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2016

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Numerical Simulation and Experimental Examination of an Oldham Coupling

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ABSTRACT

In scroll compressors, Oldham couplings (OCs) have typical been formed of aluminum alloy and have often broken issues due to the high loads which are transmitted from the orbiting scroll. This problem was especially pronounced during flooded start or slug conditions. In this paper, five pcs mass production OCs (standard OC), which are broken during a special slug test are investigated by classifying the ring broken and pin broken. During the investigation, both the quantities and the probabilities of each failure position are counted. Then, Finite Element Method (FEM) is employed in strength calculation for the standard OC and an optimized OC. The Finite Element Analysis (FEA) results explain that the cause of the ring's breakage is due to high tensile stress and the pin's breakage is due to high shear stress. After simulation, the authors design a series of strength experiments and DOE tests, with a great number of samples, which includes standard full treatment OC, CNC machined OC, half treatment OC and optimized OC, to verify the FEA results and repeat the failures in slug tests. Further, the author investigates the experiments results and compares the errors group by group. Finally, under the help of numerical simulation and experiment results, two new numerical models for OC strength prediction are proposed and validated by both strength tests and slug tests. The implementation of the prediction models are not only benefit to obtain a stronger OC or ensure it to reach a high reliability level, but also helps the develop engineers to shorten the new OC's development duration and reduce the fix expense in research activities.

1. INTRODUCTION

In scroll compressors, it is typical to employ a crankshaft to drive an Orbiting Scroll in orbiting motion with respect to a Fix Scroll (FS) or housing. In order to prevent relative rotation between OS and stationary body, OC has normally been implemented. Generally, the OC incorporates two pairs of pins, each pair of pins projecting in the opposite direction from an annular ring with one pair of pins engaging slots in the OS and the other pair of pins engaging either slots in FS or housing. Figure 1 shows a typical assembly method of an OC. An OC is mounted on the upper side of housing. Above it, located an OS which is driven by a crankshaft.

In the prior art, the Oldham couplings have typical been formed of aluminum, and have often breakage issue. This problem was especially pronounced in some larger scroll compressors and in particular during flooded start operation or slug condition. Under such worse conditions, the force transmitted to the coupling by the orbiting scroll can be substantially higher than during normal operation, causing the Oldham coupling to break.

As a result, to overcome this problem and deliver a robust design becomes an important work to develop engineers. Several approaches are tried to produce a strong OC. For example, it has been proposed in the past that some engineers use cast iron to form the OC. Although it becomes more stronger than before, the OC would be unduly heavy and cause excessive vibration issues. Another example is Titanium and Titanium alloys have been utilized in OC design and manufacture, which provides additional strength and resistance to breakage as compared to other more conventional materials such as Al alloys or cast iron.(Alexander Lifson. 2006) However, Ti or Ti Alloy OC may result in another issue – cost increase in mass production.

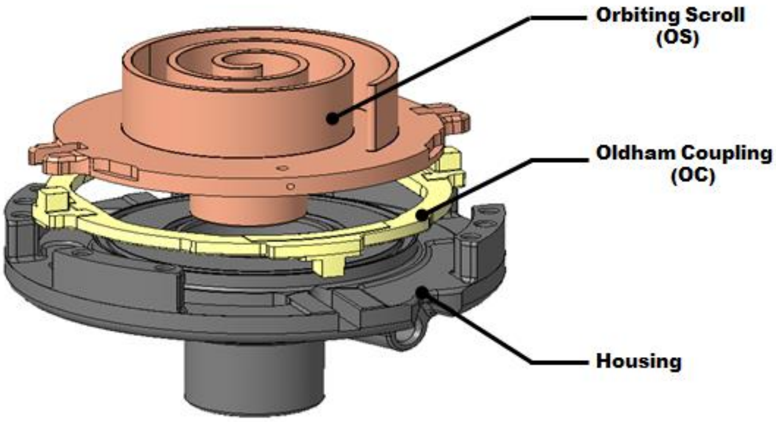

Figure 1: Assembly relationship of an OC

Moreover, the validation of a new OC often includes three main steps: First, 3D design (including FEA); Second, samples manufacture; Third, qualification tests. For each step, it needs about 4-10 weeks to complete corresponding tasks. For example, suppliers needs 6-8 weeks to prepare a new die and engineers need 8-10 weeks to finish all qualification tests. If any failure occurs in the qualification tests phase, engineers must go to the start point, or supplier prepares a new die for another 6-8 weeks. In this case, total development duration and fix expense will increase greatly.

