Magnesium HPDC Crash CAE

U. Weiss, A. Bach

Magnesium castings offer significant weight saving potential for many crash-relevant structures in the vehicle. Until now, proper cast magnesium design was difficult and time consuming, as reliable CAE tools were not available. In the European funded research project NADIA, a new set of CAE tools have been developed for AM60 and AM50 alloys that combine local casting process simulation results with crash failure CAE modelling to reliably predict component level crash behaviour. These CAE tools have been made commercially available and integrated into existing CAD / CAE codes.

Keywords: Magnesium, HPDC, Crash CAE, Casting Simulation, Local Properties, Process Scatter, Micro-Porosity, Quality Mapping, Material Modelling, Failure Modelling

INTRODUCTION

Magnesium castings offer significant weight saving potential for many crash-relevant structures in the vehicle, such as decklid / door inners, GOR's and instrument panel cross members. Until now, proper cast magnesium design was difficult and time consuming, as reliable CAE tools were not available, requiring multiple production trials and repeated component testing. The reason for this is that Magnesium High Pressure Die Cast (HPDC) components for crash applications can have significant variation in local mechanical properties as a result of the casting process conditions and the casting geometry. Furthermore, statistical scatter of properties within the same location as a result of small process variations may lead to variation of fracture behaviour. In addition, Magnesium HPDC parts tend to show a significant level of microporosity within the core of a thin-walled casting, which is not unusual in other HPDC processes as well and which is of a highly stochastic nature.

These three factors have made it difficult to use traditional CAE methods and material cards to predict the crash behaviour of magnesium HPDC components accurately and reliably because, up to now, local processing history and core microporosity effects could not be incorporated easily.

In the European funded research project NADIA, a new set of CAE tools have been developed for AM60 and AM50 alloys that combine local casting process simulation results with crash failure CAE modelling to reliably predict component level crash behaviour. These CAE tools have been made commercially available and integrated into existing CAD / CAE codes (Fig. 1).

TEST PART PROGRAM

Automotive parts exposed to crash events are designed to perform in various load situations. In order to explore all the related stress modes and to limit the extent of HPDC test tools and casting trials, a generic test component was designed. The component geometry allows to characterize local material properties and to study the part response to different loading modes as well, so that a comprehensive survey on crash resistance and energy absorption can be fulfilled.

Figure 2 depicts the final version of the so called "Y-Box" test component: wide flanges have been added to both the ingate and the opposite side. Flanges carry slots where specimens for tensile tests can be taken from. Other specimens can be cut from the flange and box. A CAE-based "Closed Loop Optimization" procedure has been applied to develop the Y-Box. Such procedure in-

FIG. 1

Concept of combined casting simulation and crash performance CAE.

Concetto di simulazione combinata del processo di colata e degli strumenti CAE per la resistenza allo schianto.

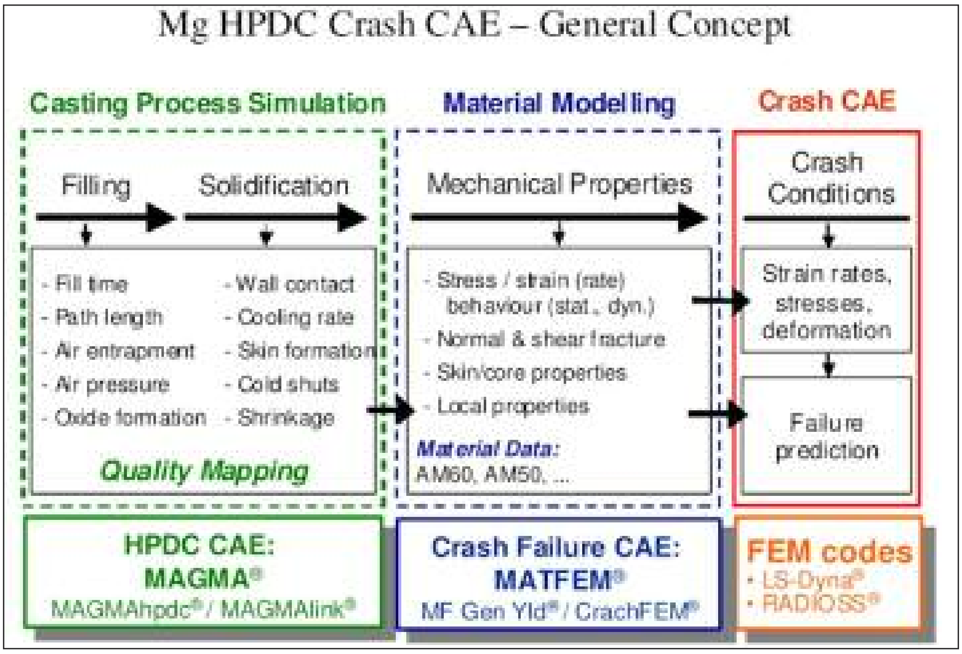

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FIG. 2 ***The "Y-Box" component casting.***

Il getto del componente "Y-box".

tegrates casting and mechanical simulations with test and forming tools requirements so that a fully integrated decision-making process was established. As for casting simulations MAGMA has developed and optimized the gating design so as to avoid or minimize any entrapped air within crucial locations like for instance those where tensile test bars were to be taken from. Figure 3 shows an example of such simulations regarding different gating designs.

The first gating solution (right ingate) has been designed to deliver a wide variety of material properties in the tests bar area. The second gating solution (left ingate) is used to feed the mould from the opposite side so that longer flow length and melting age at the test sample area are derived.

The third gating design provides good quality in the middle region while the fourth gating solution feeds the mould over the complete width granting an optimal casting quality. Such solution is named "classic ingate" as it is widely exploited in industrial applications. The "classic" ingate system was used to manufacture all the good-quality Y-Boxes for validation purposes whereas left/right ingate design was used to produce parts for studying the effect of flow and solidification parameters on local properties and part quality.

