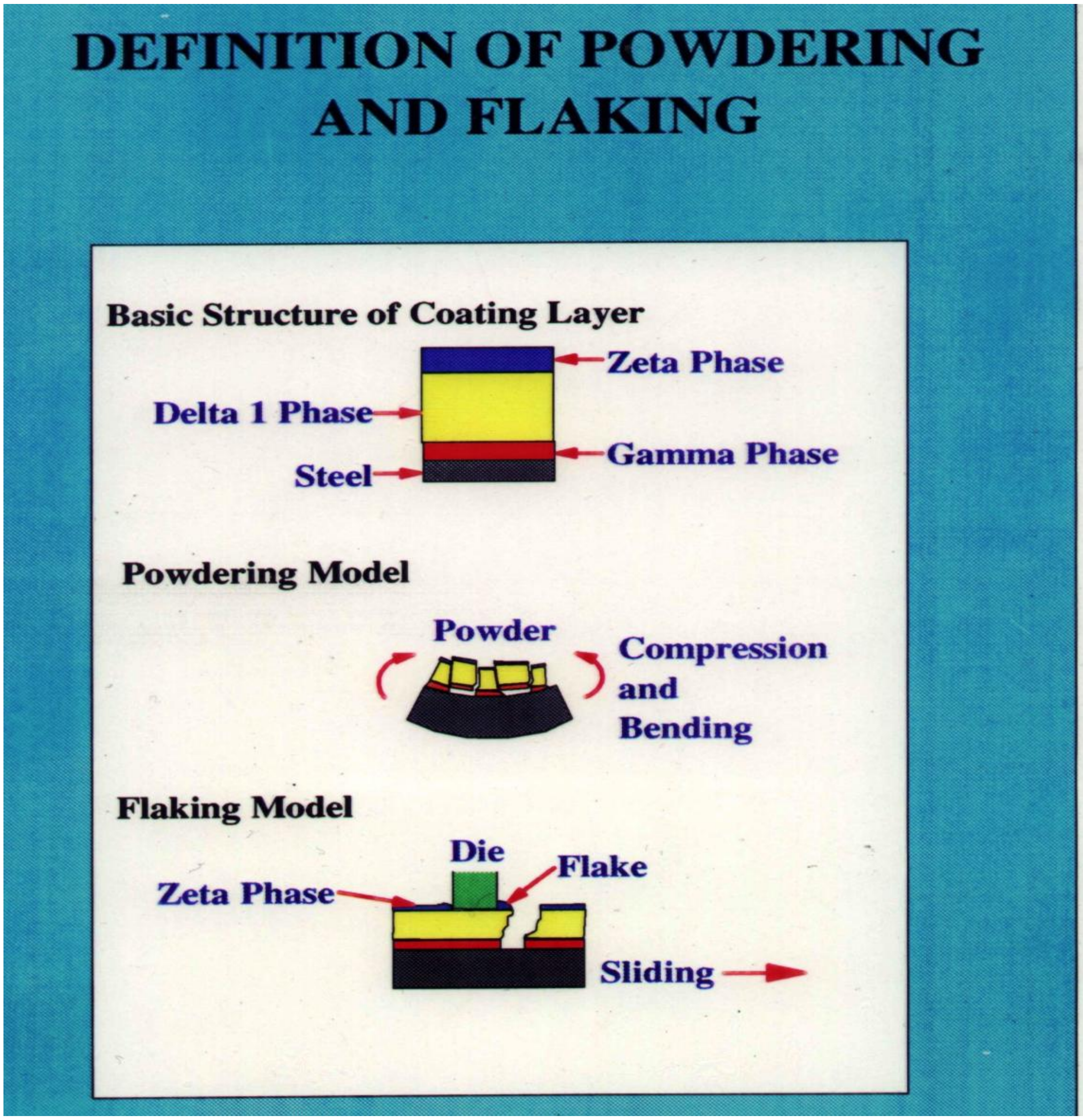


Fig 92

Fig93



Essentially, as mentioned earlier, there are two broad variations of the galvanising process. The first is hot dip galvanising. An intermetallic layer based on Fe-Zn intermediate phases forms between the steel substrate and the zinc layer. The second process is known as galvannealing. Iron diffuses into the zinc coating due to the additional heat in this process.

Fig 93 shows the order in which the different Fe-Zn intermediate phases form and the manner in which adhesion of the zinc coating suffers in the two models, one based on powdering and the other based on flaking of the coating. In the case of powdering, cracks form in the hard, brittle gamma phase when the strip is bent or pressed. The thickness and morphology of the gamma layer is critical. Powdering is worse if the gamma layer is >1micron thick. In the case of flaking, the soft zeta phase is scored by the die during press forming. When the frictional force exceeds the adhesive strength at the

zinc-coating interface, flaking occurs. The adhesive strength is governed by the thickness of the gamma phase.
(Figs 87,90 &93 are from the Welsh Technology Centre/CORUS /JACQUI NORTH/2001)

The most recent information from Tata Steel/Llanwern Works is that galvannealing is not the preferred route now .Sheet steels for autobodies are produced successfully by hot dip galvanising. This is achieved by a careful control of the chemical composition of the steel and the zinc bath as well as the process parameters so as to obtain an optimum distribution of the various intermediate phases that lie between the steel substrate and the zinc coating. Electrocoated zinc steels are not widely used at present since the process is relatively slow and, hence, not ideal for high volume, high tonnage production for the current automotive sector.