Therefore, providing a robust design and improving OS' reliability level in critical conditions with minimum expense and shorten lead-time is a significant and meaningful task for all design engineers.

2. STASTISTIC AND NUMERCIAL SIMULATION OF OLDHAM COUPLINGS

2.1 Compressor slug test and its results

In order to check and to know X compressor's reliability level during slug conditions, five pcs X series compressors are tested by injecting more liquid step by step during their suction phase. All compressors can run well until the liquid is injected 130~150% times than safety level. Since the purpose of slug test is to check the strength of OC and wrap, there must be some damages in OC or warps. Tear down compressors proves the deduction that five pcs OCs are broken. It also means that current OC becomes the bottleneck of increasing X compressor's liquid handling ability. For this reason, an optimized OC with robust design is need for X compressors.

Figure 2: Two broken OC

Figure 3: Statistic of failure zone

Two broken OCs are shown in Figure 2. From the pictures, it can be seen that breakage occurs in both pins and the ring. If take OC assembly relationship into consideration, the breakage of the ring is mainly due to high tensile stress, which is caused by OS when the compressor is compressing liquid refrigerant. The breakage of the pin is mainly due to the high shear stress applied on the contact surface through the slots. There is no doubt that breakage always starts from the most weak point or position. Thus, a further statistic is completed on those broken OCs.

The pins that contact with OS are specified as the first pair of pins and numbered 1# and 2#, while the other two pins are regarded as the second pair of pins and are numbered 3# and 4#. Second, four cross lines divides the ring into eight equal zones, see Figure 3. Pin 1# is defined as 0 ° position and the remaining positions are named from 0 ° to 315 ° in 45 ° increment along a counter-clockwise direction. This operation will be very helpful in finding out the greatest weakness zone(s) in standard OC.

Table 1 and Table 2 list the statistic results of rings and pins. "NOK" means corresponding rings or pins are broken while "OK" means they are still intact after slug tests. It can be seen from Table 1 that rings are more likely to break at 315 ° and 135 ° positions, because there are five pcs and three pcs of standard OC, respectively, broken here. For the remaining positions, the failure rate seems average. If looking at Table 2, the first pair of pins, compare to the second pair of pins, breaks more.

Table 1: Statistic of Ring broken

Compressor	**0 °**	**45 °**	**90 °**	**135 °**	**180 °**	**225 °**	**270 °**	**315 °**
x-1	OK	NOK	OK	OK	OK	OK	NOK	NOK
x-2	NOK	OK	NOK	NOK	OK	OK	OK	NOK
x-3	OK	NOK	NOK	OK	OK	NOK	NOK	NOK
x-4	OK	OK	OK	NOK	NOK	OK	OK	NOK
x-5	OK	OK	OK	NOK	OK	NOK	OK	NOK
Total of NOK (pcs)	1	2	2	3	1	2	2	5

Table 2: Statistic of Pin broken

Compressor No.	**1#**	**2#**	**3#**	**4#**
X-1	NOK	NOK	OK	OK
X-2	NOK	NOK	OK	NOK
X-3	NOK	NOK	OK	NOK
X-4	NOK	NOK	NOK	OK
X-5	OK	NOK	OK	OK
Total of NOK (pcs)	4	5	1	3

2.2 Numerical simulation on OC

Two kinds of 3D models, standard OC and optimized OC are investigated via ANSYS 14.0 software. Both the ring's tensile stress and pin's shear stress are simulated. OC's material property, which is used for simulation, is obtained by using Zwick/Roell Z100 test bench (see Figure 4) and three pcs Al alloy specimen (see Figure 5).

