Manufacture and bench qualification of a road vehicle steering knuckle produced by pressing an aluminium alloy in the semiliquid state

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Abstract

Road vehicle steering knuckles in aluminium alloy AS7U3G rheocast in the semiliquid state were pressed and subjected to a series of tests to determine the mechanical and metallurgical characteristics of this material. Bench qualification tests were then run in the form of fatigue tests simulating the most severe condition envisaged in the design stage. The results showed that the design dimensions were satisfactory in relation to the observed strength of the components.

Riassunto

Utilizzando la lega di alluminio AS7U3G, ottenuta allo stato di semiliquido mediante processo di reocolata, sono stati stampati alcuni montanti anteriori di autoveicolo. I componenti così realizzati sono stati sottoposti ad una serie di esami per l'accertamento delle caratteristiche meccaniche e metallurgiche del materiale. Sono state quindi condotte prove di qualificazione al banco mediante prove di fatica simulanti la condizione più severa di progetto. I risultati della sperimentazione hanno mostrato che il dimensionamento effettuato in fase di progetto è risultato adeguato, anche in funzione delle caratteristiche meccaniche riscontrate sui componenti.

1. Introduction

The particular fluids dynamic properties displayed by a nodular semiliquid (rheocast) alloy in the solidification range permit the employment of forming processes so far confined to the liquid state. Squeeze casting, for example, has been used in a number of interesting applications over the last ten years, including the manufacture of road vehicle components, such as wheels, pistons, etc.

In this process, a charge of liquid metal is solidified under pressure in a mould to produce a casting with few shrinkage cavities and a total absence of gas porosity.

These advantages, however, are offset by a series of operating constraints, such as the need for a time delay to allow the liquid charge in the mould to reach a minimum temperature before the plunger is operated, the need for low plunger speeds to prevent the generation of turbulence in the bath during the forming process, etc. The use of a globular alloy at a temperature within the solidification range, in addition to offering the obvious advantages stemming from the practicability of much lower forming temperatures (several tens of degrees C in the case of an aluminium alloy), permits faster deformation and hence greater productivity, thanks to the high viscosity of the charge, and at the same time results in a casting that is a perfect reproduction of the mould, something that is not always possible in conventional processes.

In comparison with conventional forging, the pressing temperature required for a semiliquid is much higher (580°C as opposed to 350°C for aluminium alloys). On the other hand, a semiliquid alloy provides the following advantages: the possibility of using low-power presses or increasing the number of figures with no change in the power required (see Table 1), the possibility of drastically reducing the number of forming steps, even for complex-geometry components (and hence fewer moulds and greater productivity), and a longer mould life as a result of less wear.

This paper investigates the application of rheocast alloy pressing to the manufacture of a road vehicle steering knuckle. In addition to the construction of prototypes and assessment of their strength and microstructure, the feasibility of the process was evaluated by bench certification of the component through fatigue tests simulating the most severe operating condition envisaged in the design stage.

TABLE 1 - Typical alloy forging pressures

Solid alloys	100	MPa
Semiliquid dendritic alloys	10	MPa
Semiliquid rheocast alloys	0.1	MPa

