LIGHT WEIGHT AND LOW STIFFNESS MAGNESIUM STEERING WHEEL DESIGN

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ABSTRACT

The steering wheel has an important influence on the occupant injury during automotive collisions. Energy absorbed by steering wheel deformations, reduce the risk of injury, depending on frame stiffness and occupant load distribution.

This paper describes light weight and relatively low stiffness AM 50 magnesium alloy steering wheel. Finite element calculations using static, dynamic and nonlinear analyses were performed on a steering wheel model. Frames with various stiffness were studied and modified to have the required static deformation and impact load distribution in light steering wheel design.

The proper prototypes were selected and produced by hot chamber died casting process. Static and impact tests, fatigue tests, fractography investigation and x-ray defect inspection were conducted in order to develop and produce high quality components.

The modification and the prototype experimental results are presented and compared with other existing steering wheels.

KEYWORDS: Design, Steering Wheel, Magnesium Alloys, Casting Process, FEM Analysis, Fatigue.

INTRODUCTION

The potential of applying magnesium alloys in a vehicle, includes chassis parts, engine parts and transmission box, structure parts and internal safety parts (Schumann and Friedrich, 1998) (Rosch, et al, 1998). The application of parts manufactured in die casting has increased in recent years and is expected to continue even further in the up coming years (Magers and Willekens, 1998). As far as developing alloys for die casting are concerned, reports indicate improvements in strength to creeping and other mechanical properties, however, these developments are still not available to the consumer as far as cost and supply are concerned (King, 1998). The steering wheel as a safely part is associated with random dynamic loads created from the driving conditions of the vehicle (Chiang, 1985), and impact loads occurring during an accident when contact between driver and steering wheel occurs (Huelke, 1982). Owing to the dynamic loads, the design process requires referring to the fatigue and performance of testing accordingly in addition to the requirements for energy absorption as specified in the regulations.

This paper presents a design and development process of a steering wheel made of magnesium alloy in a technology of die casting. This paper describes the preliminary design regarding materials, static and dynamic analyses in finite elements and identification of critical areas in geometric design, prototype manufacturing, acceptance tests and an alternative improved design. The acceptance tests in the development process included static loading testing, Dynamic impact testing and fatigue testing in variable frequencies and loads. Furthermore, the prototypes underwent x-ray testing and the effect of the defects was considered in relation to the calculated and measured results as well. Comparison of the above mentioned development to other steering wheels enables an assessment of the required advantages and improvements as indicated in the paper.

LOADING CONDITIONS

the loads on the steering wheel is three-dimensional, and can be divided as following:

a. Dynamic loads resulting from a collision. (Horsch and Culver, 1993), b.Operating loads.

c. Operation loads of the airbag. (Tzabari, et al, 1997), d.Removal forces.

Fig. 1 schematically describes the various loads aforesaid specified. It can be seen that the steering wheel is required to meet a variety of static and dynamic loading and the fatigue loads. All these should be considered in the designing process.

$(F_{X'}, F_{Y'}, F_{Z'})_{AC}$

$(M_{X'}, M_{Y'}, M_{Z'})_{AC}$ - Accident Impact Load

$(F_{X'}, F_{Y'}, F_{Z'})_{0}$ - Driving Operation Forces

F_{ZA} - Airbag Impact Load

F_{ZP} - Pulling Forces For Steering Wheel Removing.

$(F_X, F_Y, F_Z)_R$

$(M_X, M_Y, M_Z)_R$ - Column Reaction Forces and Moments

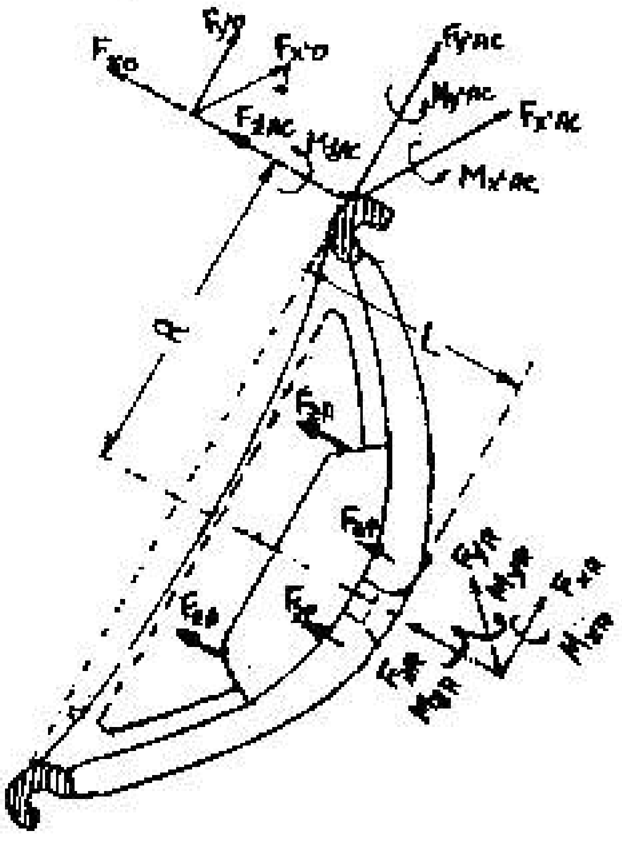


Fig. 1: Schematic description of the varied loads and the geometric parameters of the steering wheel.