Figure 4: Zwick/Roell Z100 test bench

Figure 5: Specimen for material property test

When conducting the ring analysis, a full 3D OC model is implemented (see Figure 6). According to OC assembly relationship and its constraints when the compressor is running, a unit torque and an inertial force is applied on the first pair of pins. Then, corresponding directional zero displacements are applied on the second pair of pins. Instead of using a full 3D mode, a simplified 3D model is implemented in the pin's stress analysis. Figure 7 shows that a part of the pin is taken from the full OC model; meanwhile, a block is created to simulate contact surface in the slot. Then, a unit load is applied according to the red arrow to calculate the pin's stress. After simulation, the high stress fields and high deformation zones are compared between standard OC and optimized OC.

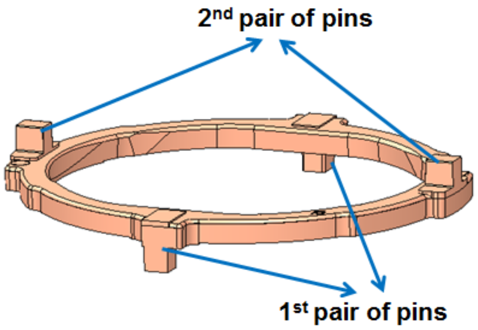

Figure 6: Ring stress analysis

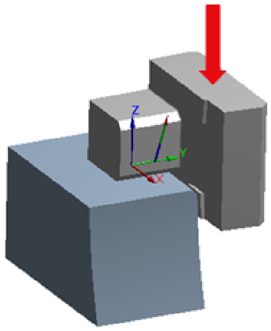

Figure 7: Pin shear stress analysis

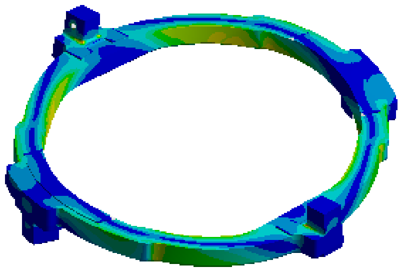

Figure 8: Von Mises stress of ring

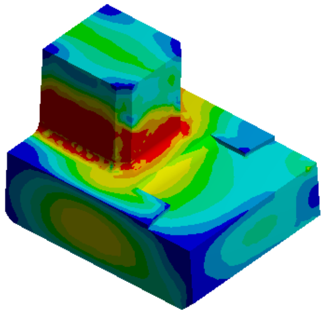

Figure 9: Von Mises strsss of pin

Figure 8 and Figure 9 show the FEA results of an OC. In Figure 8, although high stress zones are located at 45°, 135°, 335° and 315° positions, which are the same in both standard OC and optimized OC, the maximum stress values have been decreased in optimized model. In Figure 9, high shear stress zones are around the root of pins, which is not changed in optimized model, however, the max stress decreased in optimized OC. Meanwhile, the distribution of high stress zones also explains why there are so many breakages on OC.

Table 3: Summary of numerical simulation

Sample Type	std. OC (MPa/MPa)	Optimized OC (MPa/MPa)	Delta Δ (%)
Ring	1	0.816	18.4%
Pin	1	0.871	12.9%

Table 3 shows the results of standard OC and optimized OC. Here, results are normalized using denominator values, which are acquired from standard OC. After optimization, under same load, there will be 18.4% and 22.9% strength improvement in ring and pin.

3. CORRELATION BETWEEN EXPERIMENTAL EXAMINATION AND NUMERCIAL SIMULATION

In modern research and development activities, Finite Element Method (FEM) tools have wide applications and enjoy extensive utilization in the structural, thermal and fluid analysis fields. However, it is also important to recognize the limitations of FEM - that this method can reduce product testing, but it cannot totally replace it. In other words, numerical results still need tests to validate. For this reason, a series of tests have been conducted on several samples.