MATERIAL CHARACTERIZATION

A comprehensive material characterization was fulfilled on Y-Box components exploring different aspects whose involved experiments might be grouped as follows.

Tests related to ductility and Fracture limits: Specimens taken from different locations of castings produced with different casting process conditions underwent tensile tests and fracture limit curves were drawn for quasi-static and dynamic strain rate (Fig. 4). As specimens came from different casting processes the influence of local solidification time, flow length, air entrapment and casting process parameter variations on ductility was studied. Special attention was paid to the effect of machining of tensile test samples as compared to as-cast samples and to the identification of skin and core properties.

Tests related to viscoplastic behaviour and strain rate dependent hardening: Dynamic tension and compression tests were accomplished to quantify the flow stress and derive the specific energy consumption. These experiments are a basis for deriving the viscoplastic material model. In addition to this, the equivalent plastic strain at failure under dynamic compression and shear can also provide additional information for the failure limit curves. As for the compressive stress-rate-sensitivity for cast Magnesium alloys it was already observed that increasing the strain rate leads to an increase in flow stress.

Tests related to microstructure and casting defects mapping: Uniaxial tensile tests were exploited to establish a quantitative correlation between measured area fraction of defects and elongation at fracture. A comprehensive microstructure investigation was carried out so as to identify the type of fracture (transgranular, interdendritic), the plastic deformation, grain structure and microporosity so that these parameters can be correlated with flow length, eutectic composition and mechanical properties (namely YS, UTS and elongation at fracture) for specimens cast through different casting processes (e.g. different ingate systems and thermodynamic gradient). XRAY, SEM and Micro-CT scans were used to identify the characteristics of defect distribution in skin and core material and depending from the ingate system. Further microstructural studies (etching, chemical composition, fractography) focused on the identification of oxide formation, pre-solidified grains and bifilms and played a major role in the development of the Mg failure model (Fig. 5).

Corrosion tests: As the Y-Box component is made of Magnesium alloy it is prone to suffer from severe corrosion due to the Magnesium high chemical activity and the natural Magnesium oxide inability to protect the substrate from further corrosion phenomena. Tekniker applied the Plasma Electro-Oxidation (PEO) technique to deposit thick, dense and hard ceramic

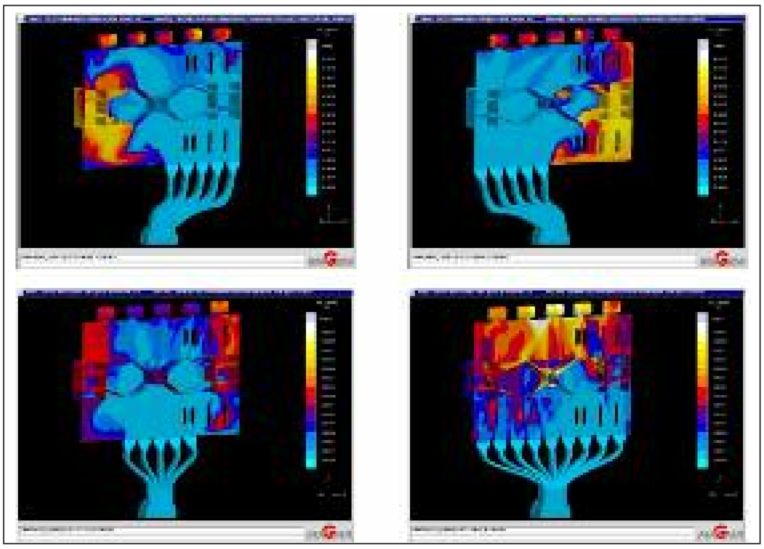
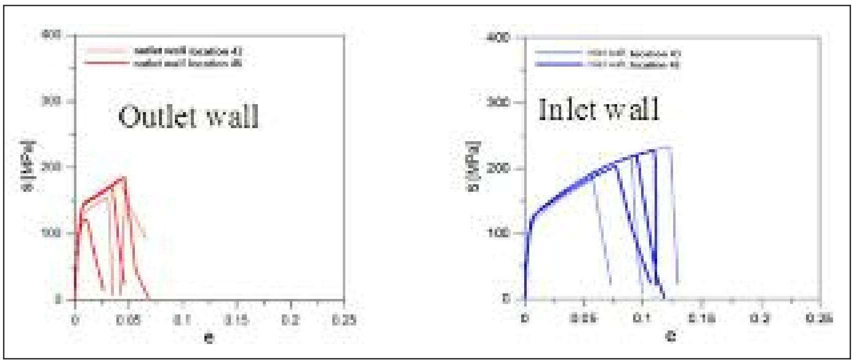


FIG. 3
Casting simulation for different ingate systems.

Simulazione della colata di diversi sistemi di immissione.

FIG. 4
Effect of sample location on mechanical properties (tensile tests).
Effetto della localizzazione dei provini sulle caratteristiche meccaniche a trazione.



