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CAST-DESIGNER: THE ALL IN ONE SOLUTION FOR CASTING BUSINESS, FROM PART DESIGN, TO MANUFACTURING, TO PERFORMANCE VALIDATION

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ABSTRACT

As the development of technologies, numerical simulation and digital technologies bring advantage to casting business, such as the DFM, casting system design and thermal/flow/stress/microstructure whole physical field simulation, this bring benefits to quality improvement and cost saving. Now, the latest Cast-Designer software can help the user to validate the casting performance directly, the casting defects could be validated in the performance software directly, such as the shrinkage porosity, gas porosity and residual stress.

Keywords: Cast –Designer, CDPE, DFM, HPDC.

I. INTRODUCTION

The highest volume of component which is used by automotive manufacturers is the Aluminum die cast parts. Now a day's these components have been expanded to engine blocks, but primarily it includes cylinder heads, chassis and power train parts. Die cast Aluminum alloy replaces the traditional cast iron engine blocks. For surface durability and material strength, the automotive part has a very high requirement. The low density of aluminum gives it greater mobility than cast iron, which can be helpful in smaller spaces. Unlike cast iron, aluminum does not rust, so it can resist corrosion much more effectively. This can be a boon in harsh environments.

Furthermore, aluminum is easy to recycle, while cast iron must be melted and recast. Aluminum also has high thermal and electrical conductivity that allows it to cool down quickly after compression. Aluminum does have some drawbacks, primarily that it is not as durable as cast iron. These aluminum castings are being used in new part opportunities, with other applications, for engineered components in the axle products and structural components. Both metals have their benefits and drawbacks, so the deciding factor should always be the performance.

II. METHODOLOGY

Typically, in-homogeneities in cast metal due to porosity or inclusions are not considered directly in part design. Instead, some safety factors used, which might do little for the robustness of the design other than increasing casting weight. Engineering approach in design and development is to consider the effects of porosity on the service performance of cast components. As iron or steel castings become lighter weight and thinner sectioned, knowledge of the location, amount, and effect t of porosity on strength and fatigue behavior is more critical than ever.

In the case of cast metals, every effort is made to produce a sound, porosity-free casting. Still porosity may occur in a part that is undetectable or that cannot be eliminated without unreasonable cost, making the part "unfriendly" to cast. Micro porosity may not result in a detectable loss of stiffness, localized stress concentration, or stress redistribution, but it can greatly affect ductility and fatigue resistance. When this knowledge is combined with casting process modeling that predicts the location, amount, and size characteristics of micro- and macro porosity, an integrated design process will emerge allowing designers to simulate the possible effects of casting production processing on part service performance. It is anticipated that such a design process will guide and improve inspection criteria as well.

When converting the casting material from iron to aluminum, and the process from gravity casting to high pressure die casting, the gas porosity and residual stress are also become more important when take account the defects to final part performance. In this case, the following manufacturing defects must be considered as well:

1) Shrinkage porosity of the casting process

2) Gas porosity of the casting process, especially for high pressure die casting

3) Residual stress of the casting process

In Cast-Designer, a new structural module called Cast-Designer Performance (CDPE) has been developed to perform the performance analysis. CDPE is a program to solve 3D finite element models for mechanical and thermal loading. An implicit framework is employed to solve the global nonlinear equations of nodal equilibrium with an incremental-iterative approach.

III. MODELING AND ANALYSIS

CDPE Workflow

CDPE is an analysis engine based on finite element technology and fully integrated to the Cast-Designer user's environment. CDPE input files have a remarkably simple, easy-to-understand structure and are readily generated from model descriptions produced by Cast-Designer or other mesh generators.

A simplified workflow would contain these tasks:

1) Mesh generation
2) Define the material data, model properties, nodal loads/temperatures, element loads, displacement boundary conditions and other control parameters.
3) Run the CDPE solver.
4) Check the simulation result in the post-processors.

Residual stress in casting process

Casting is a lower stress process when compared with the stamping, forging and welding process, but the residual stress also plays an important role sometimes. The CDPE solver can accept the residual strain and stress as pre-strain and pre-stress, so it could be imported from the standard Cast-Designer simulation result directly. The user can select the step to extract the result; also a stress factor could be applied to the extract result for some special proposal. More ever, the non-uniform temperature of the casting part could be mapped to CDPE model directly also.

Porosity in casting process

The porosity result of the casting part can bring a major affection to the final tensile stress and elongation: this is a key factor for the final performance. So, couple the porosity defects to final casting part performance analysis is widely required in the industries.