2. Preparation of the rheocast alloy

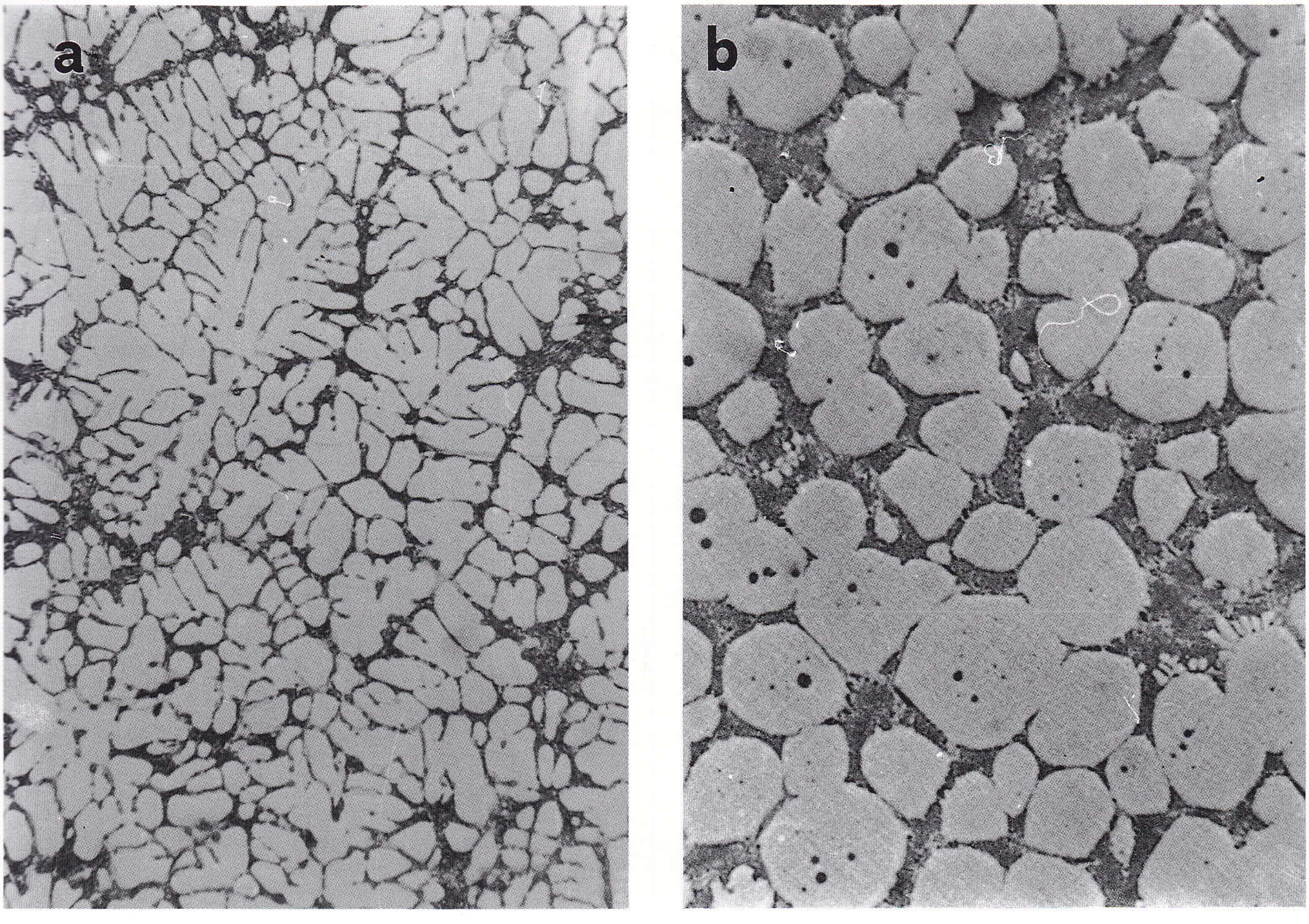
Preparation of a doughy, semiliquid alloy, i.e. with the solid phase of globular shape, requires vigorous stirring of the bath, and hence a high shear gradient between the solid particles in the mixture, so as to prevent the dendritic linkages that would otherwise be formed during solidification. The dendritic fragments are thus kept apart and tend to assume a spheroidal shape under the action of mutual mechanical collisions (Fig. 1).
A wide range of agitation techniques can be employed, provided they also allow the alloy to cool removing the latent heat of solidification.

In the agitation process patented by the Fiat Research Centre, alloy in the solidification phase is passed through a static mixer whose geometry ensures the generation of high shear forces. The viscosity of the semiliquid alloy is thus kept relatively low even in the presence of very substantial solid fractions. The mixer configuration also makes it an excellent heat exchanger for efficient removal of the solidification heat, thus stepping up the productivity of the process (1).

