Photoelastic Investigation Using New STL-Resins

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Abstract

Stereolithography is not only ideal to study the function and the design of a simple or complex component, but also for stress and strain analysis by means of photoelasticity. The basis for using Stereolithograpy components is the birefringent property of the photopolymers, which has been discovered in 1991 in the Lab of Photoelasticity and Holography [5]. Therefore, a few acrylate and epoxy resins developed by Ciba-Geigy were calibrated and compared with the most commonly used resin, Araldite B (manufactured by Ciba-Geigy, too). The experience shows that static and dynamic photoelastic investigations by using the new STL-resins are possible. The time saving for photoelastic investigations amounts to values about 10 months and the cost saving is equivalent to 90%.

Introduction

Since the beginning of this century, photoelastic investigations have been realized to get a statement about the stress and strain distribution within a component. Concerning photoelasticity, one event of the century was the introduction of phenol resins in 1931 and epoxy resins in 1950. Unfortunately, photoelasticity fell into oblivion through the years due to the introduction of FEA. By introducting Stereolithography the main problem of photoelasticity, how to get a transparent model of the prototype, vanished. The birefringent properties of the STL-resins were discovered in the Lab of Photoelasticity, Holography and Shearography at the University of Kassel in 1991. Recently, a few companies, especially from the automotive and aerospace industries in the USA, UK and France rediscovered photoelasticity as a suitable method for stress and strain analysis.
Mainly, STL-resins based on acrylates and epoxies have been investigated, which were developed by Ciba-Geigy and distributed by 3D Systems. Moreover, a few STL-components were investigated, made from resins of other manufacturers, such as DuPont and Allied Signal and were built on 3D Systems, EOS and Fockele & Schwarze machines. On principle, the most suitable resins to realize photoelastic investigations are the new Ciba-Geigy epoxy resins (XB 5170 and XB 5180), treated by using the drawing style ACES, but especially the DuPont resins SOMOS 3100 and SOMOS 3110 are suitable, too. The main problem using these DuPont resins are the unsuited drawing styles to realize photoelastic investigations. Most of the drawing styles to treat the DuPont resins are leaving cavities within the cured part in order to get fast and accurate STL-components. Unfortunately, on the mechanical point of view these components are punched discs respectively plates.
The most important disadvantage of the STL-components made from the Allied Signal resins "Exactomer" is the poor transparency of those parts, especially if the components are warmed up to the glass transition temperature. Afterwards, the color of the STL-components is nearly brown. Thus, it will be very difficult to examine the isochromatic fringe order. Apart from that, the advantage of the STL-components made from "Exactomer" are the high quality in size deviation and surface finishing.
Because of the above mentioned disadvantages we use Ciba-Geigy resins and the drawing style ACES.

Fundamentals of Photoelasticity

The determination of stresses and strains within a component by means of photoelastic testing is based on the temporary birefringence of the loaded transparent materials, mainly plastics. The birefringence of these materials can be shown in polarized white or monochromatic and non-coherent light. Birefringence separates a beam of polarized light into two beams of light oscillating perpendicularly to each other. If loaded solids are birefringent, the directions of the two beams correspond to the directions of the principal stresses. However, the speed of these two beam components is different, which leads to a path difference or relative phase difference. As a result, the difference of the principal stresses can be shown as lines of the same color, also called isochromatics. An experimental setup for performing photoelastic investigations is shown in Figure 1. It is a very simple and low-cost assembly where the light source can be a common electric light bulb. A lightwave going through the polarization filter becomes linearly polarized.