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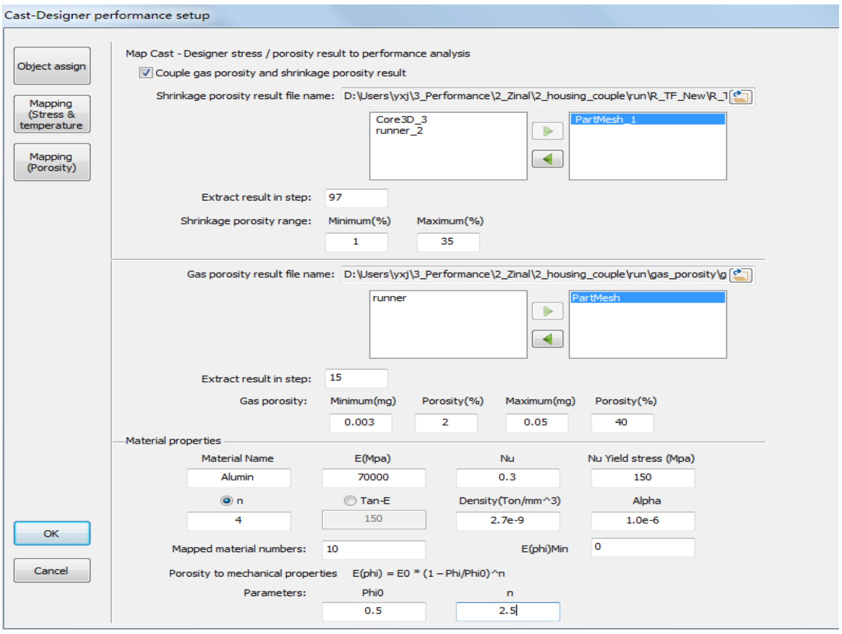

Figure-1: CDPE software interface to couple shrinkage porosity and gas porosity of Cast-Designer

The workflow of the porosity couple includes the following steps:

1) Active the 'couple gas porosity and shrinkage porosity result' option.

2) Selects the Cast-Designer result file which included the shrinkage porosity result.

3) Define the object in the original simulation model and the CDPE model; the part name should be same. Since we are only studying the properties of the final casting part, so the gating system, overflow, and others unused component could be separate to other objects in the initial Cast-Designer simulation. Moreover, we are using the mapping technology, so the mesh elements could be different in the thermal flow simulation model and CDPE simulation, but the coordinate space should be same.

4) Define the result step to extract the porosity result. The default one is the last step of the initial simulation.

5) Define the minimum and maximum shrinkage porosity value. If the shrinkage porosity result is less than the minimum shrinkage porosity then it will be set to zero; on the other hand, if the value is larger than the maximum defined shrinkage porosity, then it will be set to the maximum value. This can make a more robust CDPE simulation.

For gas porosity, the operation process is also similar. But we need to convert the gas porosity size to the same standard level as shrinkage porosity. Then summarize both the porosity together. For the element with different porosity level (includes both shrinkage porosity and gas porosity), in CDPE, different material properties will be assigned. As for study, the major affection of the porosity to material properties will be Young's modulus. The following formula could be used in CDPE

$$\mathrm{E}(\varphi) = E0 * \left(1 - \frac{\varphi}{\varphi 0}\right)^{n}$$

Where E0 is the original Young's modulus, φ is the porosity, $\varphi 0$ and n was the material parameter. As validation, for steel and aluminum, $\varphi 0$ could be set to 0.5, and n could be set to 2.5. The user can define the material numbers of different level porosity, for example 10 materials. Depended the porosity distribution of the model, 10 to 20 materials are suggested.

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IV. RESULTS AND DISCUSSION

In automotive, good brakes are essential for safe driving. Top brake mount frame is one of the key components in the brake system, which asked a high quality and high performance after casting. Figure 2 is the 3D CAD model of a top mount frame of automotive brakes system. It was originally designed and manufactured by gravity casting process in iron material. Such material and process has existed many years and widely used in the industry.

The Figure 2 (b) was the performance testing process, the punch will come down with a given force for a given time, and if the part was not broken then it can comply with the performance requirement. For this part, the minimum required force was 36KN, but consider the part fatigue in the automotive, a safe factor 1.5 to 2 is always used. To reduce the weight of the part and improve the production rate, aluminum material is suggested, and the casting process has been changed from sand casting to high pressure die casting, but performance requirement should be kept the same.

(a) (b) (c) (d)

Figure-2: 3D CAD model (a) top mount frame (b) performance testing process (c) & (d) Part crack and damage of the aluminum part after the performance test

However, in the real industrial condition, such change was not so simple. After changing the casting material and process, the yield ratio of the casting part has been reduced from 99% (iron) to 70% (Aluminum), this is absolutely could not be accepted. The major problem of the casting part was the damage problem after the quality testing. Figure 2 (c) & (d) shows the part damage and crack in the aluminum part. This problem was quite stable. So, we must address the reason of the problem and find a solution.

Numerical simulation model of the performance test

Numerical simulation also could be used for the performance test. This is not a new topic but existed quite longer time in the market. There is much structure simulation software available for such purpose. As discussed above, using theory material model and data to evaluate the performance by standard structure software is not enough; the defects of casting process may play an important role to the final performance.In this paper, CDPE was used for the performance simulation.