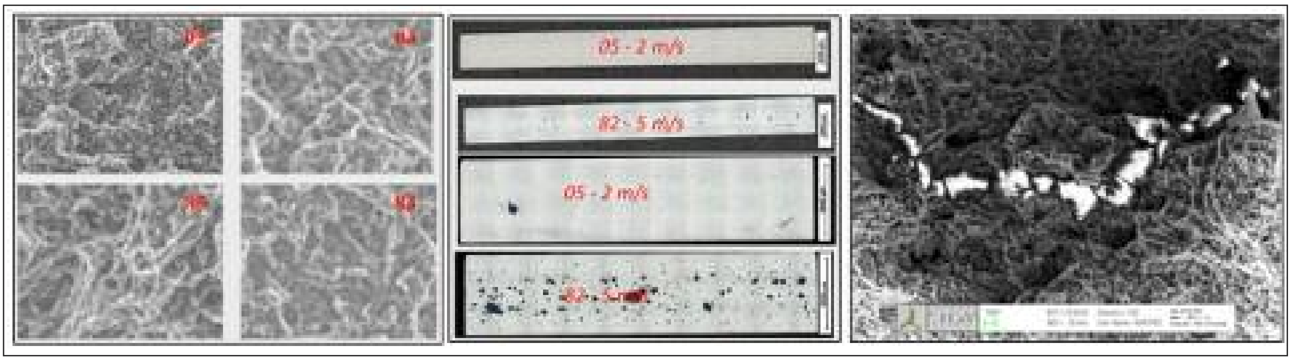
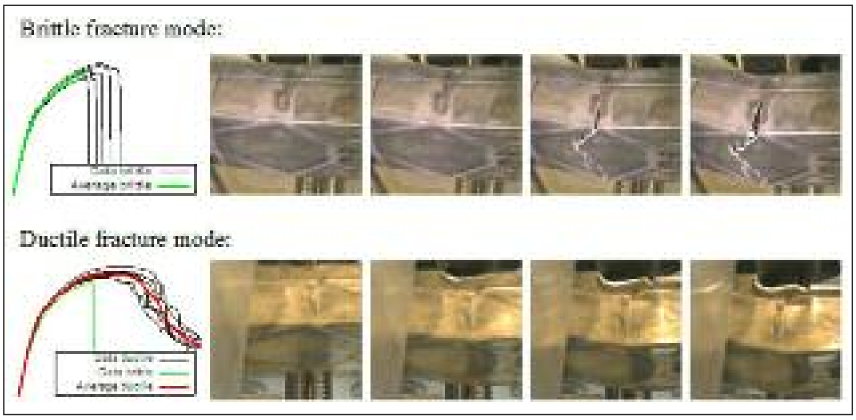


FIG. 5 ***Fractography (a); effect of process parameters on porosity (b); oxide formation (c).***
Frattografia (a); effetto dei parametri di processo sulla porosità (b); formazione di ossido (c).

FIG. 6
Failure modes in 3PB component tests (U mode) due to different process conditions.
Modalità di rottura in prove su componenti 3PB (U mode) dovuti a diverse condizioni di processo.



layers upon the component surface whose corrosion and wear resistance were then dramatically improved.

Mechanical and crash tests: The Y-Box component underwent several experiments aimed at describing its mechanical response against different stress modes. Such experiments, accomplished in both quasi-static and dynamic strain-rate regime, included symmetric and asymmetric three-point bending tests, axial compression tests and high speed crash tests.

For certain load cases and casting process conditions either ductile normal or ductile shear fracture turned out to be the dominant fracture mode. With regard to the 3PB test with symmetric loading in U-mode (impactor positioned at rib area) crack initiation was mainly caused by ductile normal fracture for both wall thicknesses whereas ductile shear fracture was dominant in the asymmetric loading mode. At axial compression both fracture modes seem to play a significant role, yet ductile shear fracture was predominant.

Y-box parts with nominally identical casting conditions turned out to show two distinctly different failure modes, one with a bottom crack (called "brittle mode"), the other with failure initiating at the flanges (called "ductile mode", see Fig. 6). This phenomenon is known for component tests producing almost identical stress levels in different areas, where only small changes in local material strength are required to switch between different failure modes. For the Y-Box this effect varied for different ingate systems and is attributed to the process scatter.

QUALITY MAPPING AND FAILURE MODELLING APPROACH

The prediction of local mechanical properties is often done by predicting the microstructure and using correlations between e.g. dendrite arm spacing and strength properties. Phenomena occurring during the filling process of thin-walled high pressure die cast components (e.g. entrapment of gases in melt) can have a significant influence on the local properties in the cast component.

Capturing all of these complex phenomena on a microscopic level, however, is not realistically possible in a macroscopic simulation tool that is to be used in process simulation in the

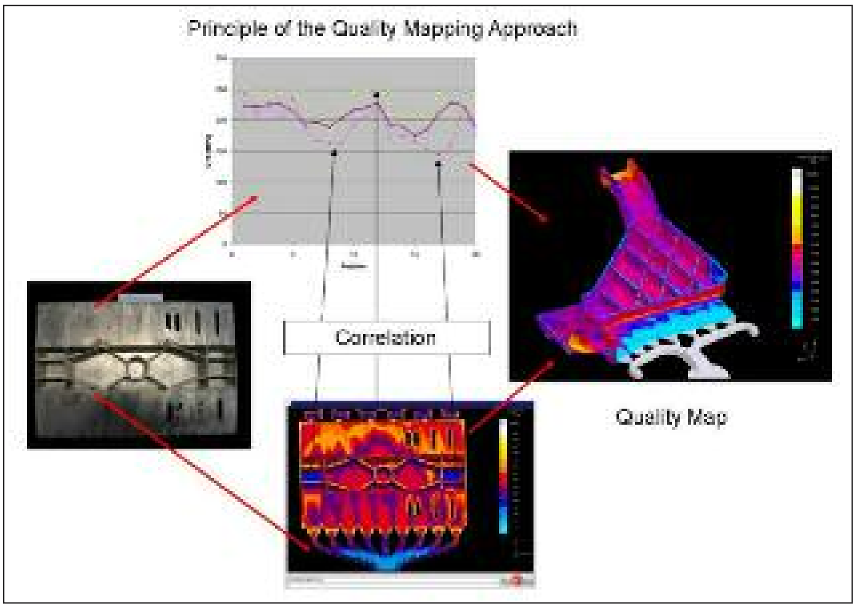


FIG. 7

Schematic illustrating the correlation of material characterization from casting trials and simulation results to obtain a quality map describing the variations in casting material properties.

Schema che illustra la correlazione della caratterizzazione del materiale da prove di colata e da risultati di simulazione per ottenere una mappatura della qualità in grado di descrivere le variazioni nelle caratteristiche del materiale di colata.