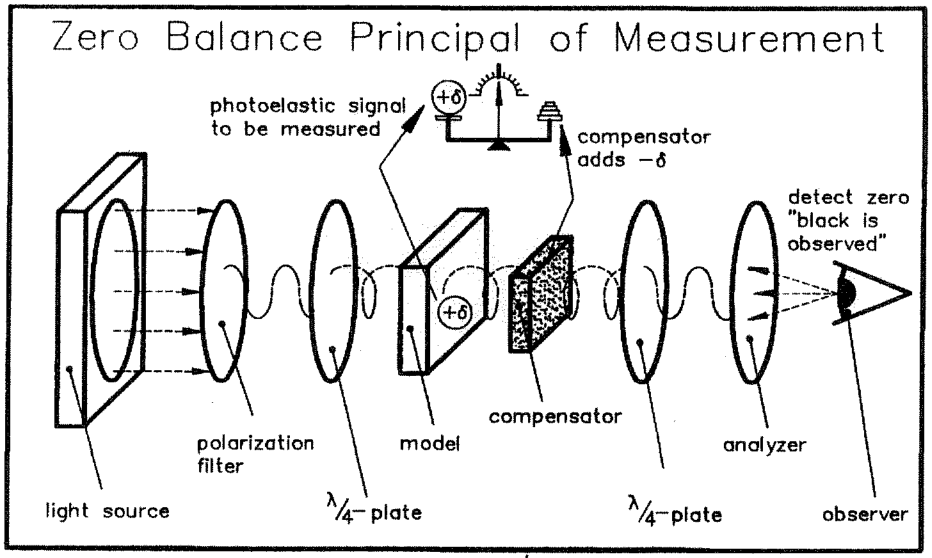

Fig. 1: Principle of a photoelastic setup including a compensator for determining the exact fringe order

If a photoelastic investigation is done in linearly polarized light, isochromatics and dark lines showing the same principal directions of stress, called isoclinics, are obtained. However, for some applications and investigations the observed isoclinics disturb the isochromatic fringe pattern. This requires circular polarized light by using two quarterwave-plates to wipe out the isoclinics. Suitable resins for photoelasticity tests must have the following properties:

- birefringence
- linear increase of the fringe order dependent on the force
- transparency
- elastic behavior

As a result of calibration tests by using circular discs, the photoelastic constant was calculated (Figure 3) by using the equation [1,6,7]

$$S = \frac{8F}{\pi D \delta} \qquad (1)$$

where F is the force [N], D stands for the diameter of the specimen [mm] and δ is the isochromatic fringe order.

If the ratio F/δ is constant, the photoelastic "constant" S has to be constant, too. But if S is depicted vs. the force F respectively the isochromatic fringe order δ, a logarithmic graph of S is obtained. The logarithmic graph determined of δ vs. F is valid for all the plastics we investigated and which are used for evaluating photoelastic investigations. However, to get the reasons for the logarithmic increase of S, Araldite B, XB 5170 ACES and XB 5180 were investigated by using a transmission ellipsometer (Figure 4). The transmission ellipsometer used is a high precision unit measuring the relative phase difference (which is equivalent to δ) of the two beam components created by the incident light beam; the unit has developed at the University of Kassel. A block diagram of the PSCA-transmission ellipsometer is shown in Figure 4.