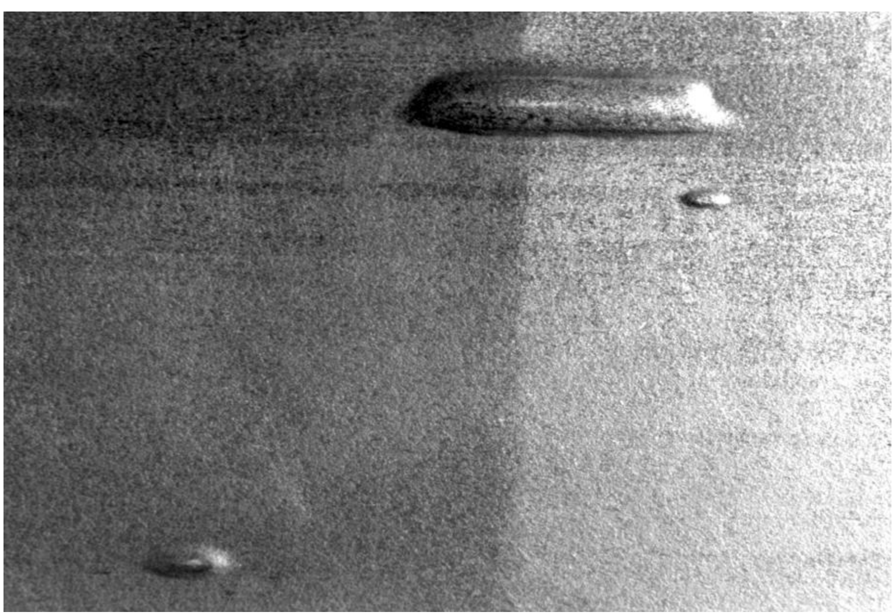
3.20 Surface defects on sheet steels which lead to rejection

Essentially, sheet steels are supplied under two categories; where the surface quality is not critical since the steels are intended for interior panels on cars, the grade is classified as ‘general purpose’ GP. For surface-critical applications such as exterior panels on cars, the grade is classified as ‘full –finished’. The latter grade is very closely watched on the inspection benches and rejection follows when the sheet surface shows defects such as those listed below.

Blisters

During steel making, argon gas is blown from the bottom of the vessel in order to agitate the bath, homogenise the mixing of the alloy additions with the liquid steel and to promote a temperature uniformity within the bath. On occasions, traces of the gas get entrapped as the steel is poured into the tundish and as solidification starts. On further downstream processing, pockets of this gas lead to the formation of blisters. Fig 94.

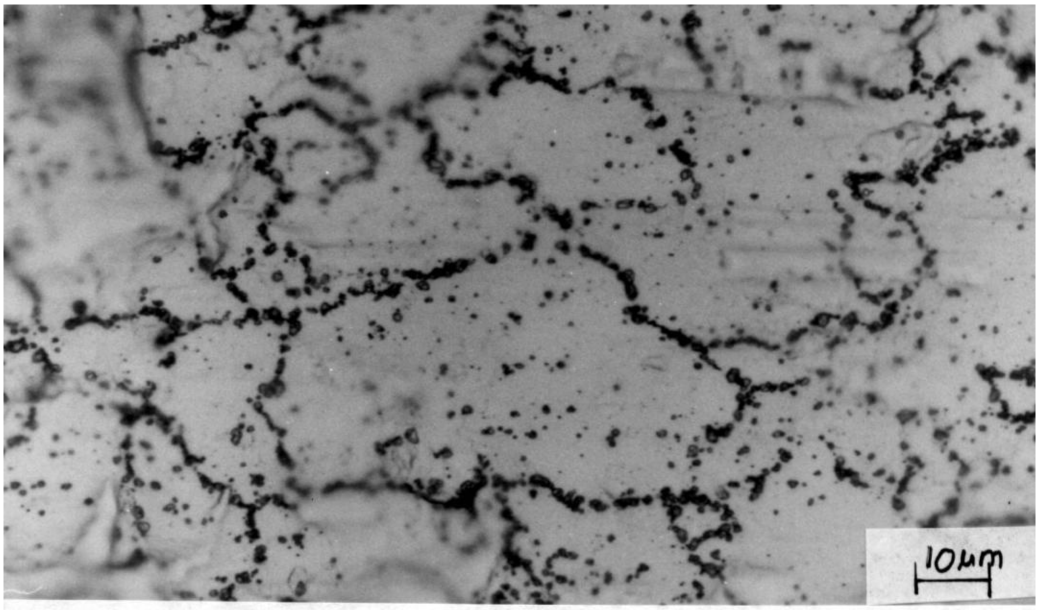
Fig 94



Concast Blue

This is a term used to describe a sheet surface that is bluish and is often the reason for rejection. This bluish appearance stems from the presence of very finely dispersed double oxides of iron and manganese. Fig 95. The grounds for rejection are that this