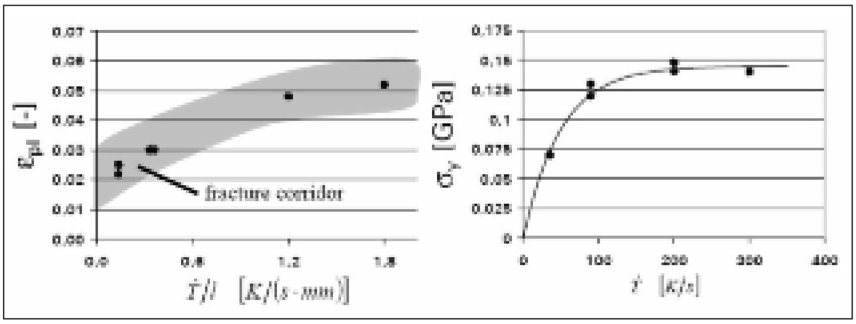


FIG. 8

Correlation between Coolrate and Flowlength to mechanical properties like fracture elongation and yield stress [12].

Correlazione fra velocità di raffreddamento e caratteristiche di flusso verso le caratteristiche meccaniche quali allungamento a rottura e limite di snervamento [12].

practical layout and design of cast components.

The methodology selected for modelling the defect and property distributions in thin-walled magnesium high pressure die castings is a so-called quality mapping [13, 17]. In this approach, macroscopic information from casting process simulation (e.g. cooling rates and/or porosity predicted during solidification, flow lengths and/or temperatures and/or entrapped air predicted during filling) is correlated with experimentally evaluated distributions of defects and/or properties in a cast component produced in casting trials. The approach is illustrated schematically in Fig. 7.

Greve [12] (Fig. 8) used a combination of cooling rate and flow length called “coolflow”. This result was used by Greve for the prediction of the fracture elongation, as an input for a crash simulation. Within the NADIA project also other empirical correlations based on the results available from material testing were investigated to predict local yield stress distribution, UTS and elongation to fracture. Such results are intended to provide an “a priori / stand alone” feature for foundry process optimization analyses to achieve required material properties.

Transfer to Crash Simulation

The results of the casting process simulation need to be mapped onto the FEM model for crash simulation, using the software tool MAGMAlink of MAGMASOFT. For crash applications, a new interface was developed to allow the export of casting process simulation results.

Crash Simulation - Overview

In the frame of this work the FEA codes LS-DYNA and RADIOSS have been used. The explicit-dynamic time integration scheme is used in both codes. As cast automotive parts typically show a complex geometry and non-constant wall thickness a discretization with standard shell elements is not always possible. Elements which have been used in the frame of the project are Belytscho-Tsay shells, Hughes-Liu shells and Constant strain 8 noded hexahedron elements. The modular material model MF GenYld+CrachFEM developed by MATFEM has been used as a basis for the development of a special solution to describe cast alloys. This material model can be linked to different commercial FEA codes with explicit-dynamic time integration scheme.

Material model MF GenYld+CrachFEM

MF GenYld + CrachFEM is a material model which can interact with commercial FE-Codes with explicit-dynamic time integration such as LS-Dyna, Abaqus, Radioss and PamCrash, through their user material interface [21]. MF GenYld (Generalised Yield model) enables the modular use of several yield locus descriptions, combined with various strain-rate dependent (anisotropic) hardening models. As cast alloys typically show a randomly distributed microstructure, an isotropic behaviour is assumed in this study. The von Mises yield locus is used. However MF GenYld can account for different hardening of Mg alloys in tension and compression by its module for anisotropic hardening [2]. Strain rate sensitivity of the material can be defined via multiple stress-strain curves or by analytical models.

CrachFEM is a comprehensive failure model for metallic materials. The CrachFEM package includes models to describe fai-

FIG. 9

Failure models and correlated failure limit curves in CrachFEM.

Modelli di rottura e relative curve del limite di rottura secondo il modello CrachFEM.

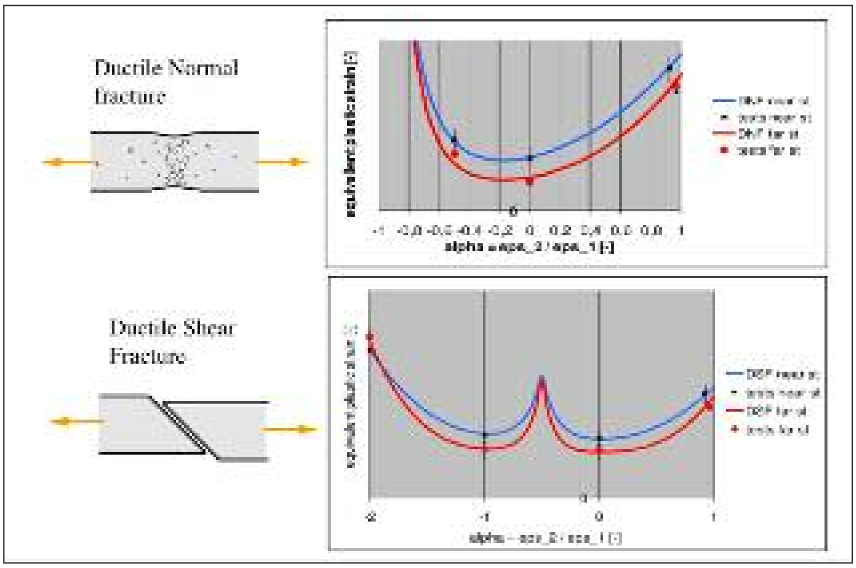


FIG. 10

Core porosity (a) + Initial microporosity at integration points (b).

Porosità al centro (a) + microporosità iniziale ai punti di integrazione (b).