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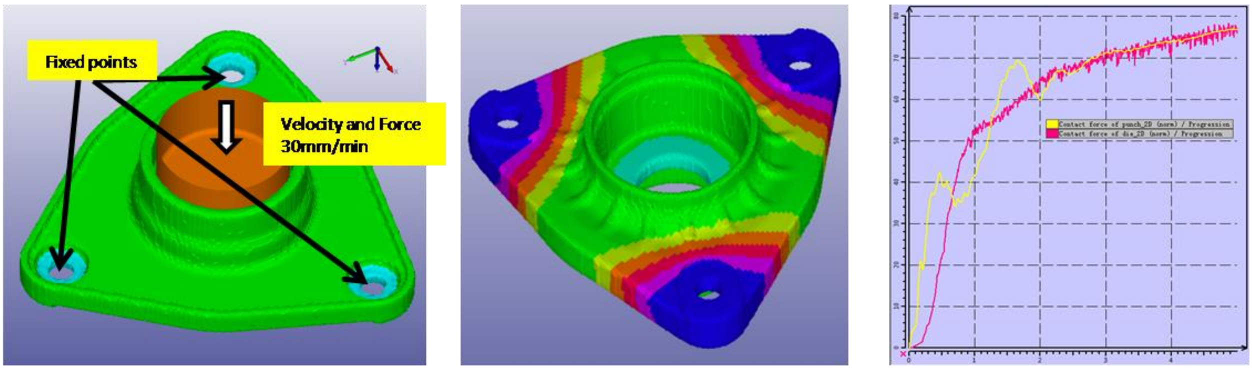


(a) (b) (c)

Figure-3: CDPE simulation (a) model (b) displacement (c) contact force

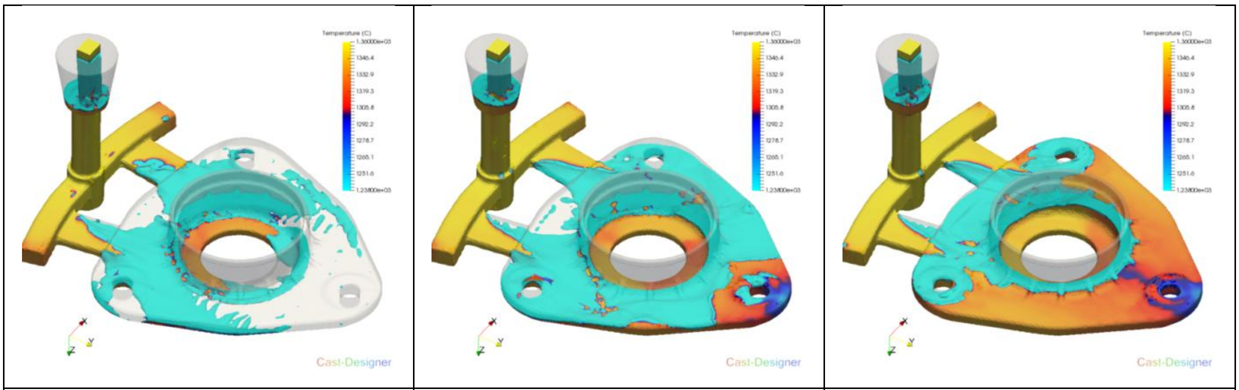
The boundary condition of the CDPE simulation model has shown in Figure 3 (a). The simulation result such as the displacement (b) and the contact force (c) also has shown in Fig 3.The basic simulation parameters of the model as below:

Table 1: Simulation Parameter of model

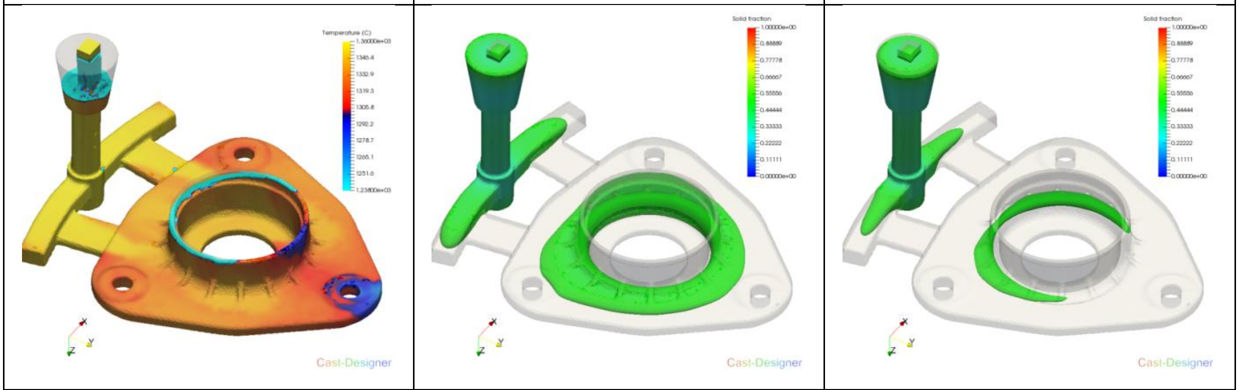
CDPE Model setting	
Analysis type	Strength
Solver	Cast-Designer Performance (CDPE)
Solver type	Implicit
Element type	Hexahedron
Material	Iron or Aluminum

Gravity casting process and simulation

To take account of the defects of the casting process, we also need detailed information of the casting process, numerical simulation also the best way for that. We do that in Cast-Designer. The original manufacturing process was sand casting in iron, the casting material was GGG40. The pouring temperature was 1370 degree and the filling time was less than 30 sec. As experience, riser is not necessary for this part. The casting system also designed in Cast-Designer system. Figure 4 shows the detailed casting process including both the filling and solidification. (a)- (d) Was the filling process and (e)-(f) was the hot spots of the solidification process. The contour of (a) to (d) was temperature.