The standard requirements regarding that matter are specified in the various standards which include the European Standard (EEC Directive 74/297), and the American Standard (FMVSS 203). The tests in the EEC and FMVSS Safety Standards are equivalent and can be summarized as:

A. An impact test of the human body: defined by the impact of a body mass of 34 kg and velocity of 6.69 m/sec.

B. An impact test of the head: defined by the impact of a mass of 6.8 kg and velocity of 6.69 m/sec.

The main requirements refer to forces and accelerations developed in the course of the testing as following:

Maximum force exerted on the body 1111 N. Maximum acceleration on the head 80 g during 3 ms.

These tests and requirements constitute safety approval tests for all the design stages of a product, up to its completion.

PRELIMINARY DESIGN AND MATERIAL SELECTION

The preliminary design is based on the geometrical dimensions of the steering wheel, especially the radius of the wheel (R) and the depth of the steering wheel (L), and on the other hand meet the demands of the above mentioned loads.

The stiffness of the steering wheel constitutes an important element determining the forces exerted on the human body at the time of an accident, and on the other hand, the level of the stresses in the determined loads. Therefore, the measured stiffness is applied in static loading, especially in the axial direction as the design curve.

Fig. 2 demonstrates an example of typical curves for steering wheel.

The decision regarding the number of the steering wheel spokes and an analytical evaluation of the equivalent bending and torsion axial stiffness enables preliminary determination of the beam section constants of the rim and steering wheel spokes.

This preliminary design was based on three spokes and the section geometry of the relatively thin and high ribs, allowing a high moment of inertia to bending, utilizing the advantage of the improved mechanical properties of the thin sections (Schindel-bacher and Rosch, 1998), (Sequeira and Dunlop, 1996), with an improvement in the porosity level and a relatively light weight of the steering wheel.

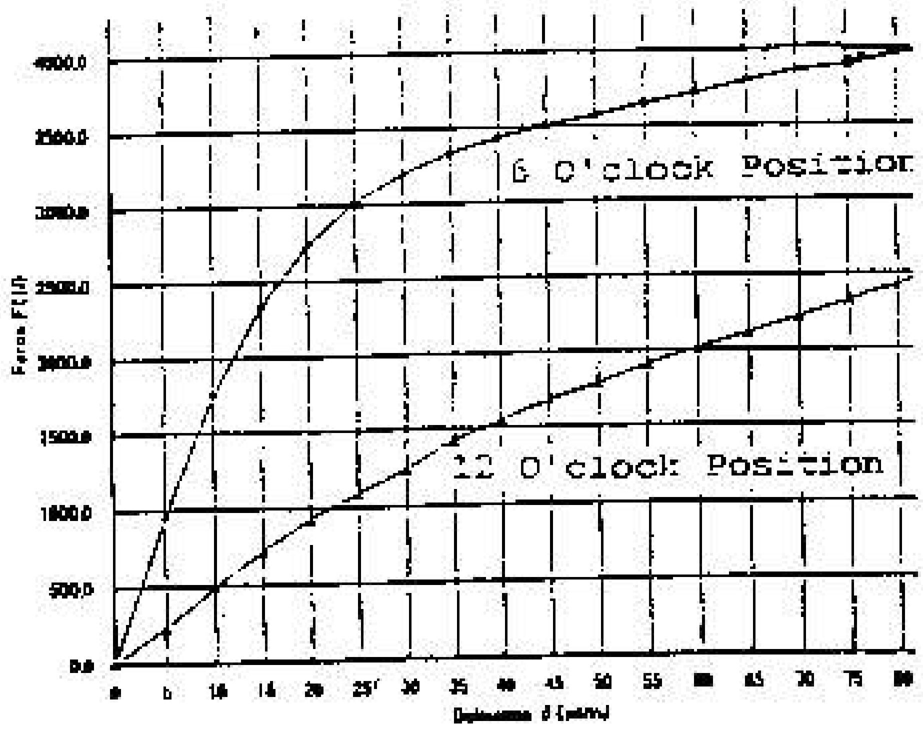


Fig. 2: Typical axial stiffness curves of steering wheel

Material selection - the potential alloys are AM 50 and AM 60 (Kawase, 1991) due to the strength and elongation properties required for the energy absorption in impact loads. The alloy AM 50 was selected because of the accumulated experience with this alloy in casting processes and its moderate advantage in elongation range and impact absorption.

Fig. 3 describes the designed steering wheel and **Fig. 4** shows the prototype that was manufactured on a 500 ton casting machine in a hot die casting systems.