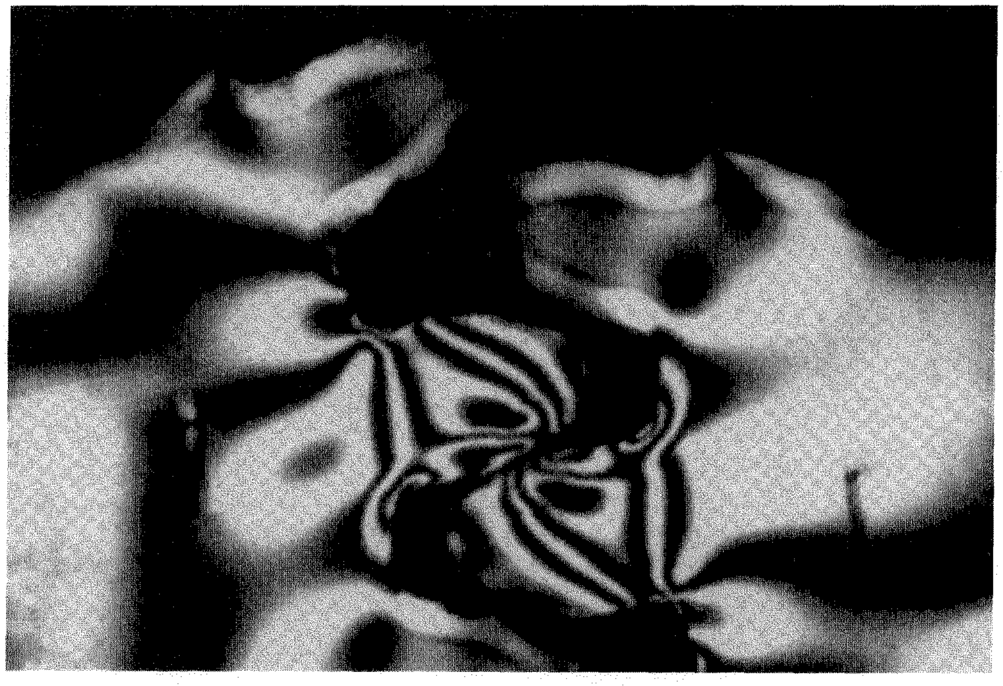

Fig. 2: Isochromatic fringe pattern in a frozen-in segment gear

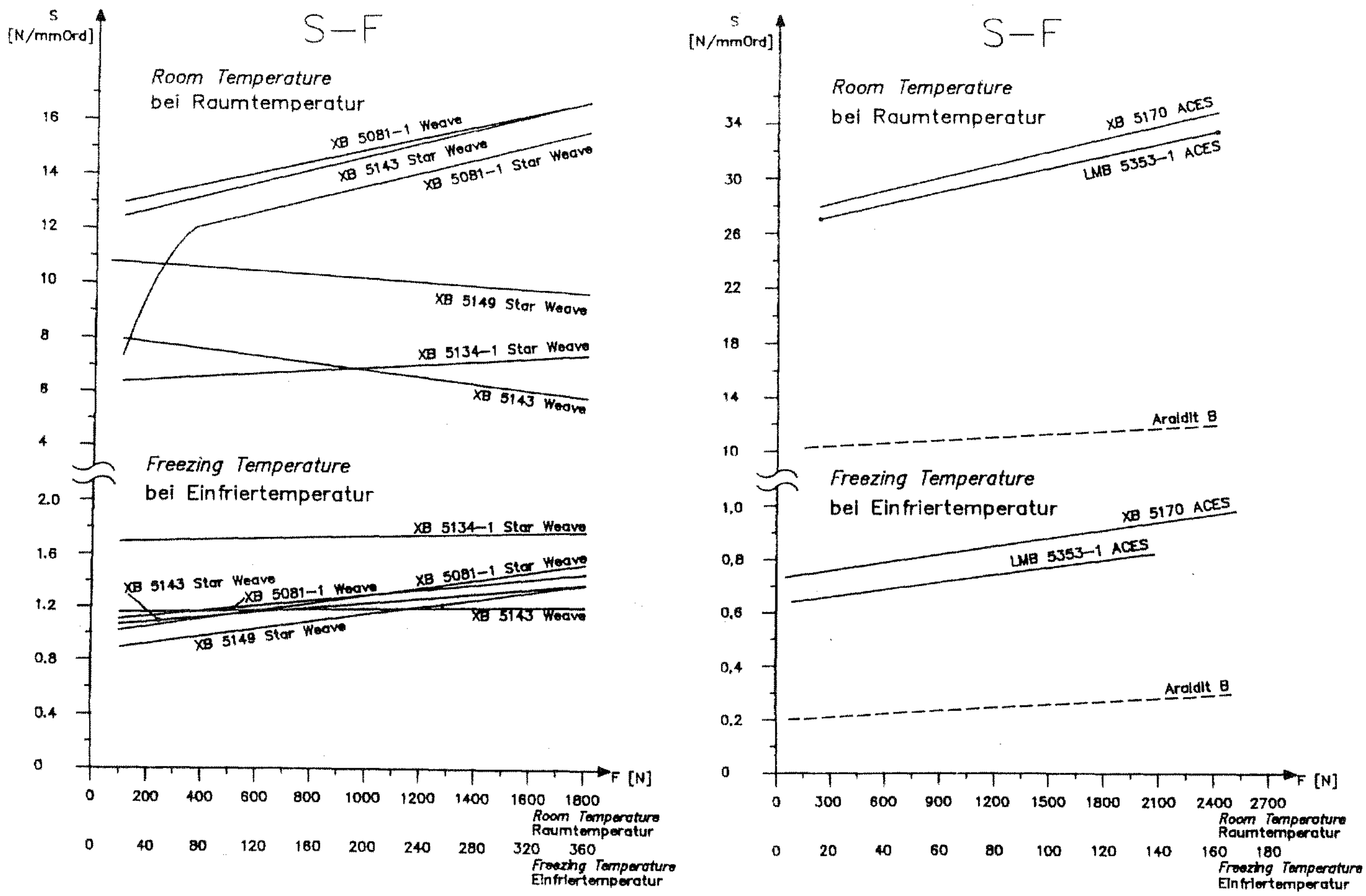

Fig. 3: Photoelastic constant S vs. force F of the most commonly used STL-resins

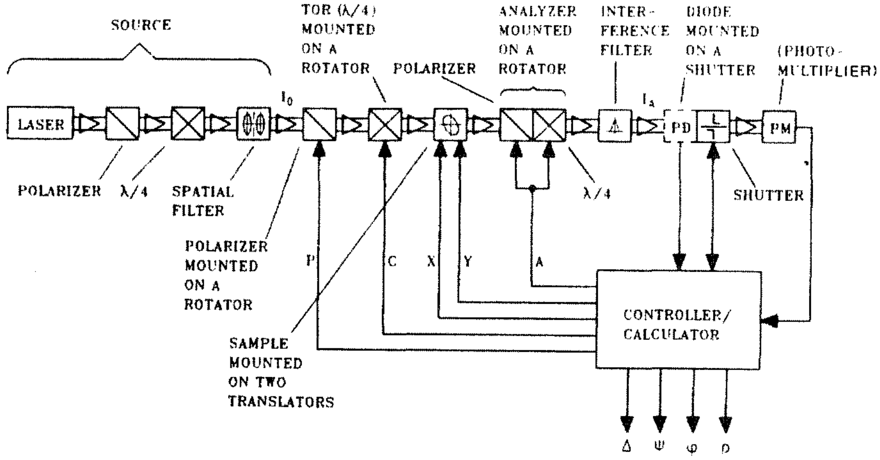

Fig. 4: Arrangement of the automatic PSCA-transmission ellipsometer

Thus, the transmission ellipsometer uses the birefringent properties of transparent materials too, but it has been developed to determine very low tension-induced birefringence or rest anisotropies of a transparent specimen. Because of the applied algorithm, it was only possible to examine the results of a relative phase difference between 0 to 90° repectively 0 to 0.5 isochromatic fringe orders. The limitation due to the restricted range of measurement is not really worth mentioning, since the highest increase of S vs. F respectively S vs. δ is around 0 to 0.5 fringe orders. The results obtained were equivalent to the results measured by a common setup for photoelastic investigations. A great advantage of using a transmission ellipsometer is the opportunity to measure the production related residual stresses, thus it is possible to avoid them and to get the exact stresses caused by the load. One can say that part of the logarithmic increase of the photoelastic constant between 0 to 1 fringe order can be explained by the production induced residual stresses within the investigated plastics. The deviation of S between 0 to 8 fringe orders amounts to 10-15% (Figure 3). Concerning this effect, the explanation could be an anomaly of the dispersion, which depends not only on the wavelength of the light used, but also on the load of the specimen. These investigations in series are not finished till now.

Poisson's ratio and Young's modulus

Further important material properties for examining photoelastic investigations are Poisson's ratio and Young's modulus.

Young's modulus, which was measured for the resins XB 5180 and XB 5170 by Ciba-Geigy, comes to approx. 2500 N/mm². The main problem by using these data of Young's modulus is that the specimen were casted between two glass panels different from building by a STL-machine. Therefore, Young's modulus was determined through a bending and a tensile test using STL-specimens made from XB 5170 ACES and XB 5180 ACES [4]. As a result from the bending test, Young's modulus dependend on the material used was obtained, which is now

E=2900 N/mm² (XB 5180 ACES)
E=3000 N/mm² (XB 5170 ACES)

The dimensions of the rods investigated have been 25 x 12,5 x 200 mm.