(a) Filling process (b) Filling process (c) Filling process



(d) Filling process (e) Solidification (f) Solidification

Figure-4: Simulation result of the gravity casting process (a-d: filling process e-f: solidification process)

It is clear that the filling process was quite stable, no risk of big turbulence and gas entrapment, the temperature distribution was also reasonable, so the gas porosity of the filling process should be quite limited. The solidification result shows the last solid region was the inside of the ring, around the ring, so shrinkage porosity or micro-porosity may exist in such region. Considering the iron expansion of the GGG material, the final shrinkage porosity also very small. The X ray photos also approved this point. We also do the stress simulation of such process; the residual stress was very small in the final part. We will use the above simulation result for the part performance simulation in the later stage.

High pressure die casting process and simulation

To improve the production rate and maintenance, a more consist quality standard as well as good surface quality, the new manufacturing process was high pressure die casting (HPDC), two parts in one cavity. Figure 5 shows the detailed filling process. The gating system was also designed in Cast-Designer. Generally speaking, the gating system was good enough, the filling process was also balanced, the overflow system was reasonable. One problem was the top of the inner gate was filled at the last; it may bring risk for gas entrapment in such region.

After the simulation, using the powerful gas analysis tools called post-solver, we can have the final gas porosity distribution and the shrinkage porosity after solidification. Figure 5 shows both porosity result. From the gas porosity result, we found that the blocked gas mass near the inner gate was more than in other places, so this is a risk for crack occurrence and growth. The shrinkage porosity was quite like in the gravity casting process, this is mainly depended on the geometry shape of the casting part, and we call it as geometry mass distribution. Again, we also do the stress simulation of the high pressure die casting process; the residual stress was also small in the final part. And we will use the above simulation result for the final part performance simulation in the later stage.

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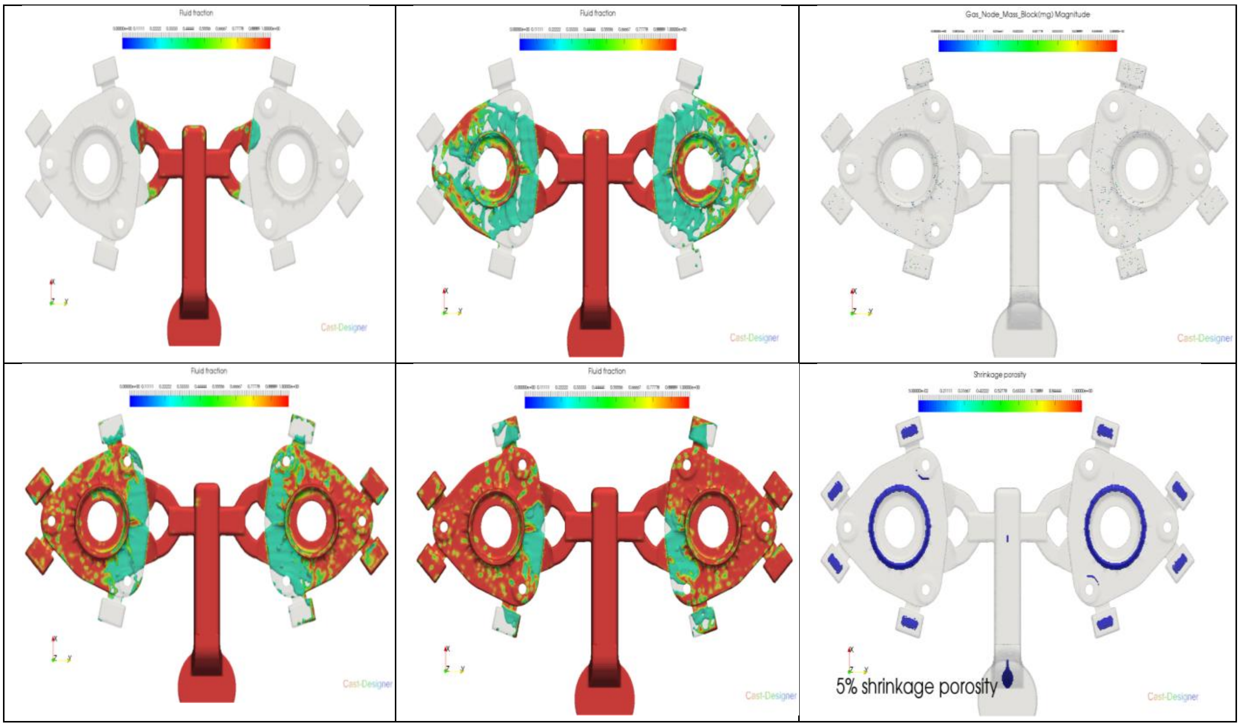