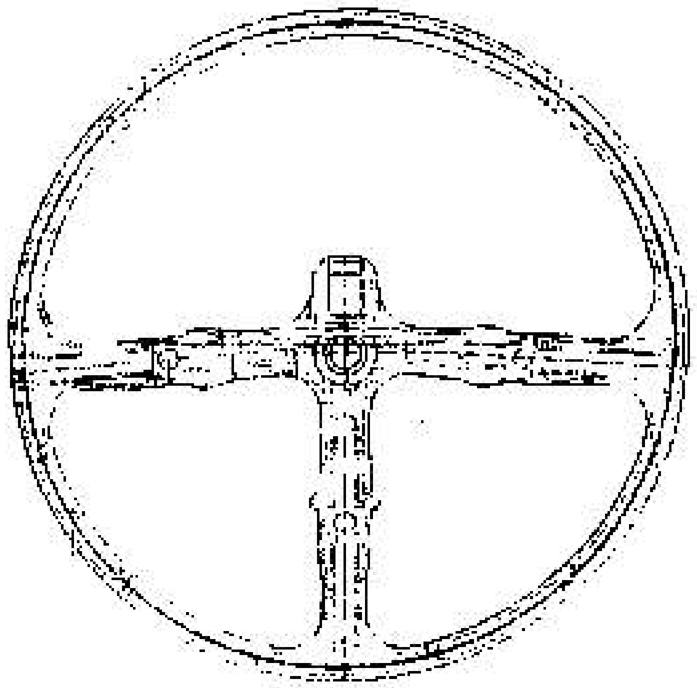


Fig. 3: Top view of the designed steering wheel

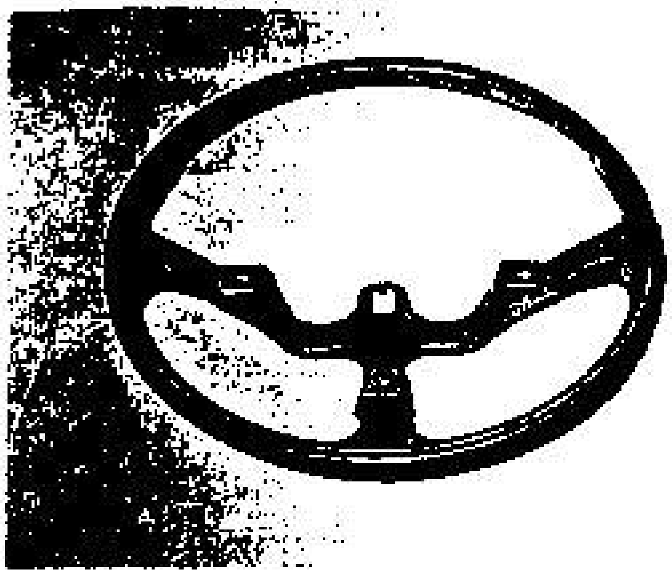


Fig. 4: The designed steering wheel

STATIC AND DYNAMIC FEM ANALYSES

Numerical analyses were performed for the steering wheel in the finite element method. A model of finite elements was constructed out of the geometrical model.

The constructed model included about 20,000 elements and 120,000 degree of freedom. Static and dynamic analyses were performed on the model using ANSYS finite element program. **Fig. 5** describes an example of the model, the displacement of the whole structure and the distribution of stresses at axial loading. The analyses were performed for radial and axial forces acted at the symmetric axis and on the spokes of the steering wheel.

The results demonstrate high stress areas around the joint of the spokes to the hub, as well as to the steering wheel rim. These results were compared to experimental tests and the required improvements were carried out to modify the preliminary design.

