Reinventing the Wheel

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Introduction

Engineering requires applying known physical phenomena and concepts to problem solving to create new devices which can aid and assist everyday life. Using this understanding, engineers must work within a specific design window, partially defined by limits of assumptions and other estimations that must be made during the design cycle. These assumptions or estimations are items that are not quantifiable, or at least so within the time and budget of the design cycle.

To aid the engineer with these problems, various analysis tools have been developed to individually facilitate the investigation of specific aspects of the design cycle. These tools range from basic geometric design using solid modeling tools, to evaluating the performance of the design using structural analysis tools, as well as the manufacture of these designs using metal stamping and metal casting software. Recent advances in hardware have allowed for analysis of very large and complex parts through faster processors, cheaper memory and the ability of multiple processors to solve the same problem (parallel processing). However, these solutions typically concentrate on the same task, be it the welding of an assembly or the filling and solidification of a six-on high-pressure die casting. A communication gap formed between these single-tasked softwares preventing the engineer from determining how various sequential manufacturing tasks would influence the performance of the designed part.

The next large advancement in analysis is the closing of this communication gap. Some software packages now have the capability of chaining analyses — for example, evaluating how the microstructure and porosity of a cast component might influence the overall performance of a part in its actual usage or in testing. In this article, the design of a magnesium automotive steering wheel is evaluated, where the results of a ProCAST casting analysis are used to create more accurate inputs for a subsequent PAM-CRASH loading test of the steering wheel. These analysis results are compared to actual measured data.

Typical Design Considerations

German automotive OEM Takata-Petri along with casting and crash analysis teams of ESI Group, a global leader in manufacturing software and analysis of materials, ventured on this task of evaluating the ability to link process development and design using numerical tools. When designing a component such as a steering wheel, certain structural requirements are taken into account, such as minimizing the mass while maintaining a level of safety.

One safety item is that the wheel must deform or fail in a certain manner during impact. During this design stage, engineers must make assumptions about the material composition and structural integrity of the cast wheel. Typically, the assumption is that the wheel is of homogeneous strength (defect-free), even though it is obvious that the casting process will create a part of varying strength due to the filling and solidification of the part and the various levels of porosity. Figure 1 demonstrates how a low quality wheel (center) will fail versus a high quality part and shows an analysis using the homogeneous material property assumption.

Figure 1 – Destructive testing using defect-free wheel (left), wheel with porosity (center) and analytical results using defect-free material properties (right)[1].

Reality of the Casting Process

To investigate the variation of strength, a typical casting was produced and a corresponding ProCAST analysis of the casting was performed. The ProCAST analysis showed a varying amount of porosity across the part (Figure 2). The higher porosity amounts were located where the wheel spokes met the wheel itself. Other critical sections were identified, such as the area around the connection of the wheel to the steering column, as well as part way along the spoke from the hub to the circular wheel. The severity of the porosity is indicated by the color scale on the right side.

The amount of porosity found via ProCAST analysis was validated with experimental results and a close correlation was seen. In the high porosity locations near the spoke to wheel interface, the ProCAST results present a value of approximately 0.34% while the cast wheel showed a range of 0.27% to 0.46% in the same section. Other sections correlated well, such as in the spoke where analysis shows 0.17% (top spoke) and 0.25% (bottom spoke) porosity, compared to cast results of 0.18% and 0.33%, respectively.

To provide an indication of the material properties in the casting, tensile bars are typically included in the casting cavity. However, these tensile bars are usually defect-free and thus cannot accurately portray the material state of the casting. Therefore, from the actual casting itself, tensile bars were extracted from the steering wheel in these three critical areas (Figure 3). Metallurgical testing of these bars was performed to analyze the variation in static and dynamic stress-strain curves, depending on the extraction location (Figure 4). These curves were also compared to the typical separately cast tensile bar specimen.