Figure-5: HPDC process simulation (filling process) & defects (gas and shrinkage porosity)

CDPE simulation when take account of the casting defects

With the above simulation result of the manufacturing process, we can start the part performance simulation now. Cast-Designer Performance (CDPE) was fully integrated in Cast-Designer user's environment; it is a template base design software with good interface. The user only needs to follow up the process guideline step by step, then complete the model setup. It is very powerful and flexible, also easy to use. For traditional general FEM software, you always need a quite longer time to learn, but using CDPE, a few hours is enough.

The user can use the same mesh model for CDPE as the casting simulation; the meshing time could be reduced to minimum and fully automatic. The result analysis of CDPE was like any other structure analysis software and could be read in the same post-process of Cast-Designer also. More ever, CDPE support big model size and good parallel computing capability to save CPU time.

Table 2: The material data of the simulation

Material	Young's modulus (MPa)	Yield stress (MPa)	Tensile stress (MPa)	Couple residual stress	Couple porosity result
A-GGG40	193000	300	420	Yes	Yes
B-Alsi10MnMg	73000	200	270	No	No
C-Alsi10MnMg	73000	200	270	Yes	Yes

Figure 6 was the simulation result of CDPE; the testing punch force was 36KN (as Figure 2). A and A' was the iron part made by sand casting, B and B', C and C' was aluminum part made by high pressure die casting, but B and B' did not couple the manufacture defects while C and C' considered the residual stress and porosity affection. The Damage Crack Criteria (DCC) could be used to evaluate the safety of the casting part in difference applied force. As we know that maximum shear stress at a point in the material will be equal to the half of difference between maximum and minimum principle stress and therefore, we will have following equation.

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$\tau Max = (1/2) \times (\sigma 1 - \sigma 3)$

Let us determine the value of shear stress corresponding to the yield point of the material. In case of simple tension, Stress will be available in one direction only and therefore at elastic limit, principle stresses will be σt, 0 and 0.

Value of shear stress corresponding to the yield point of the material = $(1/2) \times \sigma t$

Let us write here the condition of failure

$(1/2) \times (\sigma 1 - \sigma 3) > (1/2) \times \sigma t$

$(\sigma 1 - \sigma 3) > \sigma t$

If we set the yield stress of the material was σy, then we will have the following formula

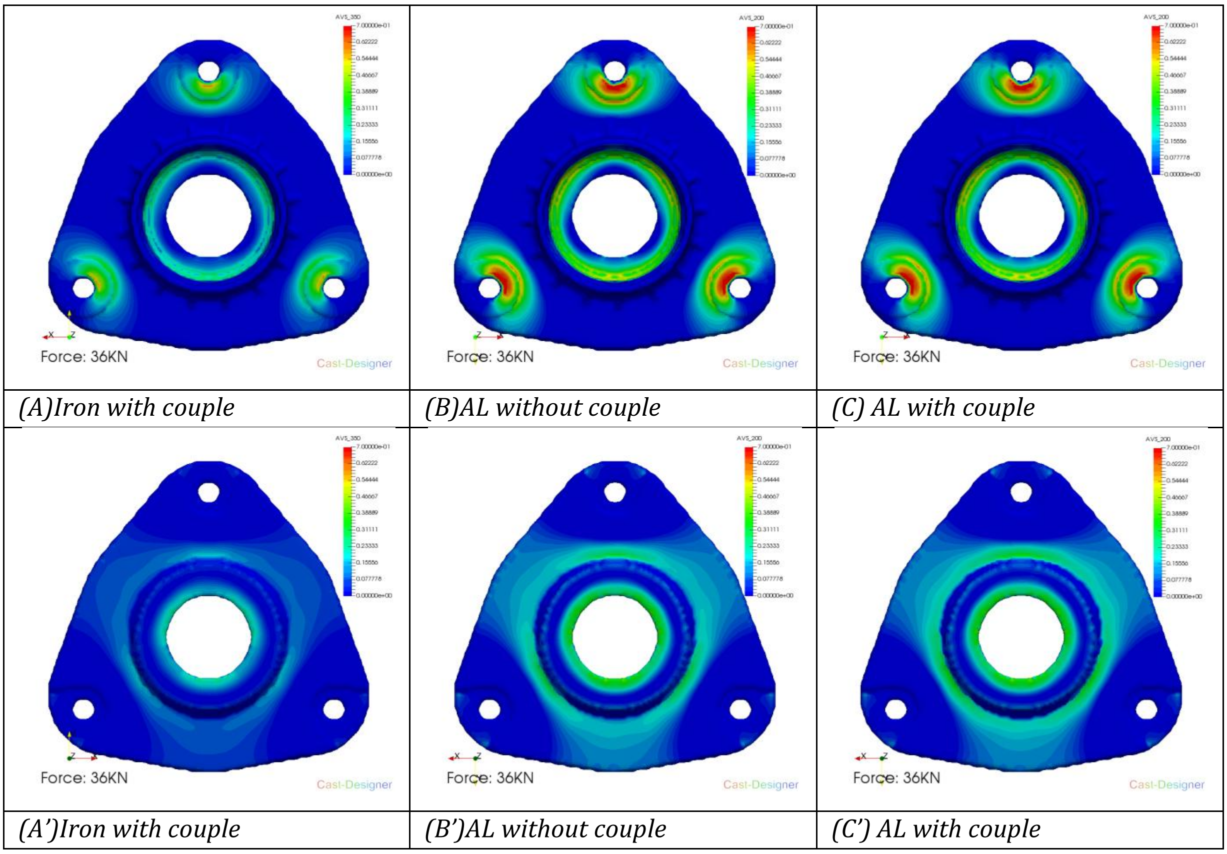
$K = (\sigma 1 - \sigma 3)/\sigma y$ (1)