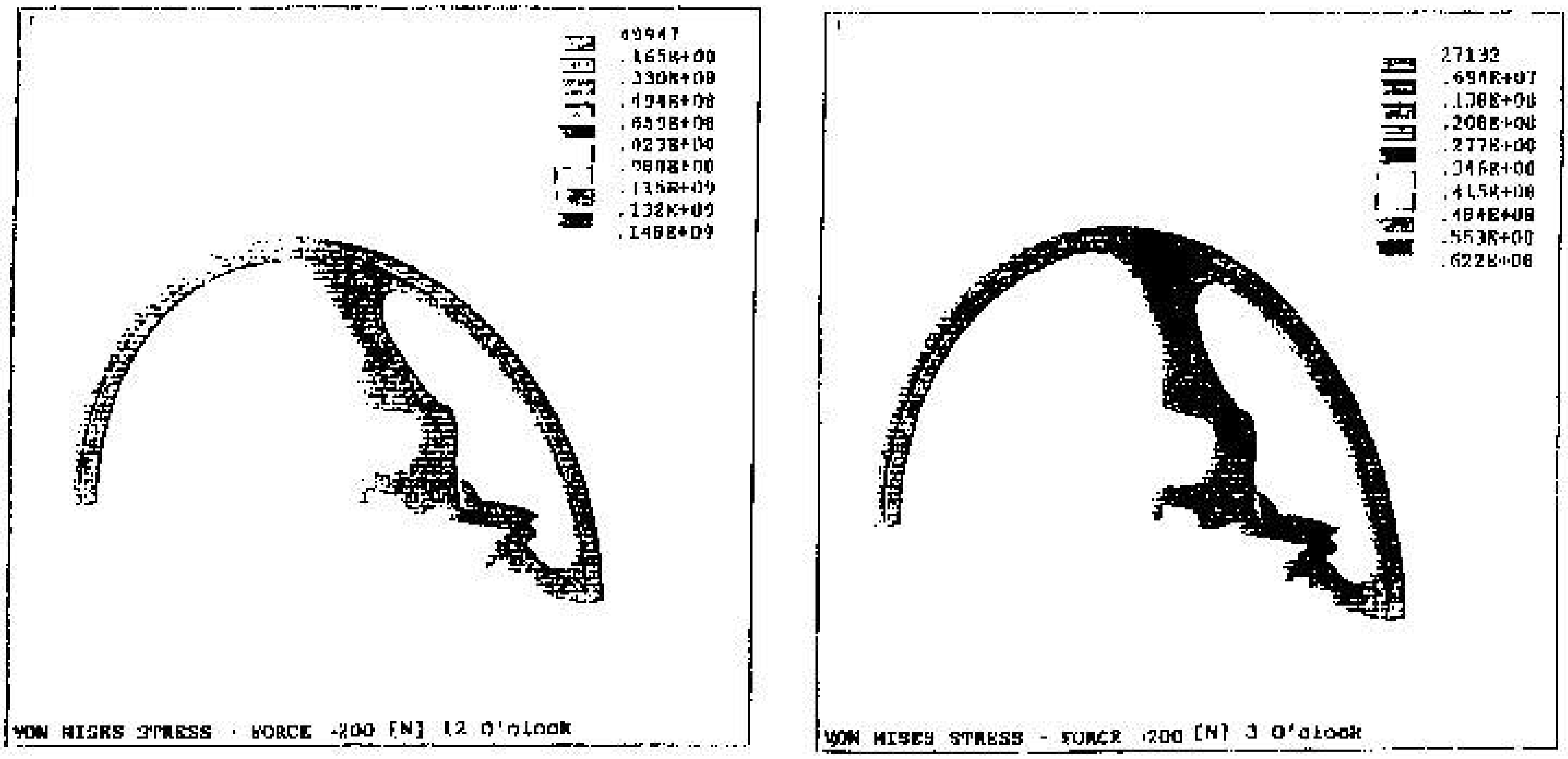
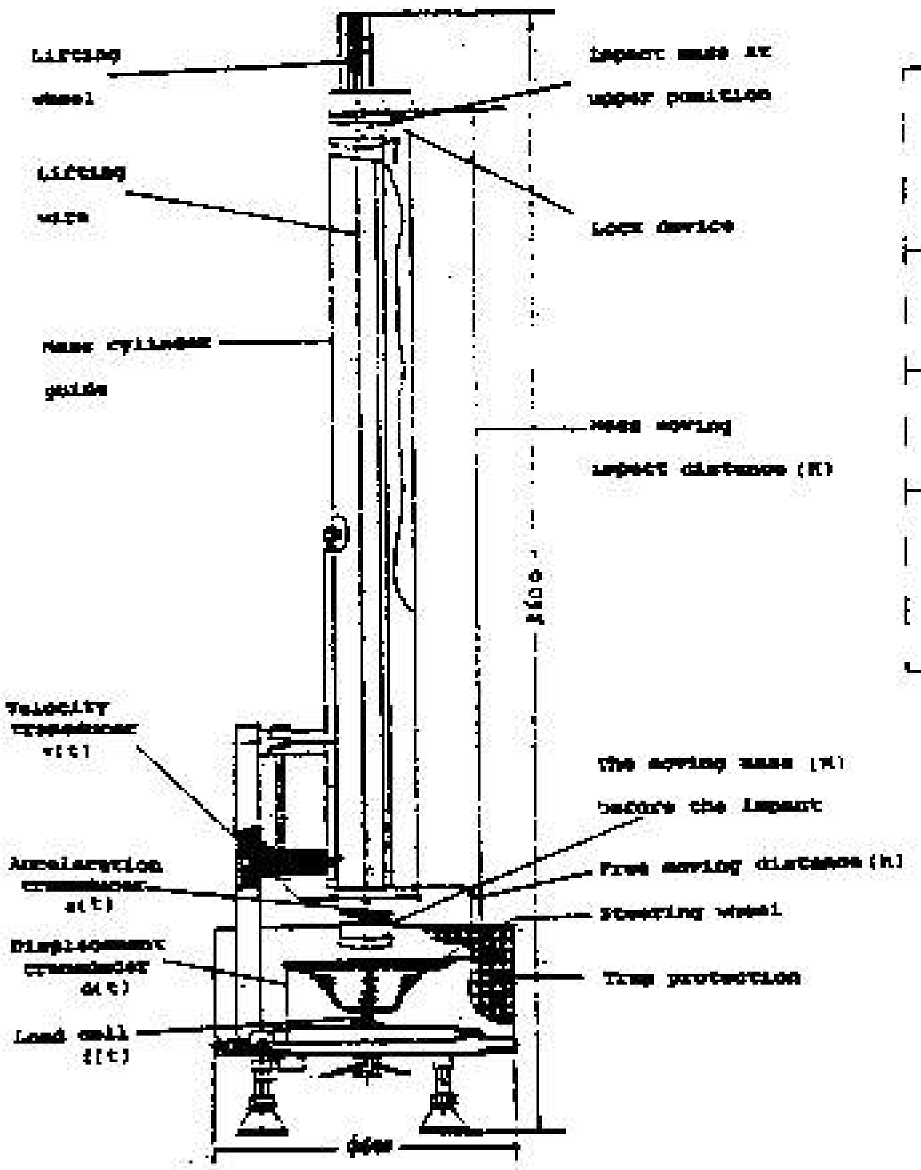


Fig. 5: Description of the distributed stress (Pa) in axial loading of 200N. force acted at 12 O'clock and force acted at 9 O'clock Under this loading, fatigue testing will be performed.

STIFFNESS PROPERTY, IMPACT TESTS AND DESIGN MODIFICATION

The prototypes were tested statically for radial and axial stiffness and for a dynamic impact on a device that was constructed to simulate the standard test of the head impact. **Fig. 6** demonstrates the device designed and manufactured for that purpose.