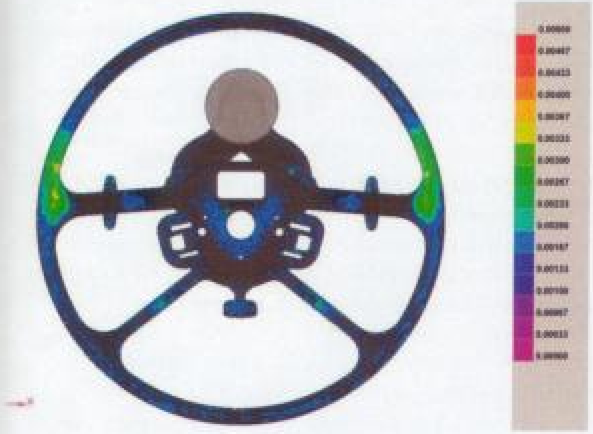

Figure 2 – Shrink porosity indication in the wheel.

Figure 3 – Imprints of Tensile Bar Extraction from Cast Part.

As seen in Figure 4, the locations indicated as having higher porosity values indeed have a lower strength compared to the separately cast tensile bar. The elastic region has a shallower slope (less Modulus of Elasticity), and the plastic section of the curve occurs with less strain (thus, lower yield strength). This experimental data clearly shows that the manufacturing process must be considered in the initial design of the component, which is becoming more possible as software tools continue to evolve and mature.

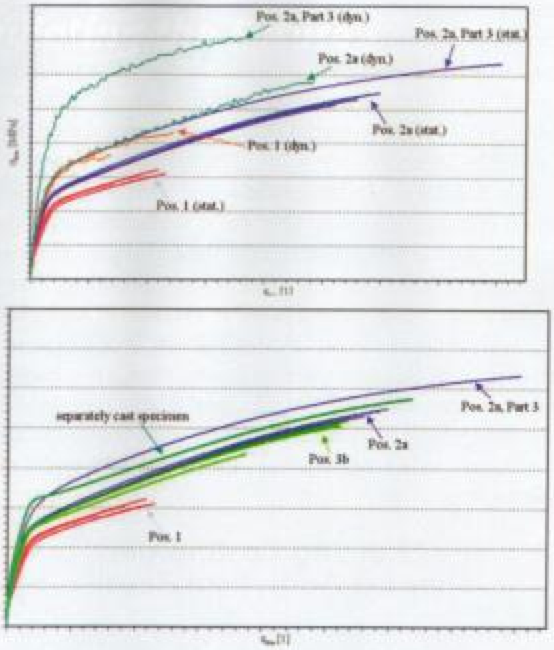

Figure 4 – Stress-strain curves: static and dynamic (top); static with comparison to separately cast tensile bar (bottom)[2].

Coupling the Casting Results with Impact Testing

The experimentally derived stress-strain curves were entered as material property information into ESI Group's non-linear high deformation software, PAM-CRASH. PAM-CRASH is well-known in the automotive industry as a world leader in crash and safety analysis. Two "crash" analyses were performed: one used only a homogeneous description of the magnesium mechanical properties as found via testing of the separately cast tensile bar, and the other included the mechanical properties of the extracted bars at various sections of the steering wheel. The analysis was of a standard destructive test where the steering wheel is moved against a metal rod to observe the amount of deformation versus the force applied to the wheel against the bar.

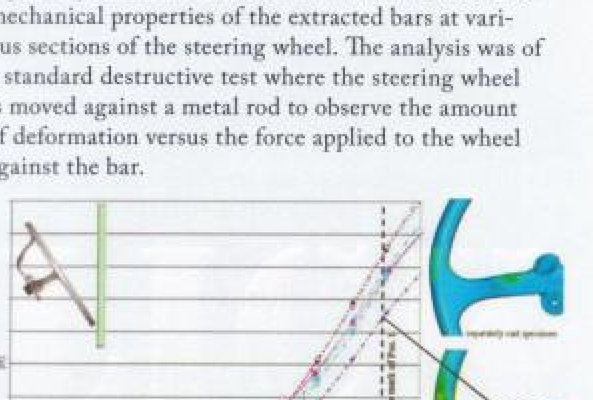

Figure 5 – Crash test results using separately cast tensile bar data (top right) and extracted tensile bar data (bottom right)[2].