In formula (1),

if K>= 1, then the damage will happen

if K<1, then the material will be safe.

We also can consider the safety factor, for example 30% as safety factor, then if the value was more than 0.7, then we need consider the risk of damage or crack. In the following pictures, the contour is the K as discussed above. We called DCC.



(A)Iron with couple | *(B)AL without couple* | *(C) AL with couple*

(A')Iron with couple | *(B')AL without couple* | *(C') AL with couple*

Figure-6: CDPE simulation result of top mount frame (in 36KN punch force)

For performance testing, in 36KN punch force, even we set 30% as safety factor, all the three cases A, B and C are safe enough. But the strength of case B is weaker than A and case C is also weaker than case B. From case B/B' and case C/C', we can find the manufacturing defects play an important role in the final

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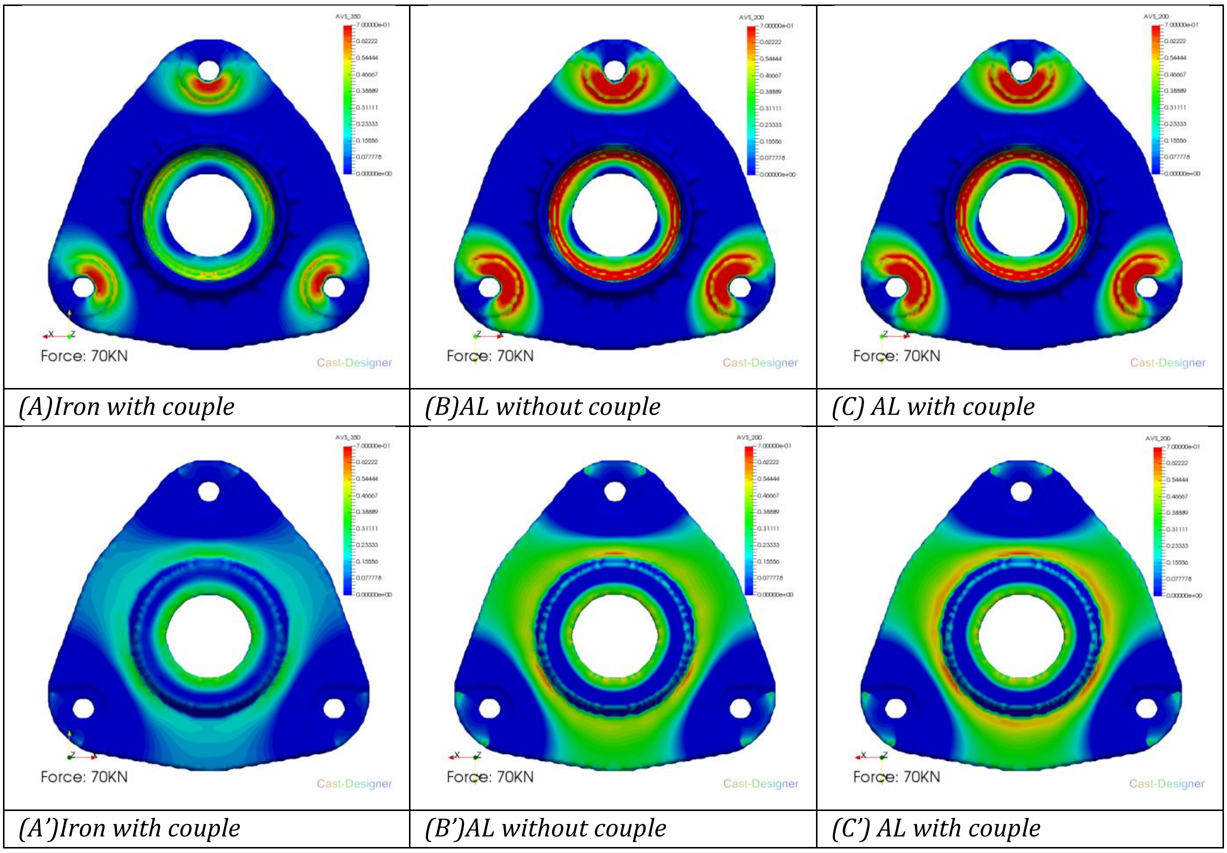
part performance. In the real working condition, fatigue and over loading is always happened. So, we also need to increase the testing force to check the performance. For this part, twice of design force is always applied as per the industrial experience, so we also use 70KN to check the performance.