Fig 95

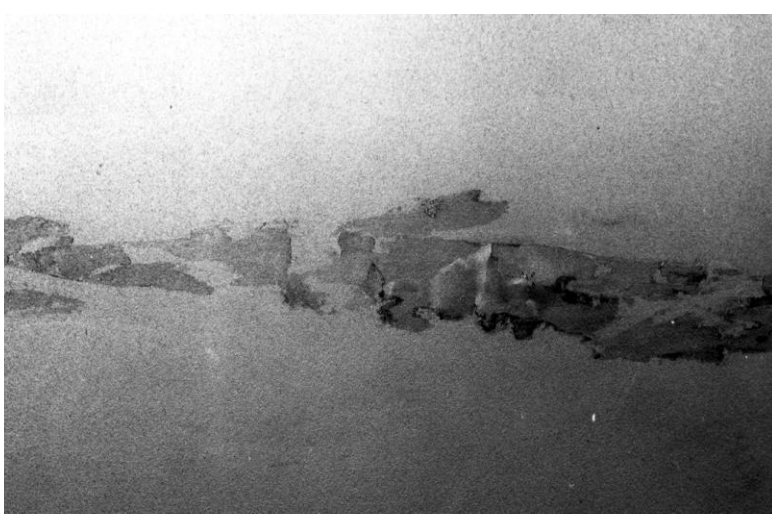


film adversely affects the paintability of the panels produced from such steels.

Laminations

Earlier accounts on non-metallic inclusions (NMIs) such as oxides, sulphides, silicates etc have shown in Figs 22-26 and 37-39 that they can initiate premature failure in otherwise sound materials. When sub-surface NMIs are present on sheet steel surfaces, they are called laminations ,Fig 96. The defect appears as slivers of steel foil that have peeled off from the surface. Sheet steels showing these laminations are rejected.

Fig 96



Sticker wrench marks

Batch annealing of sheet steels involves annealing stacks of coils of strip that has been cold reduced to the desire gauge. The cold rolled coils are wound under a given line tension. Annealing restores the ductility and formability of the steel. During the prolonged soak at the annealing temperature (~700^0 C), adjacent laps of the coils stick together by a process of local welding of the high spots on the surface of the strip. At the end of annealing, the coils are cooled down, unwrapped and fed into a temper mill which gives a slight cold rolling reduction , typically, ~0.8%. This is called temper rolling and is designed to eliminate discontinuous yielding (see Figs2-5). During this process of unwrapping and feeding into the temper mill, the high spots on the surface that had welded together during annealing now break free. This results in the formation of marks on the surface; these are known as sticker wrench marks, Fig 97. Their appearance is undesirable and this leads to rejection of the steels intended for 'surface-critical' applications.

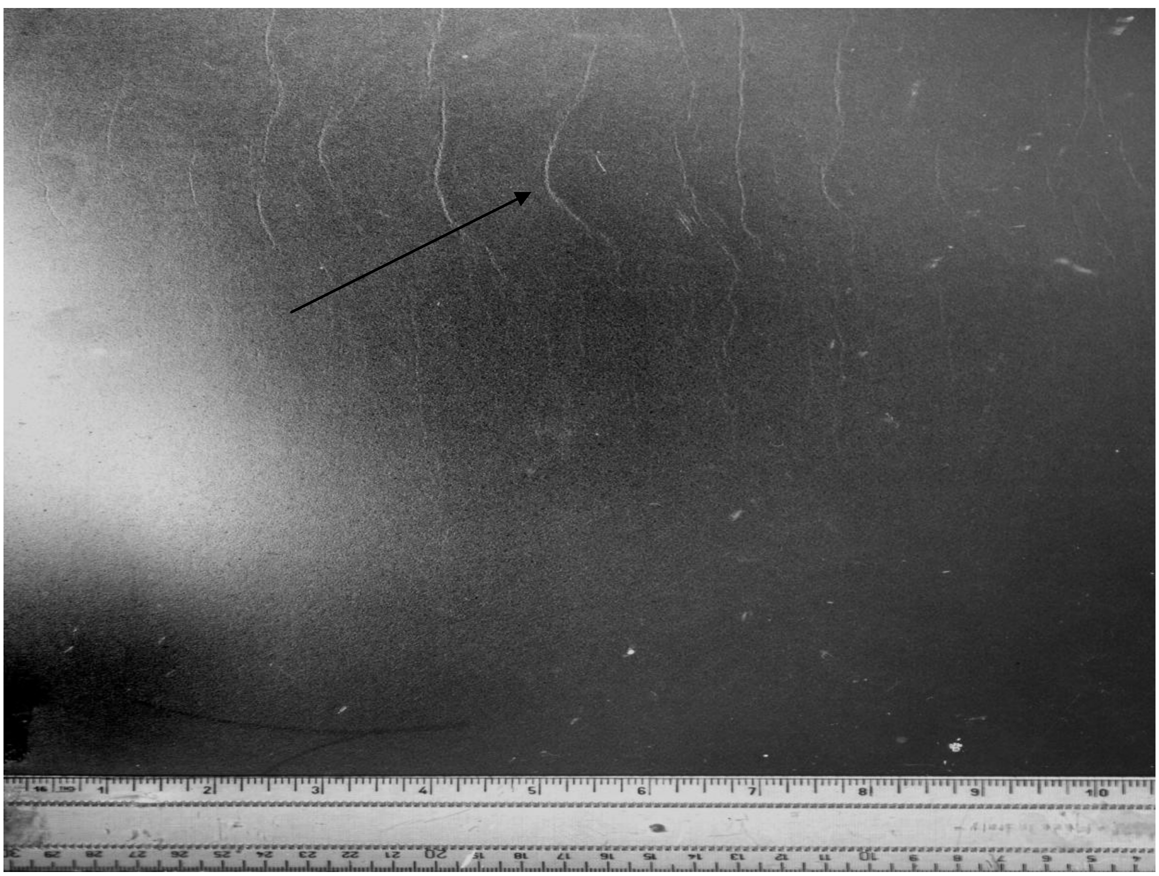
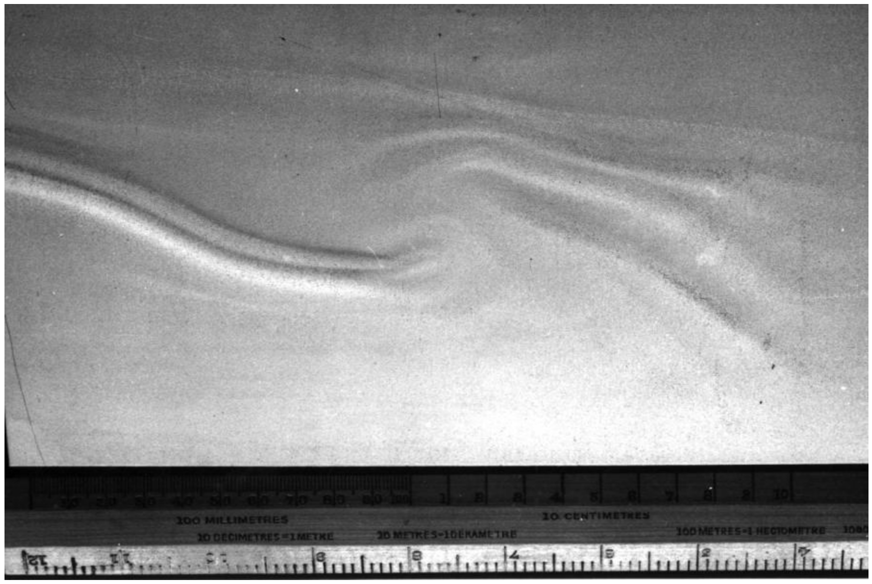