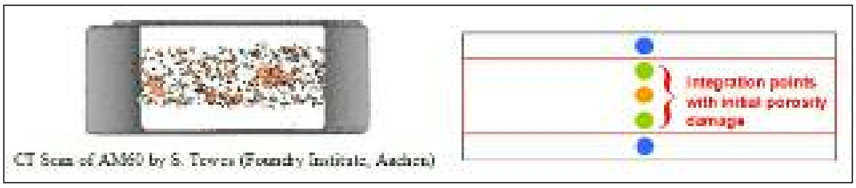
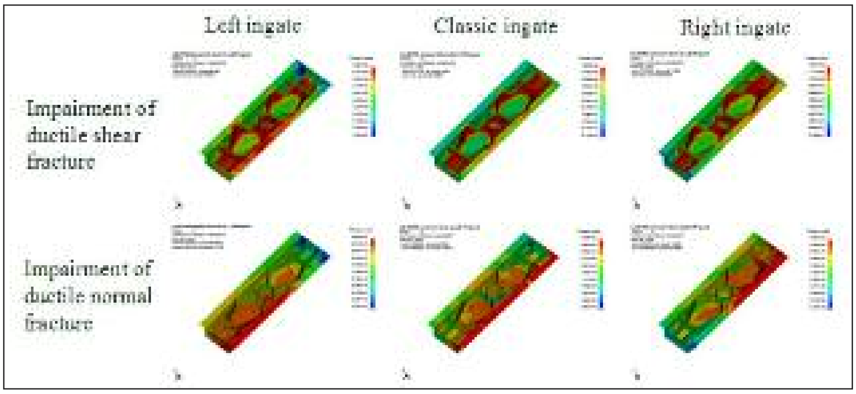

CT Scan of AM60 by S. Tewes (Foundry Institute, Aachen)

FIG. 11

Mechanical simulation – Ductility Impairment defined by Mapping + Initialisation.

Simulazione meccanica –calo di duttilità definito mediante Mappatura + Inizializzazione.



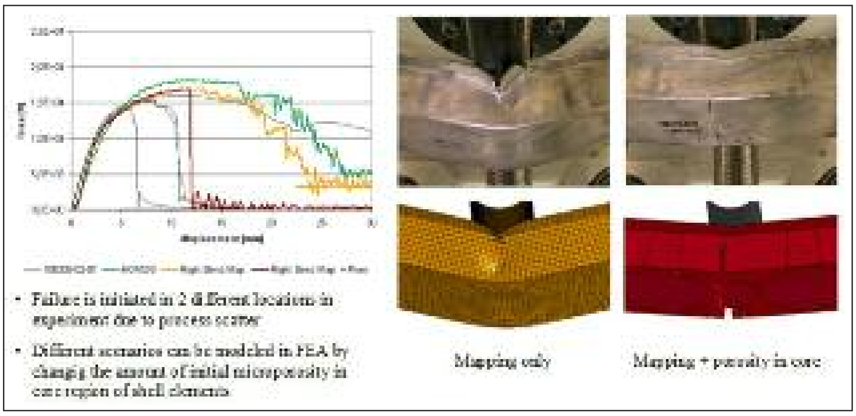
lure phenomena such as local instability (necking), ductile normal fracture (DNF), and ductile shear fracture (DSF) according to Figure 9. A failure prediction for onset of localized necking is only necessary in case of shell elements. These elements cannot resolve the onset of a neck which has a typical width of one sheet thickness. Therefore a sub model (algorithm Crach) is used which models the problem of localized necking based on the macroscopic strain paths from the shell element. The prediction of localized necking is of secondary importance for cast parts as the theoretical limit curve for onset of necking is not reached due to reduced ductility. From the available failure models ductile normal fracture (caused by void nucleation, void growth and void coalescence) and ductile shear fracture (caused by shear band localization) are the relevant phenomena for HPDC AM50 and AM60.

For the initialization of the crash failure models, the casting simulation criteria are used to calculate impairment factors, modifying the local failure limit curves for ductile normal and ductile shear fracture, respectively (Fig. 9), which depend on the principal strain ratio "alpha" in case of plain stress conditions (shell elements).

Microporosity in the core zone can be modeled by an initialisation of a non-zero porosity damage at defined integration points of a shell element. The actual solution is an initialisation of the 3 inner integration points with a non-zero porosity damage, calibrated by tensile tests (Fig. 10). In case of local macro-porosity, imported from casting simulation, this will be used instead. The evolution of porosity damage is a function of the stress triaxiality. Only the damage for ductile normal fracture is increased by porosity.

The data from component tests (three-point bending, axial compression and crash tests) were used to fine-tune the empirical correlations obtained from sample test results. In the test component layout phase, the calculations assumed a homogeneously distributed field of mechanical properties, whereas later in the NADIA project the simulations used a heterogeneously distributed field defined by empirical correlations and based on the results of casting process simulations.

The local distributions of impairment factors for the ductile shear and ductile normal failure limit as derived from casting simulation criteria results reflect the process conditions for specific design features (e.g. wall intersections) and different in-



- Failure is initiated in 2 different locations in experiment due to process scatter
- Different scenarios can be modeled in FEA by changing the amount of initial microporosity in core region of shell elements

FIG. 12
Mechanical simulation – quasistatic 3PB of Y-Box.
Simulazione meccanica –3PB quasistatico di Y-Box.

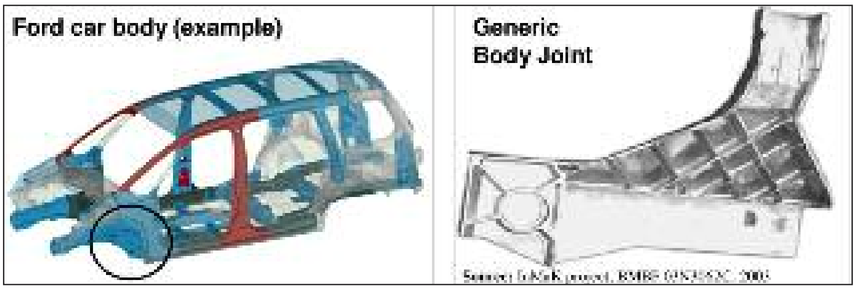


FIG. 13
Generic Body Joint produced by FORD.
Giunto generico di carrozzeria prodotto da FORD.