Figure 7 shows the simulation result of 70KN punch force, all other conditions and analysis criteria were same as above. In this condition, the iron part was still safe enough but the aluminum part has already damaged (the red region in B, B', C and C'), special for case C. the damage region was around the inner ring (B and C) and around the outer ring (B' and C').



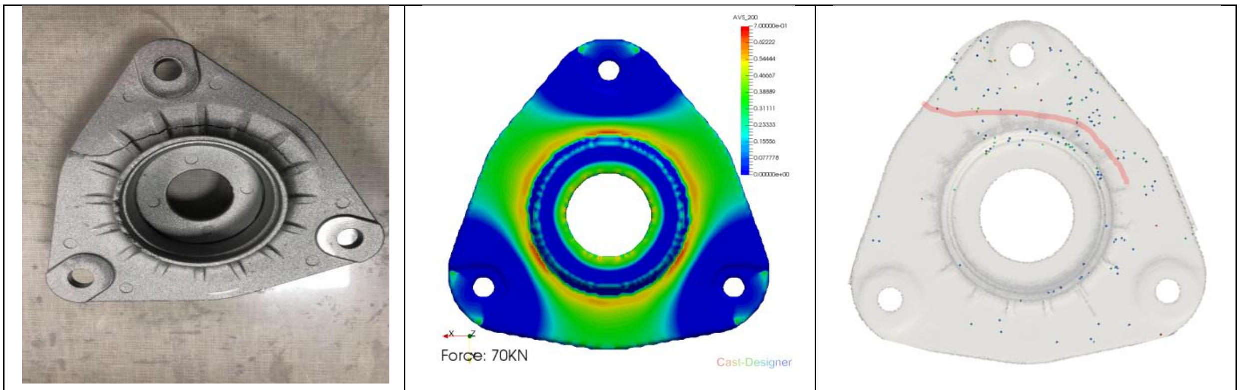
(A)Iron with couple | *(B)AL without couple* | *(C) AL with couple*

(A')Iron with couple | *(B')AL without couple* | *(C') AL with couple*

Figure-7: CDPE simulation result of top mount frame (in 70KN punch force for testing)

The simulation result had a very good agreement with the actual testing result. Figure 8 (a) shows the details of the crack of real part and (b) is the CDPE simulation result. It was exactly same. But if we only compared the actual testing part with B' in Figure 7, then we found it is similar but not exactly, special for the crack growth direction. So, it is clear, the defects of the manufacturing process must be considered well to have a more accurate virtual simulation result of the final part.

Another thing is very interesting but not so clear in the Figure 8 (b), when we compared the crack of actual testing and the gas blocked mass contour of the HPDC process Figure 8 (c) (From Fig 5 with rotation, the shrinkage porosity), we found the crack growth direction was almost follow up the blocked gas. This is really worth for us to spend more time to have a deeper study in the later stage.



(a) Actual testing (b) CDPE result (c) Gas blocked mass

Figure-8: the real damaged part and simulation result of CDPE

In view of above, replace the part from iron to aluminum is possible, but the strength was reduced, and the risk of the damage was increased. This is why the yield ratio was reduced from 99% to 70%due to manufacturing process change. To improve the production, we try to do some modification of the part design.

New Design Plan

Since the part modification with many limitations, all function features must be kept, and assembly could not change. This kind of modification must be done based on complete communication with the customer. For the top mount frame, as the detail study and discussion, we try to add a ring rib around the outer cylinder of the top surface to enhance the stiffness of the part. This plan does not bring any affection of the function requirement and assembly (Figure 9). Since this is the initial design concept, we do the structure analysis in CDPE in a simple way without considering the manufacturing defects at this stage. But as the result of Figure 7, we can have some basic idea of the manufacturing affection.

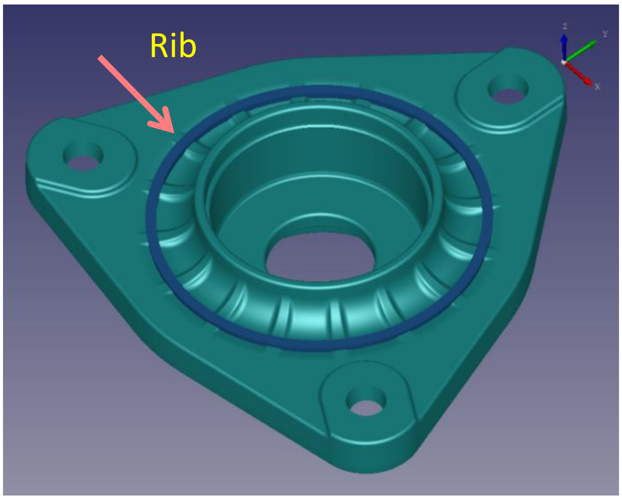


Figure-9: Revised part design (add a rib around the inner cylinder)