Fig 97

Pinch marks

These may occur when the coil is fed into the cold rolling mill or even the temper mill. Incorrect feeding, lack of the appropriate line tension or surface irregularities can lead to these surface marks, Fig 98

Fig 98

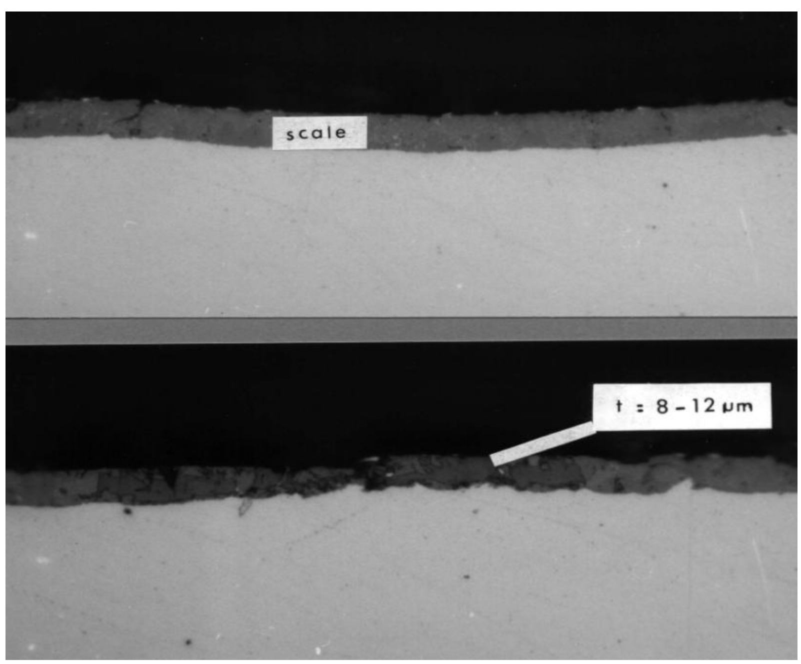


The appearance of these marks will lead to the rejection of the relevant portion of the coil.

Scale on hot rolled coils

Bearing in mind the fact that hot rolling of sheet steels starts at ~ 1200^0 C (t=~250mm) and finishes at ~ 900^0 C (t=~1.4mm), the steel is exposed to a very high temperature. This leads to the formation of a layer of oxides of iron, manganese, etc on the surface. This is known as scale Fig 99.

Fig 99



The scale is removed by agitating the hot rolled coil in a bath of dilute acid, typically hydrochloric acid. In general, the process is highly successful and the strip is free of scale and other contaminants prior to being cold rolled on the five or six stand , four high tandem mill. However, on occasions, the surface is chemically reactive with the presence of hydrogen that remains essentially dormant. When the steels is used for enamelling applications, the nascent hydrogen can affect the coating of enamel; with time, this can lead to a problem known as fish scaling.