Since it was intentional to verify these results, a tensile test was realized. The thickness of the specimen used was 2 mm. As a result from the bending test, Young's modulus of the thin tensile specimen was significantly lower than that of the thicker bending specimen. One can say that this high deviation of Young's modulus can be explained by the diffusion of humidity into the components [11]. If the slices used by a tensile test are very thin, the absorption all over the surface of the specimen will take only a few hours (it is called time-edge-effect). As a result of the absorption, the material properties deteriorate. To avoid this, the STL-components should be stored at 30°C and approximately 10% humidity. Ciba-Geigy investigated the decrease of the flexural modulus dependent on the water concentration, too. The results are depicted in Figure 5 [11].

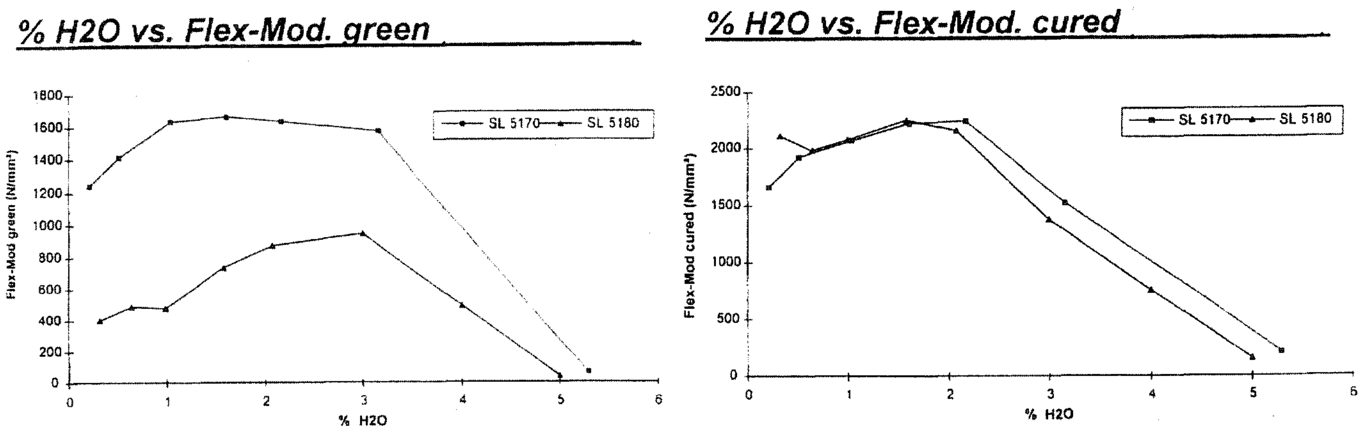

Fig. 5: Flexural modulus vs. water absorption of green and cured STL-components

Moreover, Poisson's ratio of the model used for photoelastic investigations should be the same as Poisson's ratio of the material used for the prototype. Poisson's ratios of the epoxy resins were determined by a tensile test, too. Within the range of measurement normally used (between 0 to 1.6% strain), Poisson's ratio amounts to $\approx 0.37 \pm 0.02$. At higher rates of strain within the plastic range, Poisson's ratio can vary. Unfortunately, the potential connections between Poisson's ratio and the elastic respectively the plastic range are not clarified yet.

Dynamic investigations

On principle, it is possible to realize dynamic investigations by means of photoelasticity. For this, the dynamic modulus and the damping of the material is required [4].
The damping d of the material is required by using the full width at half maximum. The dynamic modulus can be obtained from the equation of the complex Young's modulus

$$E^{*} = E' + iE'' \qquad (2)$$

where E^{*} is the time-dependent or dynamic modulus, E' is the memory modulus and E" is the loss modulus. One can say that

$$d = \tan\Theta = \frac{E'}{E''} \qquad (3)$$

where Θ is the relative phase difference. E' is a measure to describe the energy, which will be stored at the maximum amplitude of every oscillation and regained afterwards. One can say that E' is nearly the same as the common Young's modulus. E" is a measure to describe the energy, which will dissipate non-reversibly into friction respectively heat at every oscillation. However, the ratio E'/E" is equivalent to