3. Semi-liquid forming of the steering knuckle

Rheocast AS7U3G alloy (90% Al, 7% Si, 3% Cu) ingots were heated to a temperature in the solidification range (~565°C) to melt the eutectic matrix around the solid Al-Si-Cu solution globules and produce a slurry with a viscosity of 10^2 poise.
A ladle was then used to pour the slurry by hand into a mould positioned under a hydraulic press and a force of about 2MN was applied. Complete solidification of the casting was obtained in a few seconds, since about 70% of the charge consisted of solid phase and the

Fig. 1 - Microstructure of an Al-Si-Cu alloy
a) Usual form; b)Rheocast alloy.



pressure produced a very high heat transfer coefficient between the slurry and the walls of the mould (about one order of magnitude greater than that obtained in gravity casting).
Both the mould and the plunger were pre-heated to 250-300°C by suitably placed electrical plugs. A lower temperature would result in a poor surface finishing (cold laps), while a higher temperature would lead to greater mould wear and also prolong the solidification time.
A colloidal graphite-based lubricant was sprayed on the plunger and inside the mould to facilitate the extraction of the casting.

4. Determination of the metallurgical and mechanical characteristics of the castings

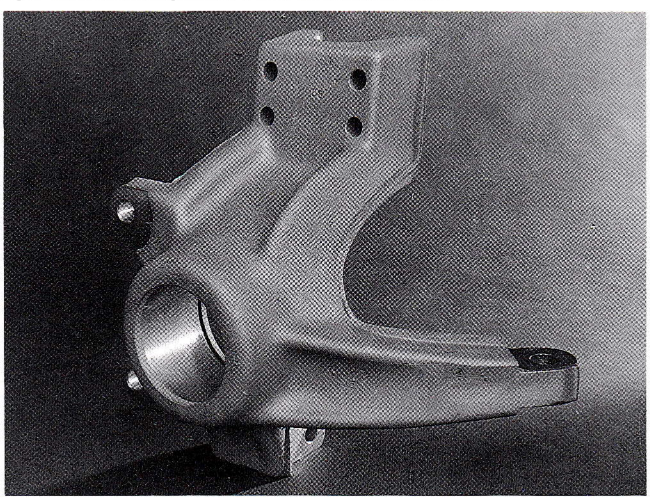
4.1 Radiographic inspection

Ten prototypes of the component were prepared (Fig. 2). Some of these were examined radiographically (see example in Fig. 3).
The castings were perfectly sound (grade 1, ASTM E 155). It is, indeed, well known that high-pressure solidification results in total disappearance of gas porosities, because they are reduced to a small volume and the pressure itself promotes gas solubilisation. In addition, the castings were free from solidification shrinkage cavities, as the liquid fraction of the charge was < 40%.

4.2 Metallography

Specimens were taken for metallographic analysis from eight metallurgically significant areas of one component to check whether segregation of the eutectic and globular phases (a recurrent phenomenon in the pressing of dendritic alloys [2]) had occured. The examination showed that the structural uniformity of the component had been attained.

Fig. 2 - Left front steering knuckle of the X 1/75 research vehicle.