3.21 Incorrect processing temperatures can lead to rejection of materials

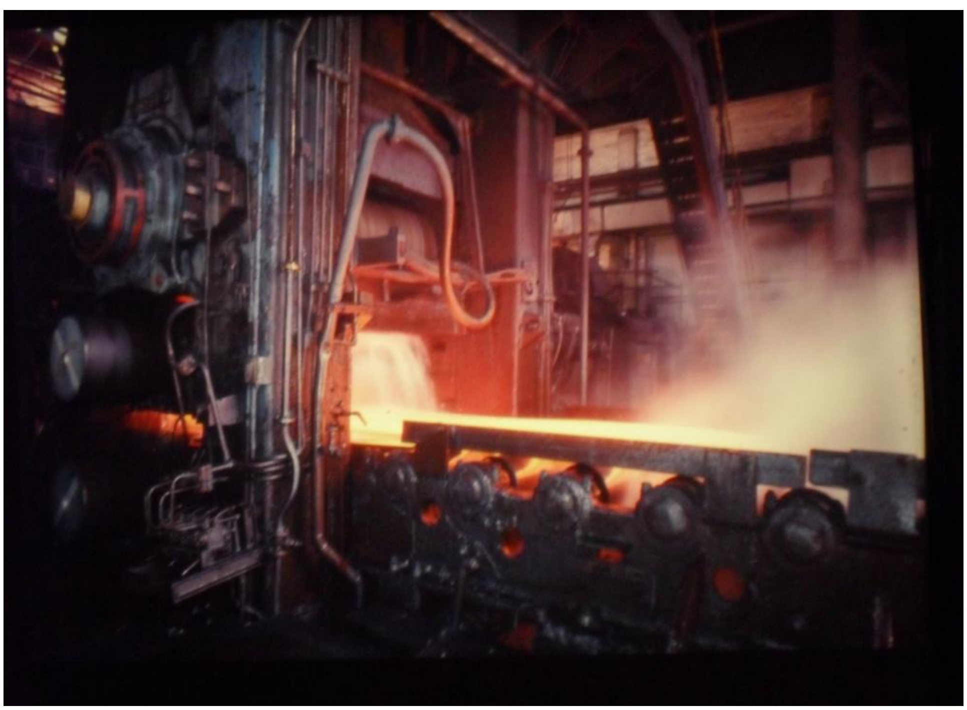
Temperature control at all stages of processing is crucial. One of the best examples to illustrate this point is the case of hot rolling of steel strip. Typically, the slabs (~250 mm thick) enter the hot mill at ~1200 ^{0} C and leave it , for example, at 900 ^{0} C (~1.4mm thick). At an intermediate stage, the steel is ~ 100 mm thick and is coiled in the unit known as the coil box. Fig100. Further hot rolling down to the final gauge is carried out



Fig 100 Fig 101 Fig 102

in the finishing mill ,Figs 101-103

, Fig 103.



If the slab or bar or strip temperature is not high enough, hot rolling ceases since the steel is too hard to be rolled. This results in a pile up of sheet steel of different thicknesses jammed between the work rolls of the mill Fig 104. This is known as

Fig 104

hot mill cobble. Roughing mill cobble arises from too much draft or the edgers being set too close. Finishing mill cobbles occur when the temperatures are low. The hot steel will have to be cooled down and burnt off. A roll change may be needed because of fire-cracking or roll bruising. Clearing out this mess and getting the hot mill back in operation can be time-consuming and expensive. The loss of production time can be significant.

Towards the latter stages of hot rolling, the strip thickness rapidly decreases and the loss of temperature along the length of the coil and across the width of the strip can be quite significant; this is clearly evident along the edges of the strip Fig 105.