The objective of these tests is not only to verify FEA results, but also to understand the correlation between numerical simulations and experimental results, especially the relationship between numerical model and mass production parts. Furthermore, the outputs from correlation analysis can be used as another inputs for the qualitative and quantitative analysis which can help to clarify the factors that affect the correlations or cause the deviations between FEA and experiments.

3.1 Test preparation

In this section, six groups of samples are implemented in strength experiments (see Table 4), which includes standard OC with mass production process (including rings and pins); standard OC with CNC machining and optimized OC with CNC machining. It is easy to understand the strength improvements can be obtained by testing standard OC and optimized OC, but the reason of involving two kinds of standard OC samples (mass production parts and CNC machined parts) is because the strength of an OC with CNC machining can represent the results that gained from FEA software much better than the mass production parts. This is because some significant surface treatments have been involved in mass production OC, which bring some benefits in OC strength, but unfortunately, the benefits is hard to be simulated in FEA tools. Thus, by using these tests samples, the relative strength improvement results in FEA can be verified via standard CNC machined OC and optimized OC. Meanwhile, absolute deviation between numerical simulations and experiments can be obtained via standard OC with mass production process and standard OC with CNC machining.

Strength tests are conducted by using Zwick/Roell Z100 test bench. Corresponding results are recorded until the samples are broken.

Table 4: List of test specimen

No.	Name of specimen	Qty (pcs)	Note
1	std. OC	4	Mass production part
2	CNC std. OC	3	std. OC w CNC machining
3	CNC Optimized OC	3	Optimized OC w CNC machining
4	std. pin	4	mass production part
5	CNC std. pin	3	std. pin w CNC machining
6	CNC optimized pin	3	Optimized pin w CNC machining

3.2 Results of experimental examination

In order to obtain a better comparison, test results are normalized using denominator value of an avg. force, which is obtained through standard mass production OC.

Test results are shown in Table 5 and Table 6. In Table 6, breakage force of CNC machined OC is just about three-quarters of the mass production OC. Even if it has been optimized, the strength is still 12.3% less than mass production parts. Since mass production OC and standard CNC machined OC are same in dimension, excluding the system errors, these gaps may due to the different manufacture methods. If looking at pin tests results, deviations still exist; but seems smaller. In Table 5, the avg. shear stress of standard CNC machined OC is about 89% than that of mass production OC. Even after optimization, it only increases 3% if comparing with standard mass production OC.

Table 5: Results of Ring strength tests

No. of specimen	Sample Type	Avg. Force (kN/kN)	Delta Δ (%)
P01 ~ P04	std. ring	1	-
S01 ~ S03	CNC std. ring	0.732	-26.8%
O04 ~ O06	CNC optimized ring	0.877	-12.3%

Table 6: Results of Pin's shear tests

No. of specimen	Sample Type	Avg. Force (kN/kN)	Delta Δ (%)
M01 ~ M04	std. pin	1	-
C01 ~ C03	CNC std. pin	0.887	-11.3%
C04 ~ C06	CNC optimized pin	1.030	+3%

Table 7: Comparison of std. OC and optimized OC

Pin	Avg. Force (kN/kN)	Improvement (%)
CNC std. Ring	0.732	14.5%
CNC optimized Ring	0.877	
CNC std. Pin	0.887	14.3%
CNC optimized Pin	1.03	

Nevertheless, if only comparing the results of CNC machined samples, it is obvious that the optimization is effective. In Table 7, there are 14.5% and 14.3% strength increments on ring and pin. Moreover, these results are well aligned with 18.4% and 12.9% Von Mises stress decrease in simulation.