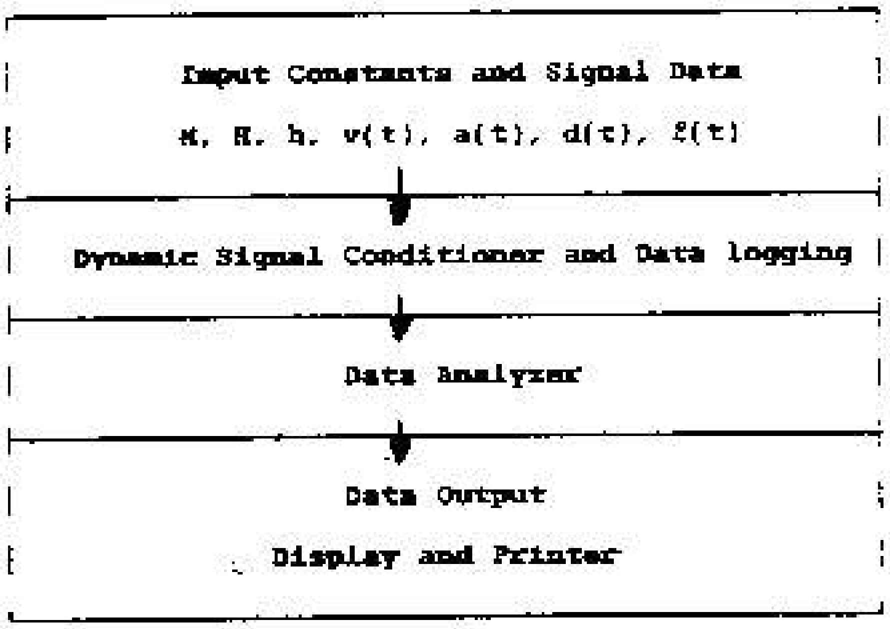


Fig.6: An impact device simulating a standard test of head impact and equipment for measuring the relevant parameters.

The typical results of the tests are described in **Fig. 7** and **8**. **Fig. 7** describes the stiffness curves of the steering wheel in the preliminary design at 12 O'clock and 9 O'clock axial loading. It can be seen that the stiffness of the steering wheel is relatively lower, which causes high displacement at a force of 400[N], residual deformations and low natural frequency.

Fig. 8 describes the deceleration measured during an impact experiment at 12 O'clock position. The maximum deceleration measured is 120g, a higher value than the Standard's requirements. In addition fractures were diagnosed in the joints of the spokes to the steering wheel hub.

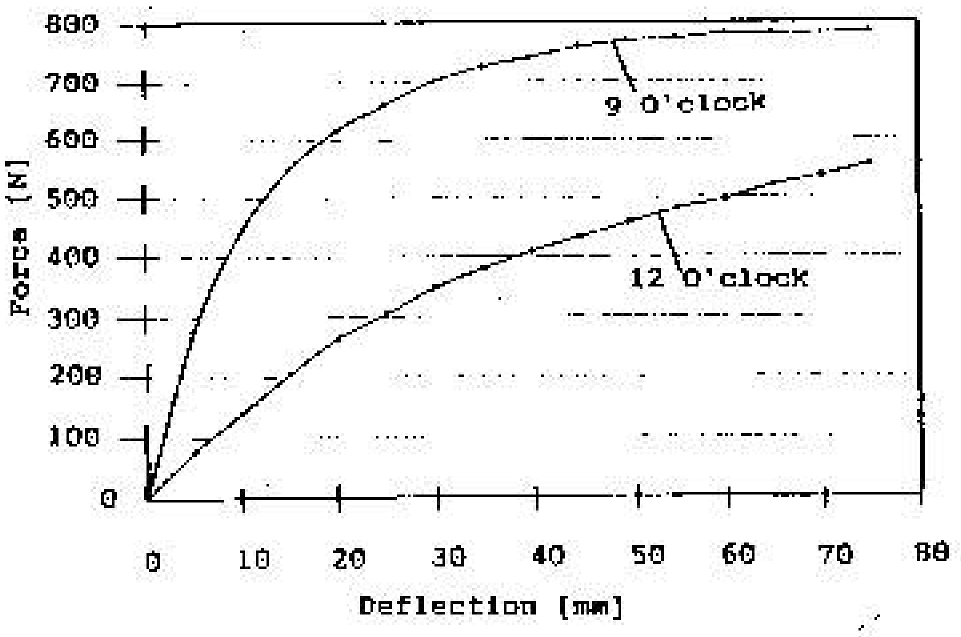


Fig. 7: The axial stiffness curves in 9, 12 O'clock position in the initial prototype

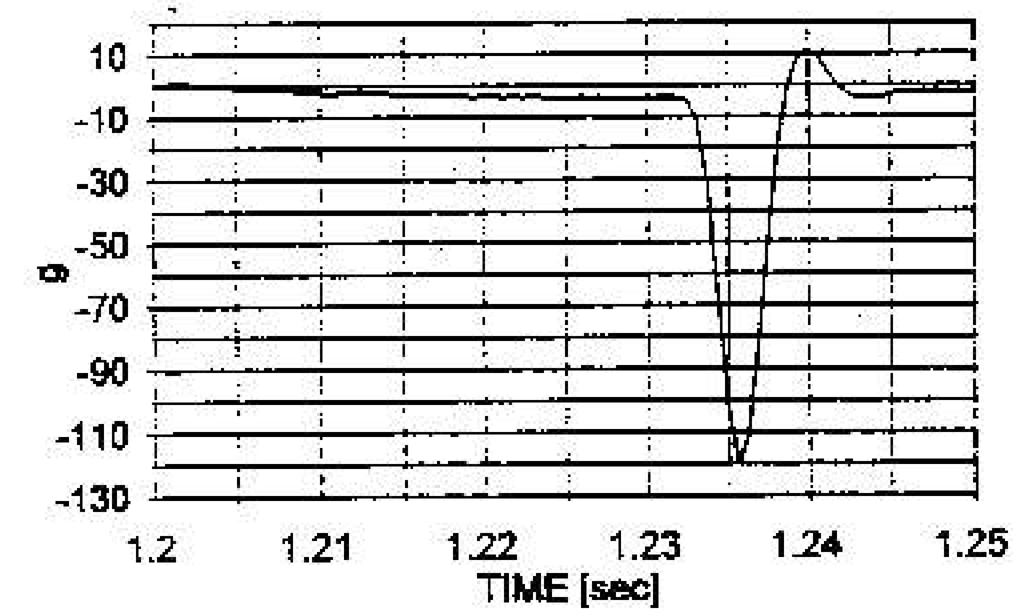


Fig. 8: The deceleration measured during an impact test in the 12 O'clock position in the initial prototype.