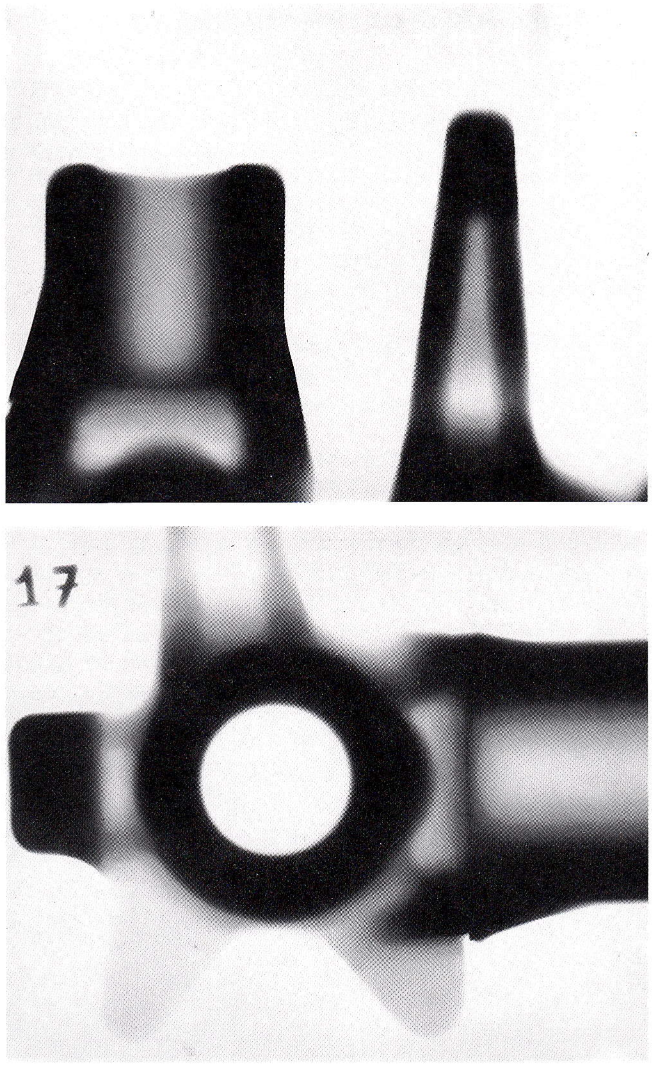


Fig. 3 - Radiographs of the component shown in Fig. 2.

4.3 Tensile tests

Eleven dissection specimens from a steering knuckle were stabilised at 220°C for 2 h and then subjected to tensile tests at room temperature to determine the tensile properties of the material after pressing, and further check the uniformity of the casting. The close similarity of the results (Table 2) provides further

TABLE 2 - Tensile test values for 11 dissection specimens from a rheocast steering knuckle

Su (MPa)	Sy (MPa)	El (%)	Z (%)
215	158	3	5
226	174	3	4
228	188	4	5
226	188	2	4
225	179	3	5
231	181	3	6
223	177	4	6
239	177	2	4
222	182	3	4
209	165	3	5
227	169	2	4

evidence of the absence of segregation.
It may also be pointed out that when this alloy was gravity cast and stabilised in the same way it displayed virtually the same ultimate strength (230 MPa) as that observed on the rheocast alloy (225 MPa).

4.4 Fatigue tests

After stabilisation at 220°C for 2 h, dissection specimens from several components were subjected to load controlled fatigue tests to determine the fatigue resistance of the rheocast alloy up to 10^8 cycles. An axial load was applied using a magnetic resonance pulsator (maximum capacity: 100 kN); the stress ratios were R = 0 and R = −1.
The number of cycles to failure as a function of the alternating stress imposed is illustrated in Fig. 4 (R = 0) and Fig. 5 (R = −1) respectively.

Fig. 4 - Fatigue curve for the AS7U3G alloy (R = 0).

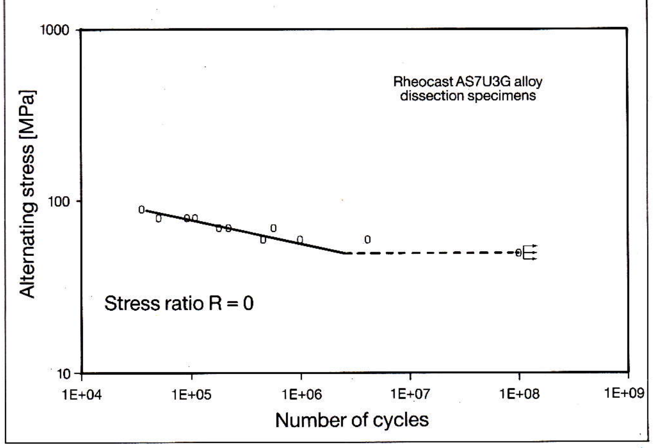
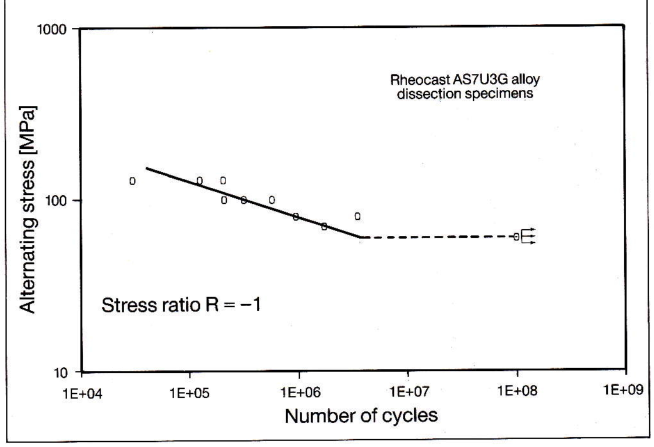


Fig. 5 - Fatigue curve for the AS7U3G alloy (R = −1).