$$d = \frac{\Delta f_H}{f_0} = \frac{\Delta\omega_H}{\omega_0}$$

where f_0 is the eigenfrequency and ω_0 is the corresponding circular frequency. The next step required is to determine the frequency range Δf_H respectively $\Delta\omega_0$ at the half maximum of the eigenfrequency. Therefore, it is required to determine the point, where the energy is equivalent to $1/\sqrt{2}$ of the maximum amplitude respectively where the amplitude is $20\lg\sqrt{2} \approx 3\mathrm{dB}$ lower than the maximum amplitude. The characteristic data are as following:

d = 2.6% (XB 5170 ACES)
d = 4.1% (XB 5180 ACES)

Furthermore, an important point to examine dynamic photoelastic investigations is the validity of the similarity laws [1,2,10]. That means, the resonance frequencies must be transferable from the model to the prototype.

In Figure 6, the frequency distributions of the cantilevers with same shape made from different materials are shown. From equation (4) the ratio of the frequencies is obtained

$$\frac{f_P}{f_M} = \frac{l_M}{l_P}\sqrt{\frac{E_P \rho_M}{E_M \rho_P}} \tag{4}$$

where f is the frequency, l is the length of the cantilever, E is Young's modulus respectively the dynamic modulus and ρ is the density. The index M stands for the model and P for the prototype. The theoretical value for the ratio f_P/f_M of XB 5180 ACES and steel amounts to 3.346 for the above mentioned cantilevers. The ratio measured was approximately 3.1 and thus lower than the theoretical value, but it was nearly constant all over the domain of measurement. Thus, it is possible to calculate the resonance frequencies of the prototype from the measured frequencies of the model.

The main problem is the knowledge of the actual ratio f_P/f_M, due to the real restraint of the specimen the frequency distribution will be lower than the rigid restraint of the theoretical calculation. Furthermore, the restraint causes additional frequencies, which superimpose the eigenfrequencies of the specimens. Thus, sometimes it can be difficult to extract the resonance frequencies of the specimen.

Effect of the Manufacturing Conditions

The manufacturing conditions and their effects on the photoelastic constant S were investigated by DoE, especially using the Taguchi method. The Taguchi tests were distinguished between room temperature and freezing temperature, because these two temperatures are relevant for realizing the photoelastic investigations. As a result, the most important factor for the absolute value respectively the deviation of S is the postcuring by UV-light or heat.

If photoelastic investigations are to be realized at room temperature, it is advisable to illuminate the STL-components for about 3h under UV-light using maximum power of the UV-oven and without a thermal postcuring. Then the photoelastic constant and the deviation will become a minimum at room temperature. The drawing style ACES is not relevant but advantageous.

In contrast, if photoelastic tests shall be performed at freezing temperature, it is advisable to illuminate the green STL-components only for 1h and with maximum power. A thermal postcuring is not required, because it will happen automatically during the investigation.