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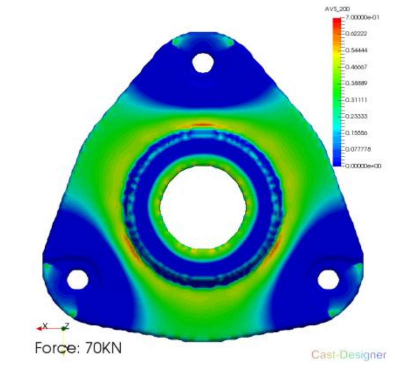
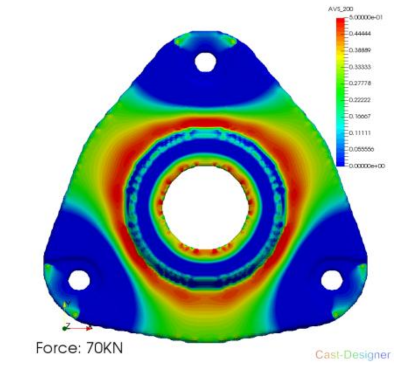
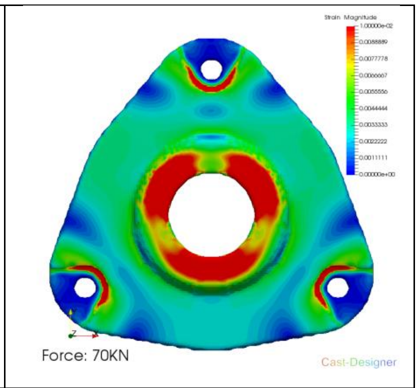
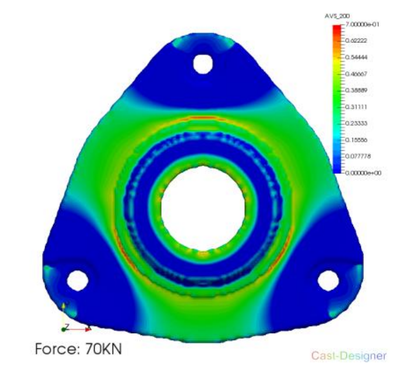
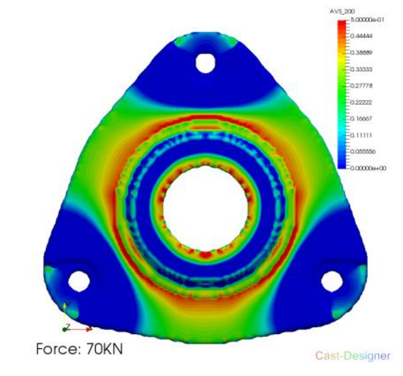
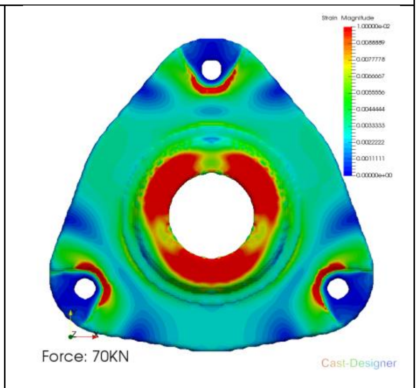
		
(A1) 30% safe factor	(A2) 50% safe factor	(A3) Strain
Original design in 70KN force (do not consider manufacturing defects)		
		
(B1) 30% safe factor	(B2) 50% safe factor	(B3) Strain
Revised design in 70KN force (do not consider manufacturing defects)		

Figure-10: CDPE result comparison (initial design vs. revised design)

From Figure 10, we found the revised design plan can improve the damage criteria and change the DCC distribution (A1 vs. B1, A2 vs. B2), the total strain distribution also had some smaller difference (C1 vs. C2). Such addition ring rib enhance the stiffness of the original part especially for the crack region, it should be useful to the part performance. Another key matter to improve the damage is to increase the yield stress of the material, because the yield stress of the given aluminum was only 200MPa but the iron material was more than 300MPa. Adjusting the chemical composition may help this.

Finally, the company selects the geometry modification plan and improves the material alloy composition, the product yield ratio has successfully increased to 96%.It was quite similar the iron material, but the production rate was 20 times more than the sand casting.

V. CONCLUSION

The Cast-Designer Performance analysis software module is a useful tool to evaluate the casting part performance, with good link to Cast-Designer thermal, flow and stress solver. The CDPE material model can handle very complex material data; include the affection of shrinkage porosity and gas porosity, as well as the residual stress. Such manufacturing defects may bring big impact to the final performance. The Cast-Designer system becomes a complete solution for the whole casting chain. It can put all data to the sole engineer to handle the design, evaluation and engineering decision.

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