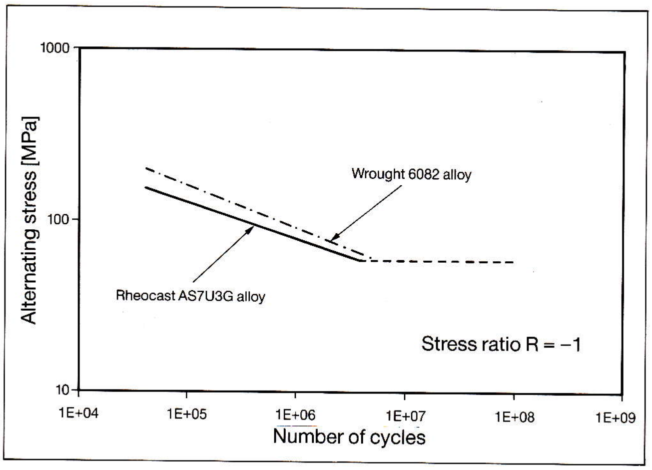


Fig. 6 - Comparison between fatigue curves for alloys AS7U3G and 6082.

A statistical regression analysis was made of the broken specimens to determine the slope k of the descending segment of the Wohler curve, and the number of transition cycles N_A corresponding to the change in k, using the equation:

$$N = N_A (S_a/S_A)^{-K}$$

where S_A is the fatigue limit at 10^8 cycles.
The following S_A, N_A and k values were observed for the two fatigue curves:
when $R = 0$ $S_A = 50$, $N_A = 2.4 \times 10^6$ and $k = 7.3$
when $R = -1$ $S_A = 60$, $N_A = 3.7 \times 10^6$ and $k = 4.8$

A certain mean stress sensitivity can be observed (S_A for $R = 0 < S_A$ for $R = -1$). There is also a slight difference in the slope k in the finite life range ($N < 5 \times 10^6$).
Dissection specimens were also taken from steering knuckles pressed made with the wrought alloy 6082 and fatigue tested with a stress ratio $R = -1$. It can be seen in Fig. 6 that the fatigue resistance at 10^8 cycles of rheocast and pressed AS7U3G alloy and pressed 6082 alloy is the same ($S_A = 60$ MPa), though the latter performs better in the finite life range.

5. Qualification of the rheocast steering knuckle

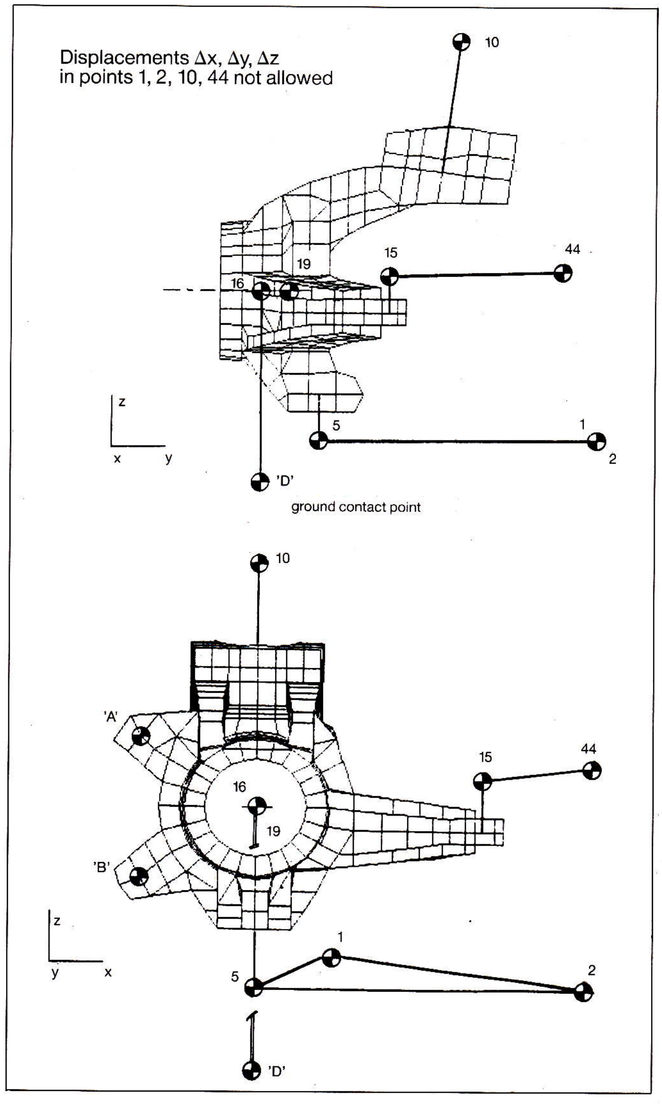
The left front steering knuckle was designed as part of the X1/75 research vehicle project, developed in the Italian National Research Council's " Progetto Finalizzato Trasporti ". The main aim of the research activity discussed in this paper was to determine whether a safety component such as a steering knuckle can be made in aluminium alloy, instead of steel or nodular cast iron.