3.3 Correlation between numerical simulation and experimental examination

If the experiments help research engineers to validate the FEA results of an optimized model and let them know that there will be some deviations when the samples are manufactured by different surface treatment methods, then the correlation analysis will help to complete the quantitative analysis for the factors that generated the deviations and corresponding weights. Thus, in this paper, correlation analysis contains two aspects. The first one is to compare the relative design improvements, which are obtained from numerical simulation and experiment examination by using standard OC and optimized OC. In this way, engineers can know whether current approaches, such as a simplified OC 3D model, material properties, load application method and their values are correct or not. The second target is to learn the difference between two different machining methods, which will help engineers to understand how to estimate the influence weights of the factors that cause the deviations in experimental tests. In addition, there might be more benefit in further investigations.

As discussed in section 3.2, FEA results align with test results within about <10% error. Therefore, it can be said that the simplified 3D model, material properties, load application method, and, FEA solution settings can be implemented in other OC design or optimization tasks.

Although the optimization has been validated through tests, there is still an obvious deviation between mass production OC and CNC machined OC. Thus, understanding how the gap is generated and closing it by giving corresponding weights accurately become an interesting work. However, before giving the weights, knowing why mass production parts have better strength performance is more important. Except the minor difference in dimension for example, the variance of tolerance and errors in the tests system, the key difference between two samples is the process. Unlike CNC machined parts, before delivery, mass production OC are treated by two significant surface treatment methods: aging and shooting. Aging is to heat the casting parts to certain temperature and then to keep them for a certain period in order to achieve a high tensile strength, or good plastic/ductility performance. Meanwhile, shooting, as another important treatment method, can introduce very good finish to final components. More, they also increase OC tensile and fatigue stress capacity by conducting high compressive residual stress on the surfaces (Björn Aurén, Guocai Chai. 2002).

3.4 Inspection of two surface treatments

According to preliminary study, since the minor differences and system errors exist in all test samples, the influences of these factors become normal, or can be considered as a constant value. However, the influence of two surface treatments, aging and shooting—or maybe three factors if considering their interaction effects, are variable. For this reason, a two-level factorial DOE test has been conducted in Minitab for the investigation. Thanks to this test, several interesting questions, such as which factor (or factors) play(s) a significant role in strength improvement, and whether the two factors are independent or interactives can be confirmed.

Aging and shooting are assigned as two discrete factors while the samples' breakage forces are set as the response in a four replicates DOE tests. According to the tests plan, four groups of samples are implemented, including standard samples with full treatments, samples without any treatments, samples only with aging and only with shooting. For each group, four pcs samples (pin and ring) are prepared. All samples are tested until broken, then, corresponding forces are recorded for factorial design analysis.