Modifications were performed by increasing the rim section, filling material at the joining area of the spokes to the steering wheel hub and making the central rim more flexible so as to distribute the energy absorption. These improvements were tested statically, dynamically and for fatigue on the new prototypes, and the results were mainly positive. The typical results of the static and dynamic tests of the improved prototypes are demonstrated in **Fig. 9** and **10**.

Fig. 9 describes the stiffness curves of the improved steering wheel in axial loading at 6, 9 and 12 O'clock positions. A significant increase of 50% in the stiffness can be seen. However, the wheel is still characterized by low stiffness in relation to the stiffness of other wheels **(Fig. 10)**, yet lower in weight than them.

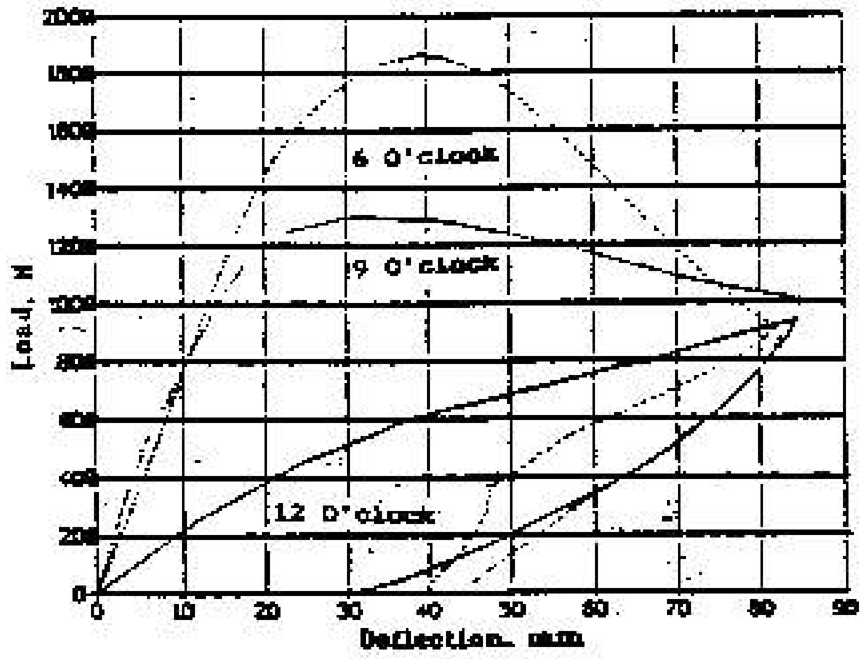


Fig. 9: the stiffness curves of the improved steering wheel in axial loading of 6, 9, 12 O'clock positions including residual deformations

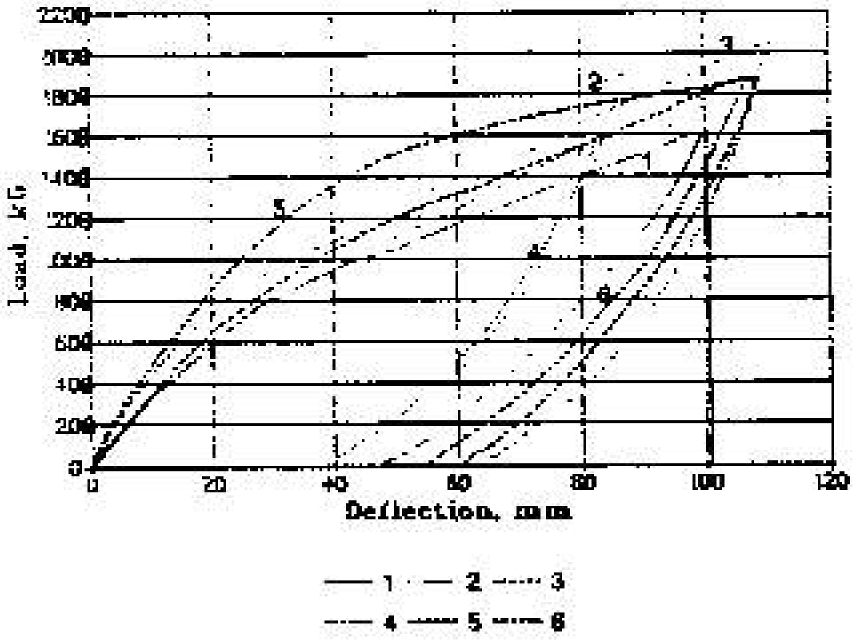


Fig. 10: The stiffness curves of various commercial steering wheels in axial loading of 12 O'clock position including residual deformation

A significant improvement was also seen in the dynamic impact, the maximum deceleration obtained in 12 O'clock position is 75g (**Fig. 11**) which is lower than the maximum permitted value in the Standard. Also no fractures were detected in the steering wheel after the test.