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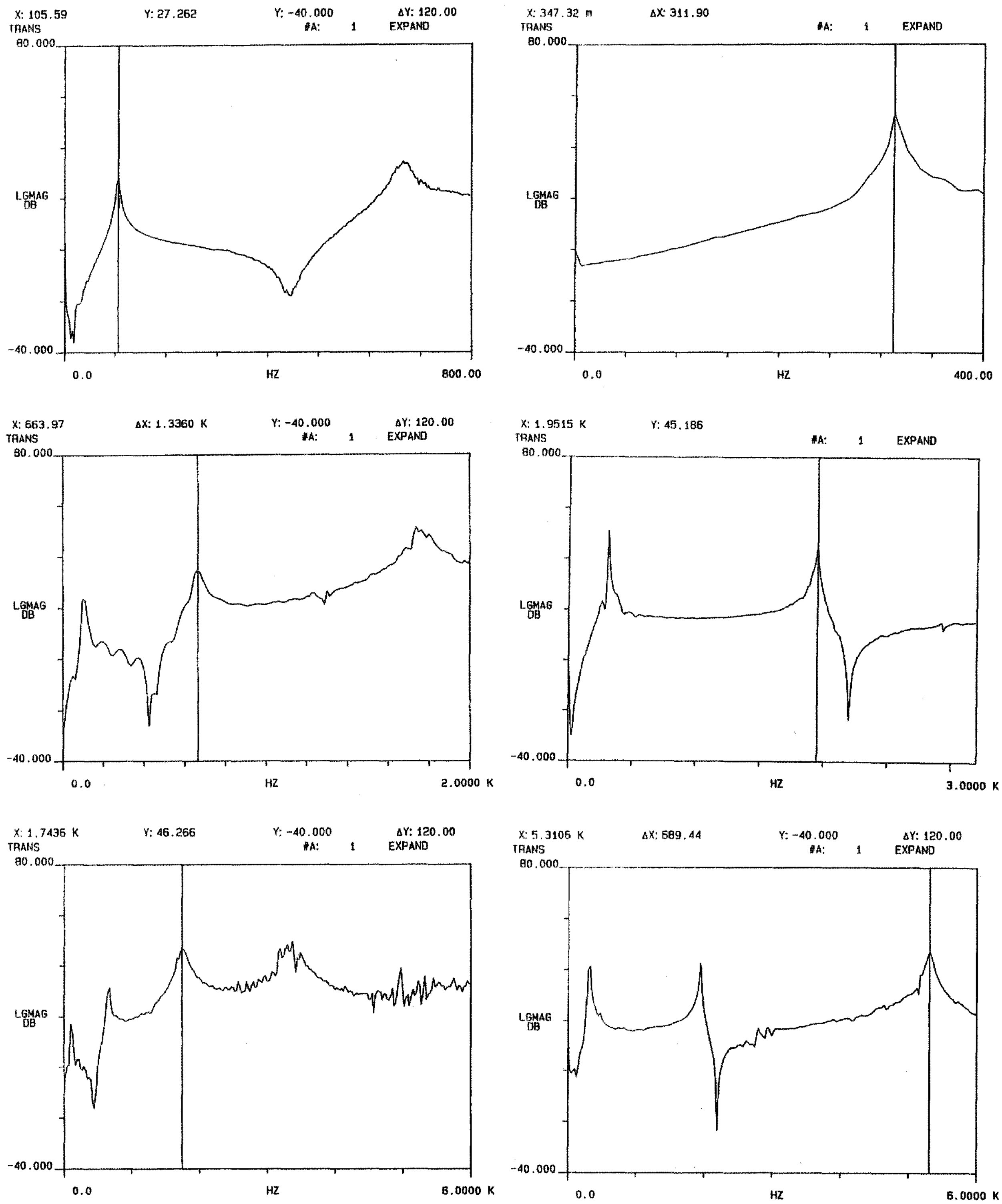

a)

b)

Fig. 6: Frequency distributions and resonance frequencies of XB 5180 ACES (a) in comparison with steel (b)

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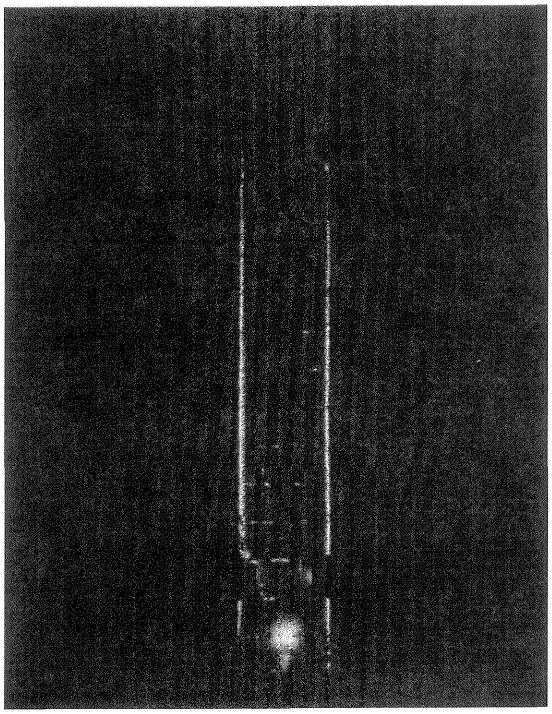