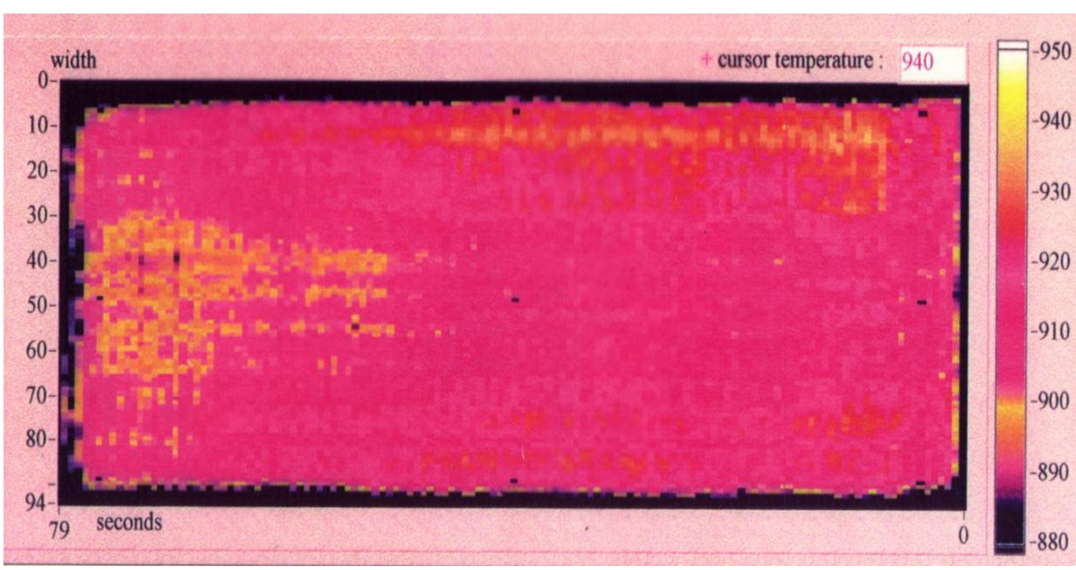


Fig 105

Fig 105 can be interpreted as follows.
1.the edges are at ~880 ^{0} C or less. This means that the parent austenite would have partially transformed to ferrite. Once transformed, these ferrite grains continue to grow.
2.the regions away from the edges are still at a temperature (>890 ^{0} C)high enough for the austenite to remain untransformed.
3. when the strip eventually reaches the water sprays at the ‘run-out’ table, these austenite grains in the regions away from the edges now transform to fine ferrite grains.
4. the outcome is a mixture of large ferrite grains at the edges and fine ferrite grains away from the edges.
5. Fig 106 shows a part of the microstructure on the plane of the sheet ie across the sheet width. .The very large ferrite grains are at the edge (bottom of Fig 106) and the fine ferrite grains are seen in the region away from the edge. The same pattern occurs at the other edge.

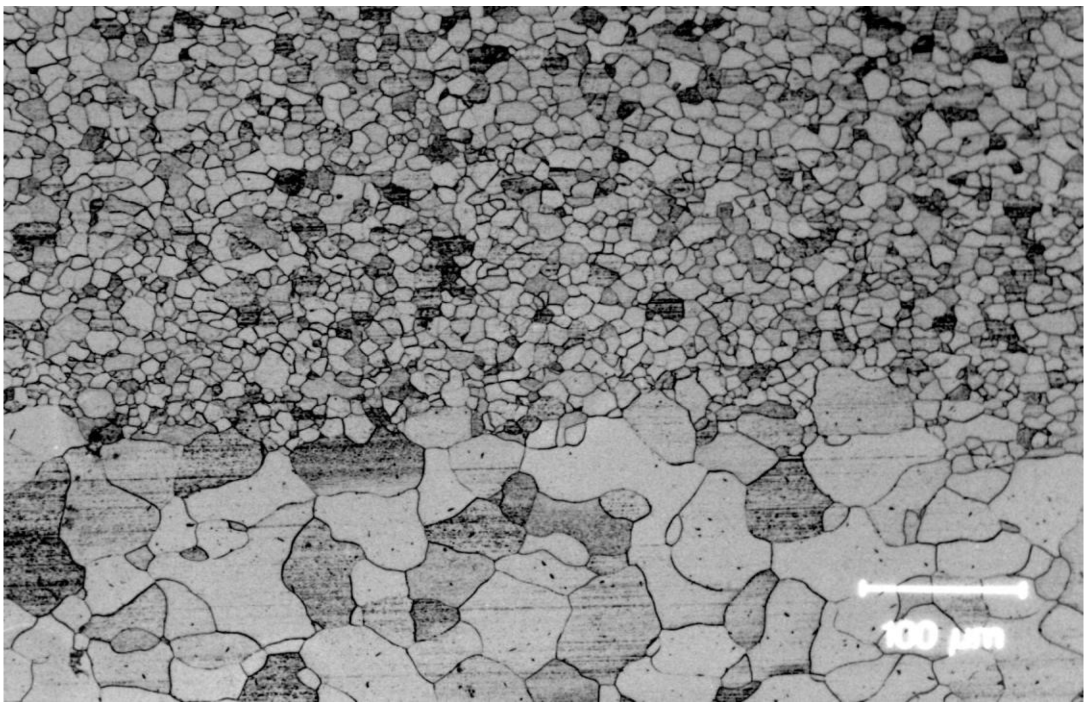


Fig 106

The consequence of this grain size variation across the width of the strip is evident when the hot rolled sheet is later cold rolled in the cold mill. The larger grains at the edges are softer and hence, are cold rolled more than the regions away from the edges. This over-rolling in the cold mill can lead to the formation of wavy edges seen in Fig 107. The strip would hence be rejected due to poor shape.