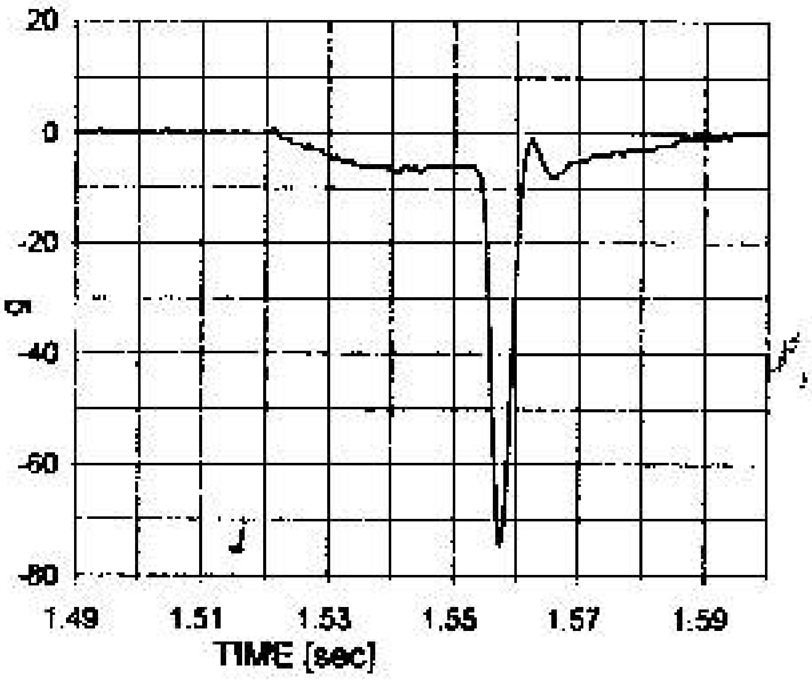


Fig. 11: The deceleration measured in the impact experiment at 12 O'clock position of the modified prototype.

MODIFIED STEERING WHEEL FATIGUE EXPERIMENTS

As mentioned, the steering wheel is required to meet the demands of fatigue tests characterizing the operating loads. These loads, as demonstrated in **Fig. 1**, include axial, tangential and radial loads acting on the steering wheel in different conditions. The fatigue tests are performed in an integrated way (operating the three force components simultaneously), or by operating each component separately. The currently acceptable force amplitude is in the range of 200N at the frequency of 1 Hz or 2 Hz for a duration of 100,000 operation cycles, when the requirement is to prevent a complete fracture and/or a significant decrease in the force amplitude. In this case, fatigue tests were performed and axial and tangential force were applied (each component separately) on the steering wheel at 12 O'clock position under the above specified conditions. These tests were performed as acceptance tests, and the modified prototypes met the demands successfully.

Furthermore, fatigue tests were conducted up to the complete failure of the wheel. During the tests the defects casting influence were tested as well as the possibility that the final failure would indeed develop from the existing defect. The level of the defects was characterized in x-ray, prior to the cyclic loading and upon their completion.

The loading amplitudes were selected in such a way that the low amplitude would be of such a rate that causes statically a calculated stress of about 1/4 tensile yield stress at the critical areas, a value which is lower than the fatigue limit.

The high amplitude was selected so that it would cause a stress close to the yielding stress at these areas. The fatigue properties of the magnesium alloys in die casting were examined by Mayer, et al. (1997), presenting the test results of AM60 alloy whose mechanical properties are close to AM50 of which the wheels were manufactured. The S-N curves demonstrate that the fatigue limit at room temperature under loading conditions of R= -1 is at the range of 40 ÷ 50 MPa. The tests were performed on models of 5mm thickness, thicker than the wheel elements, and at an industrial porosity level. Based on this data, cyclic loading of 100N, 200N, 300N and 400N were selected. These loads create statically equivalent stresses that were calculated in the finite element method at an assessed rate of 300, 600, 850 and 1050 MPa at critical zones.

The experiments were performed on INSTRON 1273, as shown in **Fig. 12**, and the test results are demonstrated in **Fig. 13.**