The two PAM-CRASH runs produced very different results (Figure 5). The steering wheel using the homogeneous mechanical properties showed much less plastic strain in the critical sections of the wheel as compared to that which used varying properties as indicated by the extracted tensile bars. Plastic strain is an indicator of sections more likely to fail; thus, showing potential failure in the critical sections is cause for concern.

This trend is duplicated in the actual testing of the wheel (Figure 1). A wheel that was manufactured with no irregularities in x-ray matched the simulated final deformation state of a likewise analysis. However, the wheel that shows x-ray defects indeed failed at a section of high plastic deformation as shown in PAM-CRASH. Therefore, it is easily seen by this example that having correct mechanical property information in the structural analysis is critical to obtaining an accurate result, enabling engineers to see how the as-cast and/or heat treated part will perform under real-life loading.

Chaining Casting and Impact Analytical Results

The ability to calculate mechanical property data based on alloy composition, process definition and casting history is currently being realized by high-end casting software. By coupling the phase information for a given alloy via empirical phase transformation data with the solidification kinetics such as cooling rate and porosity, ProCAST is capable of predicting the microstructural composition of the component across the entire part. Areas of weakness due to slow cooling or porosity, combined with dendrite and secondary dendrite arm spacing, create a resultant definition of the strength of that region. Yield strength, modulus and other information pertaining to the mechanical definition of the alloy in every local region will be passed from the casting software to the structural software, enabling software packages such as PAM-CRASH to use the most accurate and detailed input data available.

ProCAST has the additional capability to couple the thermally-induced stresses generated during the casting process into the transferable data. Therefore, residual stresses, final part shape (including after degating), plastic strains, hot tears/cracks and any other information relating to the state of the part will be available for the subsequent loading analysis.

Conclusion

The possibility to obtain more accurate and more detailed results of the relation between casting process and component performance opens a new set of doors for the design engineer to examine. By understanding how the casting process affects the strength of the part, a process window can be defined which would ensure a quality part. Part savings can be realized by making specific changes to the design that will directly improve strength, instead of blindly or globally making modifications that the engineer "hopes" will improve results. The seamless integration of the data transfer will give analysts the ability to perform these tests earlier in the design cycle and work with designers to produce the best quality wheel with a clearly defined working manufacturing process, thereby reducing the time of the design cycle and ensuring that even the first set of manufactured parts comes off the line as quality, ready-to-use components.

About the Author

Dr. Thomas Pyttel studied mechanical engineering at the University of Dresden from 1987 to 1992, where he earned his PhD four years later. In 1997, he started his carrier at ESI Group. In 2004, he switched to academic life and is now a professor of mechanical engineering.

Adi Sholapurwalla has been associated with the casting industry for more than 15 years. He is one of the core members in the development of ProCAST, the world leader in casting simulation software. He has been associated with several NADCA, AFS and ICI committees. He is currently the director of engineering at ESI NA.

Sam Scott is the casting technical lead for ESI Group NA and has been working directly with ProCAST since 1996. He can be contacted at sam.scott@esi-group-na.com. Information regarding ProCAST, PAM-CRASH or any of the ESI Group analysis tools can be found at www.esi-group.com.

Ole Koeser (born 1964) finished his studies of physics at the University of Bremen (Germany) in 1993. From 1996 on, he has been working in the domain of casting simulation with ProCAST. Since 2003, he has been with ESI in Switzerland, where he is responsible for innovative projects.

Elke Lieven earned his degree of Diplom-Ingenieur in mechanical engineering at Gerhard-Mercator-University Duisburg in 1998. Since then, he has been a development engineer of numerical simulation at Takata Petri AG, Aschaffenburg, where he is responsible for application engineering frontal protection (Crash; Process; Fatigue; Modal).

References

Lieven, E.; Wuth, M.: Product: *Product Development Process Optimization by Linking Design numerical Simulation and Process Development*, Magnesium 2003, November 2003, Wolfsburg.

Lieven, E.; Koch R.; Böhme, W.; Schwarz, Simone: *Influence of the Microstructure and Local Mechanical Properties of Magnesium Die Cast Components made of MgAl6Mn on the Quality of Numerical Simulations*, Magnesium 2006, November 2006, Dresden.