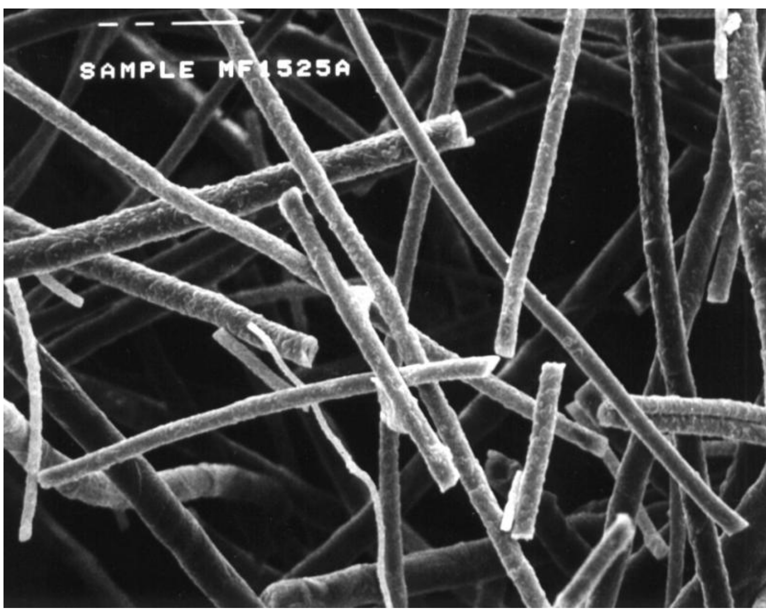
Fig 107

3.22 Examples of failures in composite materials

There are several types of composites used in the industry. In general, a relatively soft and ductile matrix provides the base into which are embedded different types of hard fibres based on , for example, carbon or ceramic materials. The nature of the environment determines the choice of the matrix , the type of fibres and, whether the fibres are aligned in relation to the principal stress axis. Aligning the fibres helps to control the propagation of the cracks since they absorb a part of the energy of deformation. A carbon-epoxy resin combination absorbs more energy than steel.

With high temperature applications such as in aerospace, the issues are; temperatures can be up to 1500^{0} C and above., a service time of ~1500 hours and an oxidising atmosphere. Vacancy diffusion at such temperatures can be very high, stress-aided diffusion needs to be prevented and this requires that the fibres are aligned and that dislocation multiplication is prevented. To stop dislocation motion, a high enough Pierels stress is needed. In Formula 1 racing cars, carbon fibre-epoxy resin panels are used with the fibres being aligned to produce laminate sandwiches.

Examples of alumina fibres are shown in Fig 108.



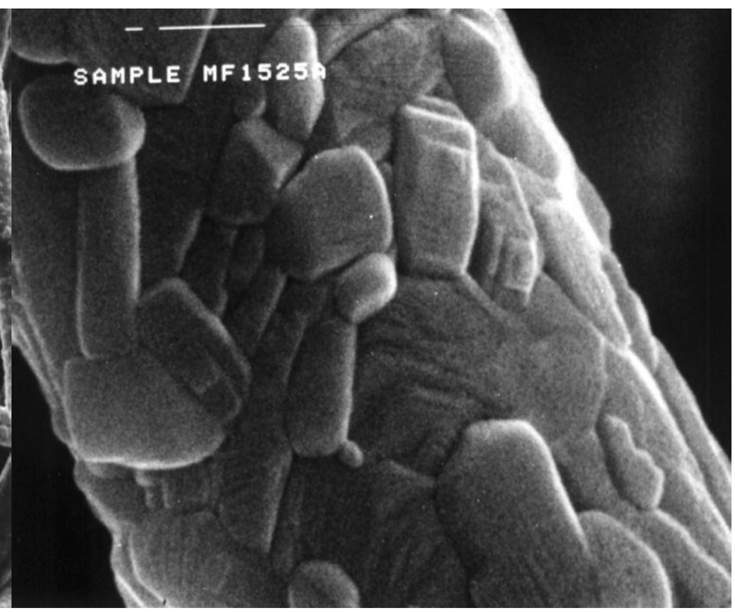
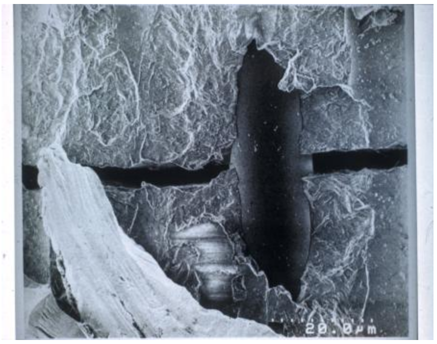
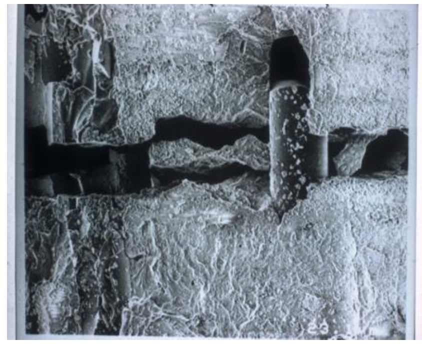


Fig 108 Fig 109

At high magnification, Fig 109, the alumina fibres are clearly seen to be recrystallised.

The bonding of the fibres to the resin matrix is a critical issue. In the absence of a good bond, fibre-pullout can occur which can lead to the failure of the component. Equally, there are instances where a certain level of fibre-pullout is deliberately allowed for since this helps to absorb the energy of deformation. Examples of failures are shown in Figs 110-115.