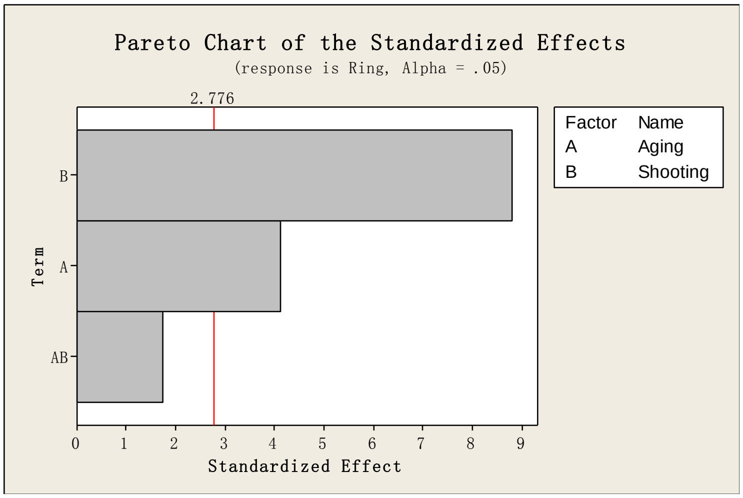

Figure 10: Pareto chart of ring

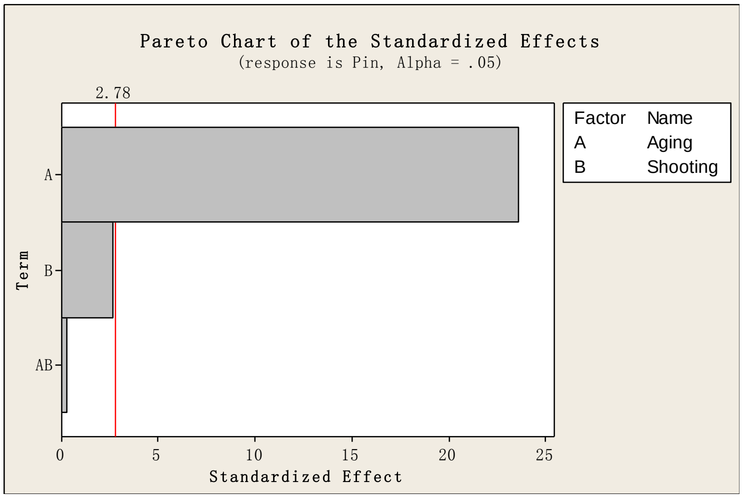

Figure 11: Pareto chart on pin

Figure 10 and Figure 11 show the Pareto charts of two tests. It is obvious that in Figure 10 that both aging and shooting are significant factors to ring's strength, while the interaction effect is not. However, in Figure 11, only aging is the key factor. Meanwhile, shooting and the interaction impacts become less important factors. Since the interactive influence is not a significant factor in two charts, aging and shooting, can be considered as independent factors.

The data, which are used in influence weights analysis, are taken from DOE tests. Here, test results are still normalized using as denominator value of average results obtained from mass production parts. Now, it is more easier to understand how the gaps are generated in section 3. Take the ring's results as an example. As discussed in section 3.2, a big gap (26.8% ring strength deviation) is found between mass production parts and CNC machined parts. Then, in Table 8, Row 2, after removing all surface treatments, the ring's strength will drop about 23%. Or, it can be said that ring's strength can increase at least 20~25% if proper surface treatments can be implemented in OC production. Then, a further analysis shows that if only one surface treatment method is introduced into mass production, the increments of corresponding strength is +5% for aging and +19% for shooting, which aligns with the outputs in two-level factorial DOE tests that only aging and shooting are significant factors for ring's strength. If looking the pin's strength, there are similar results. The difference between treatment parts and non-treatment parts is 10%, which aligns with Table 6 that pin's strength -11.3% on CNC machined parts. If introducing the aging process in production, there will be about 8% improvement. Although shooting also donates 2%, its influence is very limited. Now, the influence weight becomes clear that current aging treatment can bring +5% in ring strength and +8% in pin strength, while shooting can contribute +19% in ring strength and +2% in pin strength. If taking system error (about 5~10%) into account, there will be a slight variance for the weight factors.

Table 8: Influence weight analysis

Code of specimen	**Note**	**Rings avg. Broken Force (kN/kN)**	**Delta Δ (%)**	**Pins avg. Broken Force (kN/kN)**	**Delta Δ (%)**
P01 ~ P04	Full treatments	1	-	1	-
1# ~ 4#	w/o treatment	0.77	-23%	0.90	-10%
5# ~ 8#	Aging only	0.82	-18%	0.98	-2%
9# ~ 12#	Shooting only	0.95	-5%	0.92	-8%

4. STRENGTH PREDICTION MODEL AND VALIDATION TESTS

According to traditional products development procedure, research engineers cannot validate a new design until it is manufactured and passes enough qualification tests. For example, the development of an OC. First, qualification tests are required to be conducted on mass production OC or at least die made OC, which means engineers have to wait at least for 8-10 weeks to have final parts after design frozen. Second, the qualification tests, such as performance, vibration and critical life tests mean high fix expense and long test durations. Third, if there are any failures during the qualification tests phase, unfortunately, engineers must go back to step 1 and step 2. This procedure is very common in R&D; however, under the background of less expense, shorten new product launch time and obtain more achievements; current product development procedure becomes a kind of waste. Thus, to develop a model, which can be used for new component performance prediction before its manufacturing or help to shrink the lead-time for new product validation becomes a challenge and meaningful task.