Bench qualification of the rheocast steering knuckle was therefore carried out through fatigue tests simulating the most severe condition envisaged in the design stage, so as to provide experimental confirmation of the calculation results and identify any areas in which the design of the component could be optimised.

5.1 Test conditions

The design calculations took into account four extreme operating conditions: full bump, emergency braking, lateral force in maximum lateral acceleration and maximum longitudinal acceleration.
Analysis of the stresses generated by the loads applied

Fig. 7 - Test constraints and load application points.



showed that the most severe condition was the maximum lateral acceleration (coefficient of adhesion = 1) Fig. 7 illustrates the test constraints and the load application points postulated in the project. In this condition the load applied at ground contact point " D " is 3150 N in the Z direction and 3400 N in the Y direction. This is equivalent to the application of a force of 5000 N at point D at an angle of about 45° from the Y direction in the YZ plane.

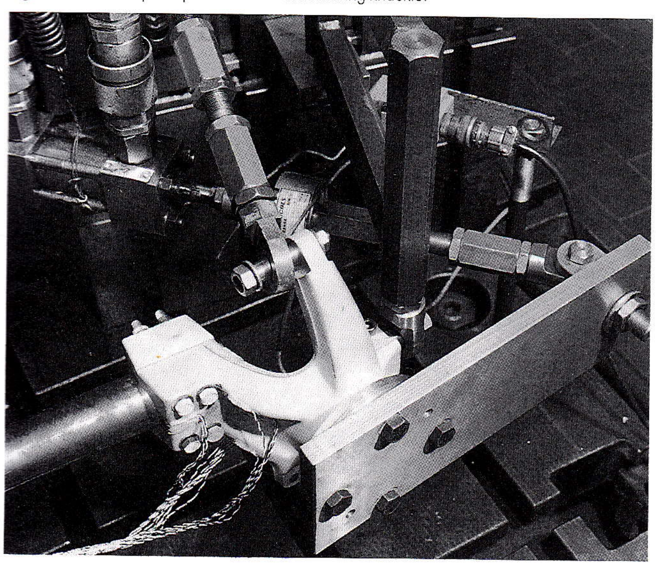
This project condition was checked both statically, i.e. by ensuring that no higher-than-yield stress was applied to any critical area of the steering knuckle, and dynamically, i.e. by ensuring that the load could be repeatedly applied for at least 10^6 cycles.

5.2 Test set-up

The test bench (Fig. 8) was set up to reproduce the way the component would be mounted on the vehicle as closely as possible.

Five particular expedients were adopted:
- A shock-absorber simulating its real counterpart during full bump was fitted.
- The wheel hub bearing was replaced by a hot-pressfitted bushing.
- The two mechanical linkages between the steering knuckle and the steering arm (point 15, Fig. 7), and the lower arm (point 5, Fig. 7), were realized by means of pins and uniballs.
- The hub was reproduced and a rigid plate, in substitution of the wheel, was attached to it for application of the force at point " D ". A hydraulic actuator applied the force at an angle of 45° from the Y direction in the YZ plane (Fig. 7).
- Points 44,1 and 2 (Fig. 7) were rigidly fixed to reaction supports.