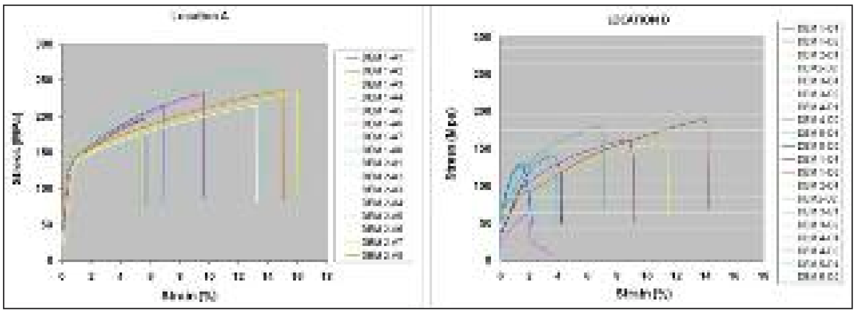


FIG. 14
Property scatter at different locations in the Generic Body Joint.
Variabilità delle proprietà in diversi punti nel giunto generico di carrozzeria.

gate systems (Fig. 11). The results of this casting data processing procedure are consistent with the foundry process optimization tool described earlier.

Simulations based on mapping only and assuming no (or very low) porosity impairment for a 3PB test show that failure from ductile normal fracture (DNF) initiates at the top nearby Y-Box flanges and then gradually proceeds downwards. On the contrary the heterogeneous model with initial mapping and higher porosity levels in the core predicts an earlier failure with starts at the bottom and then rapidly moves upwards. This is in excellent agreement with the component test results (Fig. 12). The same good correlation is achieved in case of an axial compression test. The model with homogeneously distributed properties and no initial porosity fails in a nearly symmetric way whereas the heterogeneous model failure is non-symmetrical.

DEMONSTRATOR PART IDENTIFICATION AND ANALYSIS

For validation purposes a so-called Demonstrator Part has been chosen resembling a generic body joint (Fig. 13). A batch of sound parts have been produced at a FORD supplier and tested in XRAY scan, material analyses and component tests. The alloy of the Generic Body Joint is AM50, known for superior ductility compared to AM60.

The development of the AM50 material card was based on samples taken from the ingate flange (best quality material). In addition more samples have been taken for validation purposes. The main material characterization results listed in short (Fig. 14):

- In the core region all samples show casting defects (mainly shrinkage and pores) of different size and shape.
- The number of defects increases when the wall thickness increases.
- Reduced values of mechanical properties were found in samples taken from the top end of the demonstrator (location D)

Different component test load cases for the Generic Body Joint validation study (pure bending, combined in-plane crush / bending, pure in-plane crush) have been developed using the newly developed CAE tools and material data (Fig. 15).

As pre-defined in the analytical load case development, the deformation and failure mode of each load case shows distinct differences, which are reflected in the plastic deformation, the failure behavior and the force-deflection diagrams of each load case (Fig. 16).

As LC 1 is a pure bending load case, the forces are relatively low and the plastic deformation concentrates on the ribbed area close to the clamping device (see Fig. 16 left). In LC 3 an axial crush is triggered. Consequently the forces are significantly higher (Fig. 16 right). There are differences in the second deformation phase, depending on the failure history of the first phase. For example Part LC3-11 represents widespread plastic deformation, resulting in maximum

FIG. 15
Load case definition for the Generic Body Joint.
Definizione di casi di sollecitazione per il giunto generico di carrozzeria.

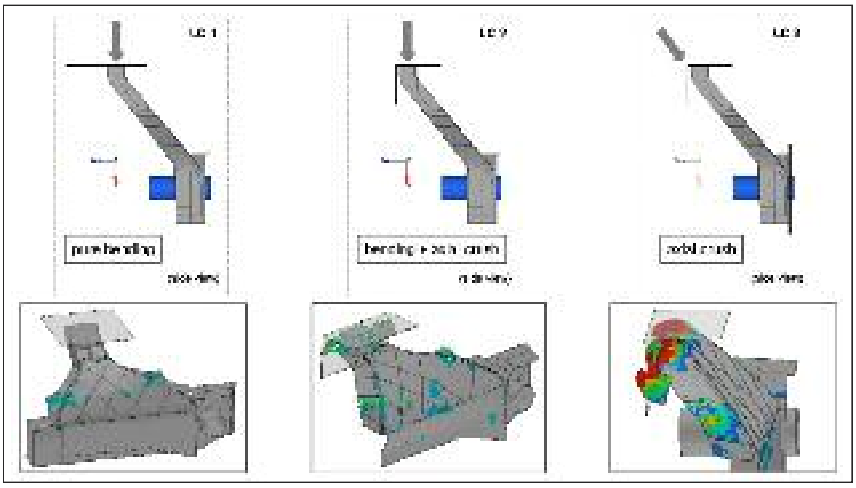


FIG. 16
Load case test results (LC1, LC3) for the Generic Body Joint.
Risultati delle prove sui casi di sollecitazione LC1, LC3) per il giunto generico di carrozzeria.