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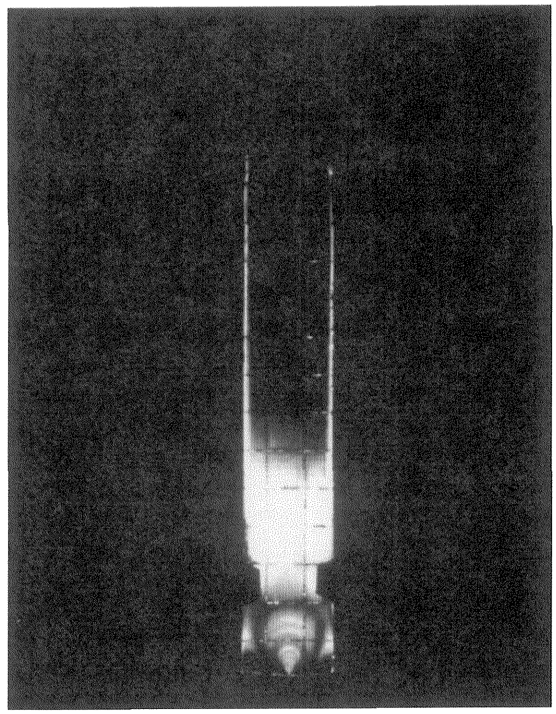

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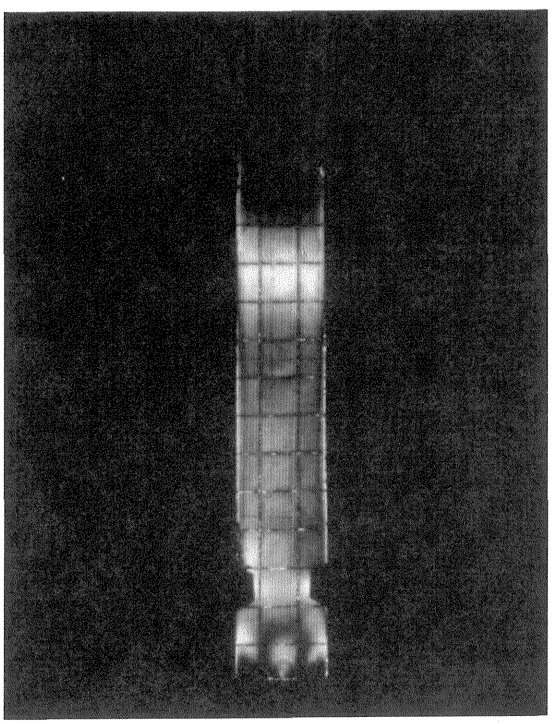

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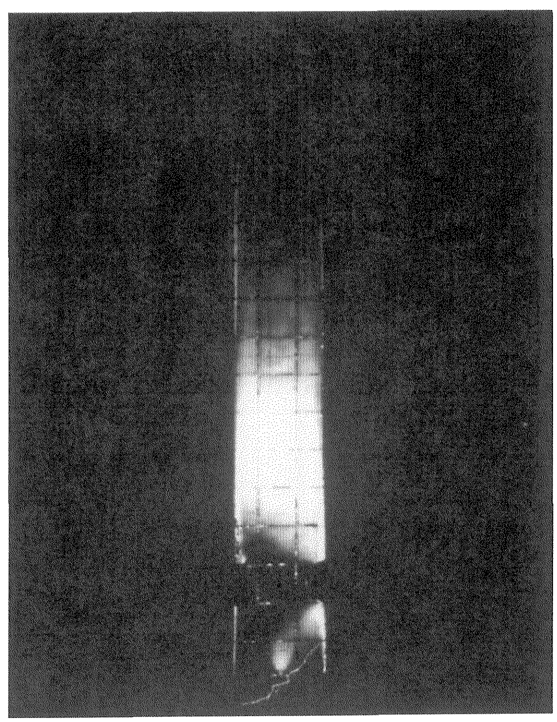

0,091 [ms]

Fig. 7: Propagation of a shock wave through a rod in [ms] after an impact

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