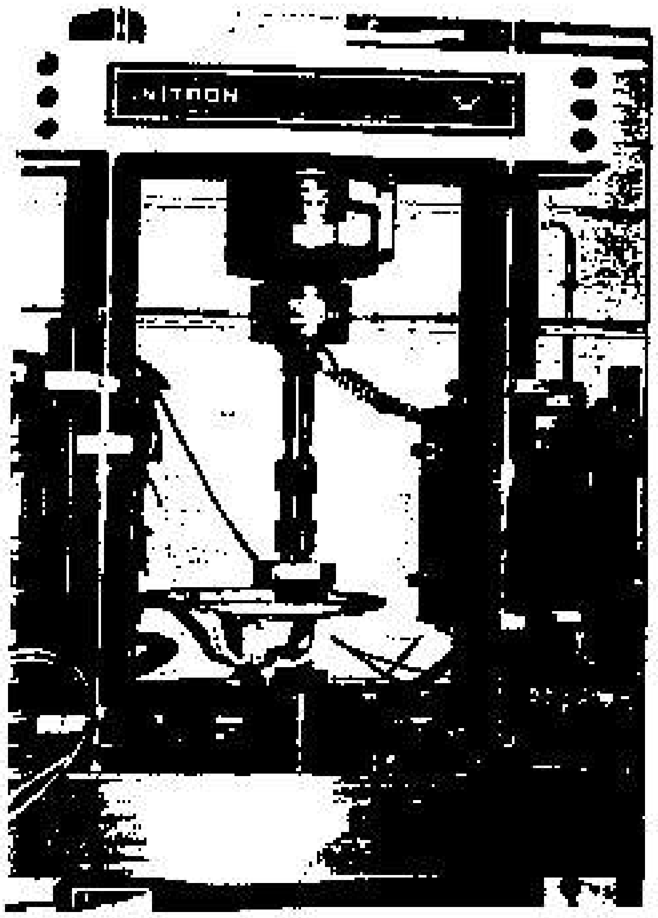


FIG. 12: Fatigue test for steering wheel

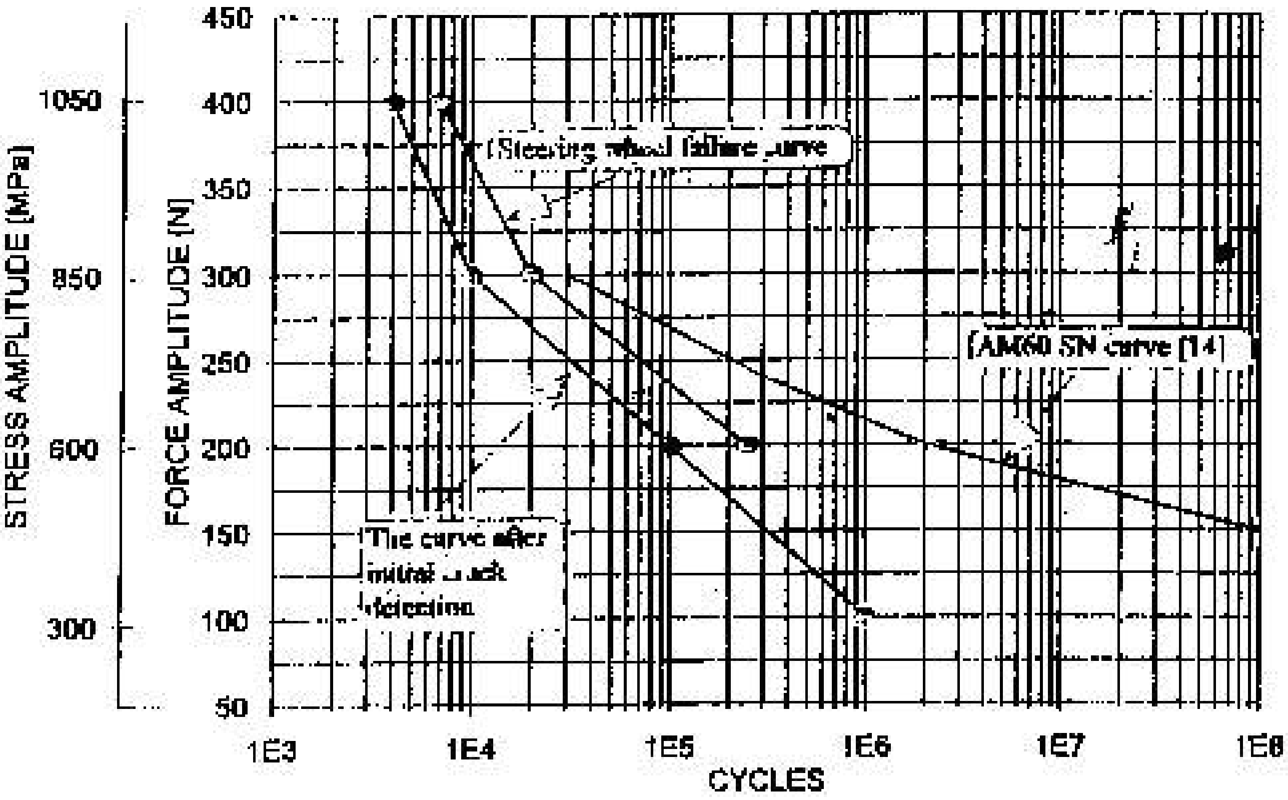


Fig. 13: the fatigue test results for the modified steering wheel

The crack developed at a critical area and does not include the areas of the ejector pin points or any other typical casting defect. The development of the crack in this area repeated itself in all the experiments and the crack evolved up to a final failure.

DISCUSSION AND SUMMARY

The test results and the numeric calculations demonstrate that the improved design was tested as a prototype and met the loading requirements and the standard requirements. In the course of the development, structural improvements were made in the rim, spokes and the hub steering wheel. The above included increasing the thickness of the side which contributed to increase the stiffness of the steering wheel. The final wheel is of 450 gr., a relatively light weight for steering wheels as reported in the literature, yet also of a lower stiffness than them. When low stiffness can reduce resistance to fatigue, thus decrease the natural frequency of the assembled wheel. However, lower weight is more advantageous and economical.

It should be noted that the numeric analyses are based on the mechanical theoretical properties of the material, when in reality the properties are lower as depending on porosity and casting quality, and improvements of the casting parameters in conjunction with the geometric improvements of the design are required in order to obtain optimal performance of the part. Porosity and casting defects, not necessarily disqualify the part, and the stress field assessed in the operation loads should be taken into consideration. However, the presence of defects demands examination using static loads and fatigue tests to study the degree of their influence in working conditions.

In the specified case, the tests revealed that the defects at relatively low stress areas did not affect the steering wheel's meeting the acceptable requirements, and the final failure occurred in the high stress critical area.

On the other hand, it is necessary to continue the study of the presence of defects, especially on the fatigue properties of magnesium alloy cast parts.

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