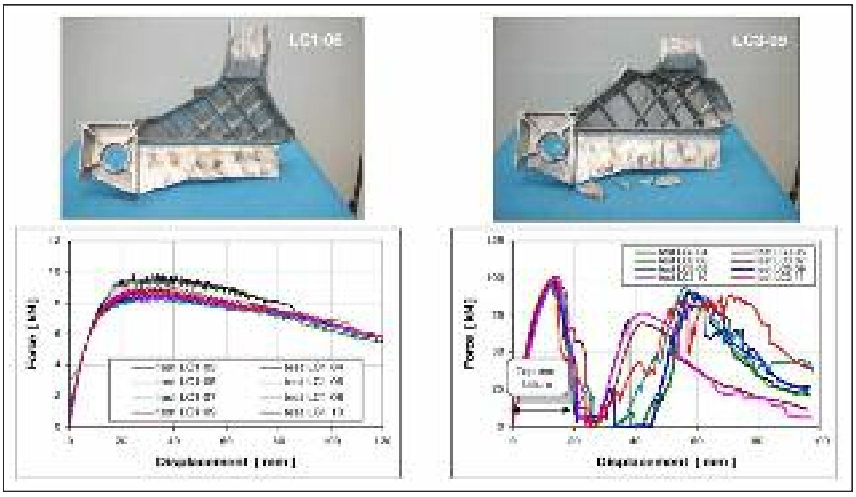
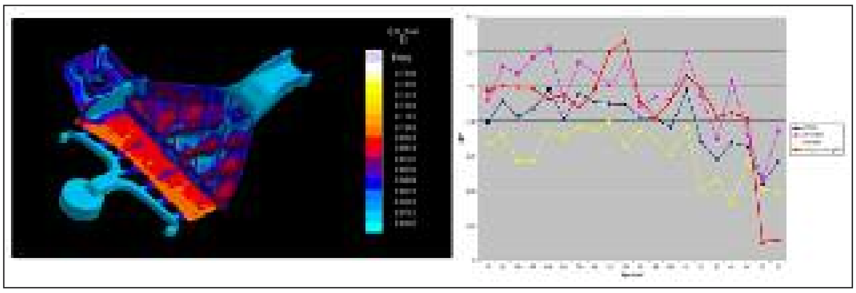


Fig. 17
Application and validation of the MAGMA Quality Mapping tool for the Generic Body Joint.
Applicazione e validazione dello strumento MAGMA Quality Mapping per il giunto generico di carrozzeria.



energy absorption.

MAGMA has provided a set of mechanical property results for the demonstrator casting, based on the Quality Mapping (Fig. 17). The overall correlation is very good, identifying areas of low and high ductility correctly in a global sense. More detailed identification of local mechanical properties is being left to future updates of the Quality Mapping tool.

The full application of the NADIA methodology results in a set of local distributions for each of the impairment factors (Fig. 18). These distributions are reflecting the effect of local mechanical properties on the different failure mechanisms. Global Initial Porosity is based on microporosity and therefore in the beginning not a local function, but voids will develop locally depending on the stress and deformation state. As already mentioned, in case of local macro-porosity, imported from casting simulation, this will be used instead.

The application of the full CAE procedure on the Demonstrator part is capable of predicting all the relevant failure modes and locations accurately and reliably (Fig. 19).

The significance of casting process effects and local property distributions can easily be demonstrated by comparing full crash simulations with and without the application of Quality Mapping. Not only the Force-Displacement results are very different, but also the deformation and failure behaviour of the component (Fig. 20).

The final CAE analysis procedure for magnesium HPDC crash relevant body components (Fig. 21) provides a “stand alone” feature for foundry optimization analyses as well as a full Closed Loop Optimization procedure. The CrachFEM simulation captures the influence of locally varying properties, the growth of initial micro- and macro-porosity and the effect of different stress states on shear and normal failure. This new and advanced procedure and the newly developed NADIA CAE tools are currently being integrated into the FORD Product Development procedures.

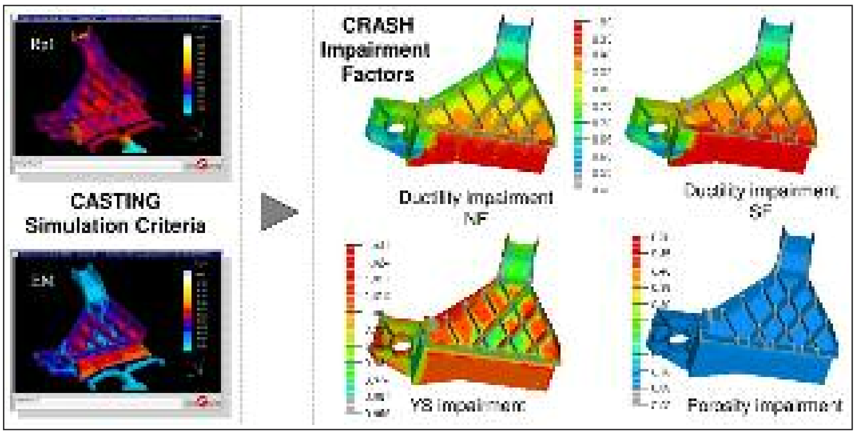


FIG. 18

Application of the full CAE procedure (incl. Quality Mapping) to the Generic Body Joint.

Applicazione dell'intera procedura CAE (incluso Quality Mapping) al giunto generico di carrozzeria.

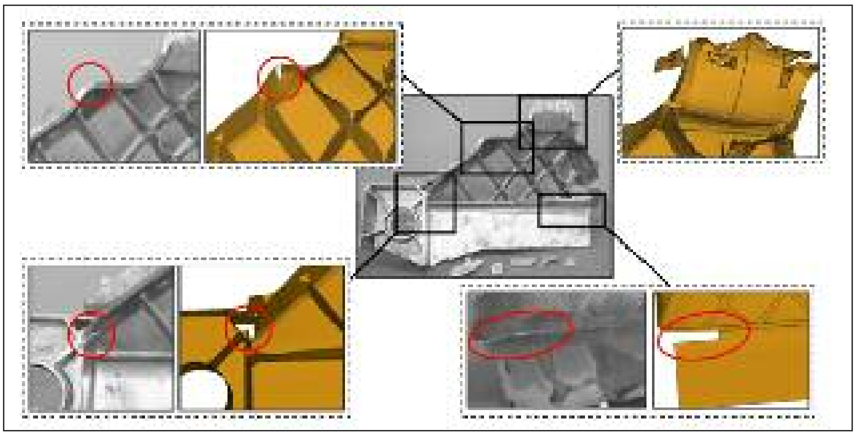


FIG. 19

Validation of the full CAE procedure (incl. Quality Mapping) for the Generic Body Joint.