Fig. 8 - Bench set-up for qualification of the steering knuckle.



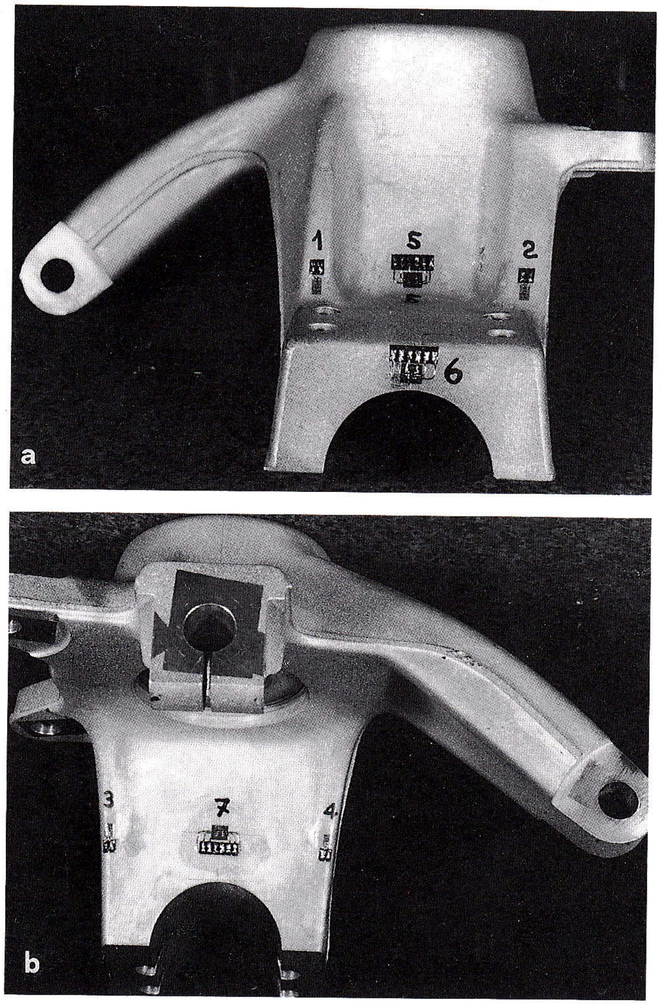


Fig. 9 - Location of strain gages and rosettes on the steering knuckle.

5.3 Component instrumentation and stress measurements

The steering knuckle was instrumented with strain gages and rosettes to measure the stresses acting on the critical areas identified in the design stage.
The locations of the four strain gages and the three rosettes are shown as nos. 1-4 and 5-7 respectively in Fig. 9.
The deformation induced by the application at point " D " of 1000 N load steps up to the 5000 N maximum corresponding to maximum lateral acceleration was then determined. The stresses measured by the strain

gages are illustrated in Fig. 10. The Mises equivalent stresses calculated from the data taken from the rosettes are shown in Fig. 11.

The results of the static check showed a linear behaviour throughout the load application range. It can thus be deduced that the stresses are less than the material proof stress limit.
As far as the comparison with the stress values calculated by means of the finite elements method is concerned, it is interesting to analyse the data for the most heavily stressed areas of the component i.e. the two ribs on which strain gages 1 and 2 were applied (see Fig. 9 a).