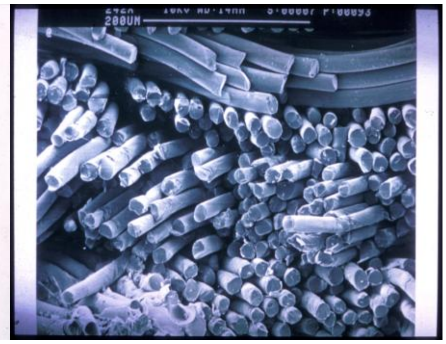
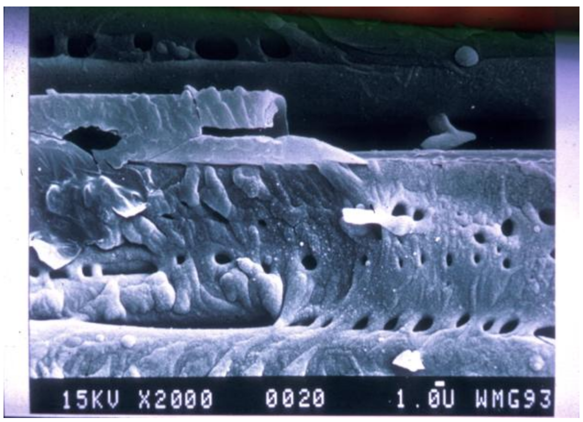


Fig 110 Fig 111 Fig 112



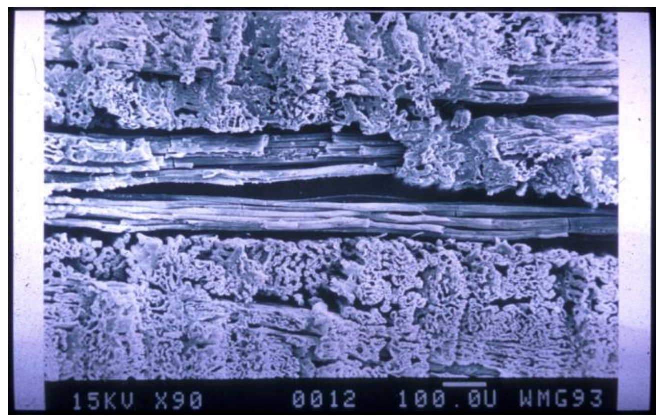


Fig 113 Fig 114

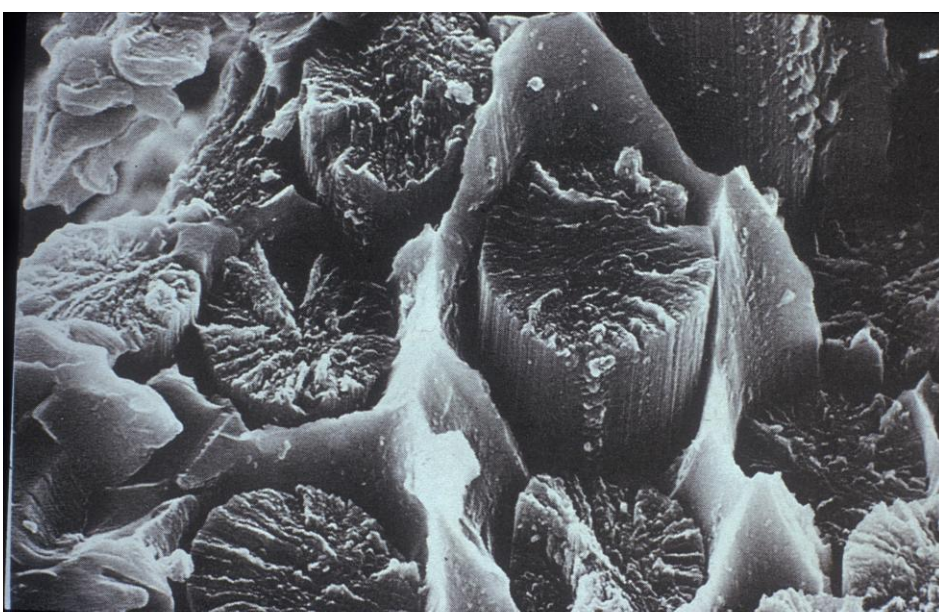


Fig 115

Aligning of the fibres can be seen in Figs.112 and 114 whilst fibre –pullout can be seen in Fig 113. Failure of the matrix is seen in Figs 110 and 111. Fig 115 shows the soft, ductile, flowing nature of the failure in the matrix; in contrast, the hard fibre has failed in a brittle manner. In some respects, these examples of ductile and brittle failures are similar to those seen earlier in metallic materials, Figs 20-22 and Fig 32.

4. Remarks in conclusion

This compilation is merely a small window through which the reader can get some appreciation of why materials and components fail in industry. Over one hundred photographs, illustrations and other data have been provided in order for the student to identify the nature and appearance of the defect, recognise it if it occurs in the future, understand why this occurs, what will be consequences if it goes undetected and what can be done to prevent the recurrence of it in the future. It is hoped that this compilation will prove to be a source of reference to the broad spectrum of fractures, failures and rejections of engineering materials and components.

5. Acknowledgements

The illustrations given here have been drawn from several sources. Wherever relevant, these sources have been mentioned. A significant amount of data has been obtained during my visits to the Rolls-Royce plants at Barnoldwick, Lancashire, Bristol and Derby as well as to the Customer Support facility of Rolls-Royce in London. Information and data have also been collected during my visits to the Ford's R & D centre based in Dunton, Essex. Some of the illustrations and examples cited have been extracted from my reports and notes made during my days at the Welsh Technology Centre, (formerly Corus/ now Tata Steel) Port Talbot. Finally, the few remaining examples have been derived from the internet; references to these are given in the text.

I place on record my gratitude to the people in the above institutions who gave me the information that enabled me to undertake this compilation.