Validazione dell'intera procedura CAE (incluso Quality Mapping) per il giunto generico di carrozzeria.

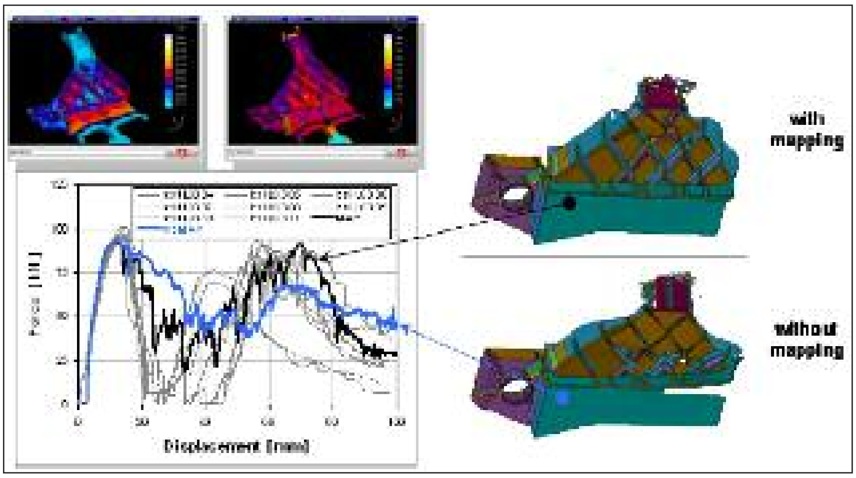


FIG. 20

Significance of the Quality Mapping tool for the Generic Body Joint.

Significato dello strumento Quality Mapping per il giunto generico di carrozzeria.

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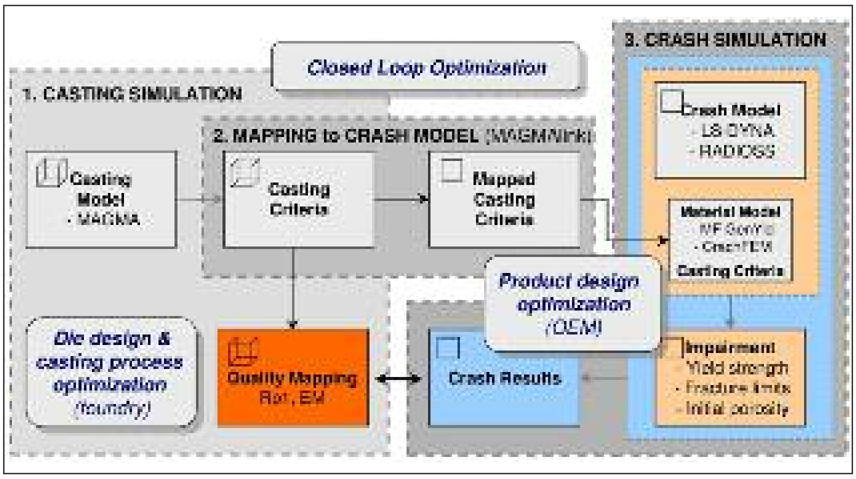
FIG. 21
Final CAE strategy for Closed Loop Optimisation of Product and Process cast criteria.
Strategia finale della procedura CAE per l'ottimizzazione dei criteri di processo di fusione e prodotto.



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Abstract

Progettazione di getti pressocolati di magnesio resistenti al crash

Parole chiave: metalli leggeri, magnesio e leghe, pressocolata, simulazione numerica

I getti di magnesio offrono un significativo potenziale di risparmio di peso per molte strutture automobilistiche che abbiano rilievo nella resistenza allo schianto. Fino ad oggi una corretta progettazione di componenti in magnesio è risultata difficile e laboriosa, in quanto non erano disponibili strumenti di calcolo affidabili, ed erano necessarie ripetute prove di produzione e collaudo dei componenti.
Ciò perché i componenti in magnesio pressofuso ad alta pressione (HPDC) per applicazioni che richiedano resistenzaallo schianto possono avere significative variazioni delle caratteristiche meccaniche locali come risultato delle condizioni del processo di colata e della geometria del pezzo. Inoltre, la dispersione statistica delle caratteristiche entro una stessa zona, causata da piccole variazioni di processo, può determinare variazioni nel comportamento a frattura. Le parti in magnesio HPDC tendono poi a mostrare un livello significativo di microporosità al centro di una parete sottile di fusione, il che non è inusuale anche in altri processi HPDC ed è di natura altamente stocastica.
Questi tre fattori hanno reso difficile utilizzare metodi tradizionali di calcolo e le tabelle del materiale per prevedere in modo accurato e affidabile il comportamento allo schianto dei componenti in magnesio HPDC perché, fino a ora, è stato impossibile incorporare facilmente gli accadimenti locali di fabbricazione e gli effetti della microporosità.
Nel progetto di ricerca europeo NADIA, è stata sviluppata una nuova serie di strumenti di progettazione per leghe AM60 e AM50 che combinano risultati della simulazione di processo locale di colata con modelli CAE di rottura da schianto per prevedere l'adeguatezza di resistenza all'urto dei componenti. Questi strumenti CAE sono stati resi commercialmente disponibili e integrati negli esistenti codici CAD / CAE.