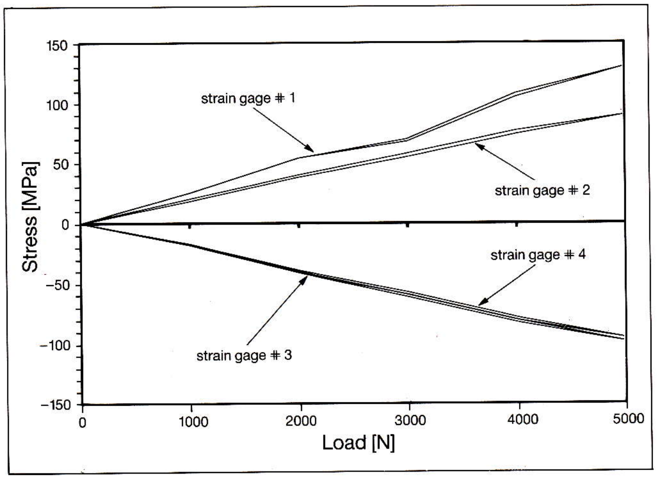
An excellent fit, in fact, was observed when the calculated stress values (125 and 80 MPa respectively) were compared with those determined experimentally, namely 130 and 90 MPa.
Lastly, it should be noted that an equivalent stress higher than 130 MPa was not calculated for any area of the component, nor was this value exceeded experimentally.

5.4 Fatigue tests

The apparatus just described was also used to fatigue-test the rheocast steering knuckles by applying a dynamic load cycle ranging from 0 to 5000 N.
Some components were loaded up to 2×10^6 cycles with no visible damage. Dynamic confirmation was thus obtained of the correctness of the project conditions relating to maximum lateral acceleration.

It should also be noted that the 1×10^6 endurance limit was exceeded by some forged 6082 alloy prototypes, and others (of different design) made of nodular cast

Fig. 10 - Stress patterns shown by the four strain gages.



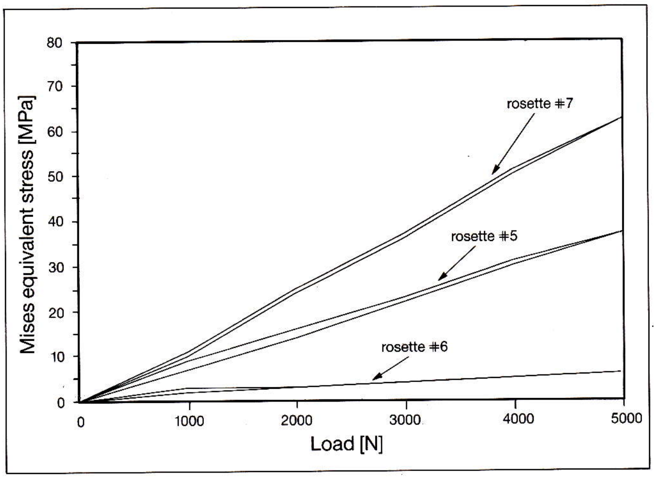


Fig. 11 - Mises equivalent stress patterns taken from the three rosettes.

iron weighing about 50% more than the aluminium ones.

5.5 Discussion of the results

Only one, albeit the most severe, of the four project conditions was checked experimentally. The dimensioning carried out proved both statically and dynamically fit.

The endurance of the bearing must be checked under operating conditions before the component can be fully certified. The difference between the thermal expansion coefficient of the steel bearing and the aluminium steering knuckle could give rise, e.g. during braking, when temperatures of more than 120°C are reached, to plastic deformation of the aluminium, perhaps accompanied by ovalisation of the hole due to the loads acting on the hub.
The onset of this phenomenon, together with possible collapse of the bearing, can only be checked by means of a special experimental rig not yet available at the Fiat Research Centre.

6. Conclusions

Prototypes of a car left front steering knuckle were hot-pressed from semiliquid rheocast AS7U3G aluminium alloy.
Radiographic inspection and metallographic analysis demonstrated the soundness of the castings, and the uniformity of their structure, including the complete absence of segregation of the eutectic and globular phases. Mechanical tests on dissection specimens showed excellent static and dynamic characteristics.

Bench qualification of the component was also carried out by means of fatigue tests simulating the most severe condition envisaged in the design stage. Stress measurements obtained with strain gages and rosettes mounted on the component showed that its behaviour was perfectly elastic across the load range applied. A close fit with the stresses calculated at the project stage by means of the finite elements method was also demonstrated.

Some prototypes were loaded up to 2×10^6 fatigue cycles with no visible damage. The dimensioning carried out thus proved to be fit. The endurance of the bearing under operating conditions, however, must still be checked to fully certify the steering knuckle.

7. Acknowledgements

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