4.1 Strength prediction

Based on the results in section 3 and section 4, the prediction model for mass production OC stress σ_m can be given by:

$$\sigma_m = \sigma_c * (1 + \delta\%) * (1 \pm C\%) \tag{1}$$

Where σ_c is max tensile stress which can be tested via CNC machined samples, $\delta\%$ represents the overall impact weight of two significant surface treatment methods, which includes two parts:

$$\delta\% = \alpha_a\% + \beta_s\% \tag{2}$$

where $\alpha_a\%$ and $\beta_s\%$ are the corresponding influence weights of aging and shooting. Once the process parameters are changed—for example, temperature or time, there will be some variance in two parameters. In this paper, two parameters are valued as α_a=5% and β_s=18% according to test results, so $\delta\%$ equals 23%. $C\%$ can be regarded as a sum of all system errors, a constant value, which is in a result of the minor differences in samples dimension, tests system, etc. In the view of previous analysis, C is assigned as $\pm 10\%$.

The prediction model for mass production OC pin's stress τ_m can be given by:

$$\tau_m = \tau_c * (1 + \mu\%) * (1 \pm C\%) \tag{3}$$

Where τ_c is max shear stress that is tested via CNC machined samples, $\mu\%$ is the influence weight of surface treatment. Be different with tensile stress, only aging is the significant factor for shear stress, while shooting and interaction effect are not. Thus, according to section 3.4 results, μ equals 8%. The last term $C\%$ represent system errors which have the same value as equation (1).

According to the prediction model, new OC tensile strength and pin's shear strength will increase to 1.15MPa/MPa and 1.16MPa/MPa with 5% tolerance.

4.2 Prediction of optimized OC and test validation

Some optimized OCs, which are same as the one shown in Figure 12, are made according to standard mass production process. Then, two kinds of tests are conducted for design validation. In the strength tests, five pcs optimized OCs are tested. Prediction results and test results are compared in Table 9. According to the prediction model, the optimized OC's max tensile and max shear stress will increase to 1.1MPa/MPa to 1.2MPa/MPa. Physical tests show that that ring's maximum tensile strength increase to 1.2MPa/MPa while pin's max shear strength is up 1.17MPa/MPa, which are in the range of prediction.

Figure 12: Optimized OC with full treatments

Figure 13: Slug tests

Table 9: Results of strength validation test

Group of samples	Note	Tensile Strength (MPa/MPa)	Shear Strength (MPa/MPa)
I	Current design (Full treatments, 3pcs)	1	1
II	Optimized design (Prediction)	1.08~1.21	1.11~1.20
III	Optimized design (Full treatments, 5pcs)	1.20	1.17

Beside strength tests, five pcs compressors are constructed with optimized OC and subjected to slug tests (see Figure 13). Final results indicate that after optimization, the new OC's slug performance will increase at least 50% than current OC.

5. CONCLUSIONS

- The approach which is implemented in the investigation and optimization of X compressor failure OC is proved to be feasible. Results of FEA, prediction results and physical tests results are aligned well. Although there are some deviations, the gaps are under control. Furthermore, both the factors and gaps can be identified and closed by qualitative and quantitative analysis.
- Several groups of tests prove that aging and shooting are two significant surface treatment methods, and plays a significant role in OC production. In future design activities, beyond adding more materials to obtain stronger components, engineers should consider to introduce more useful surface treatment methods to achieve a robust design.
- A prediction model has been given and validated by strength and slug tests. By using this method, both the new OC product development lead-time and fix expense can be controlled under a very small level. Furthermore, a similar model can be developed and implemented in other components design or optimization works.

NOMENCLATURE

The nomenclature should be located at the end of the text using the following format:

σ	Tensile stress	(MPa)
τ	Shear Force	(F)
δ	Influence weight	(%)
μ	Weight of process (shear)	(%)
C	System error	

Subscript

m	Manufacture parts
c	CNC machined parts
f	FEA result
a	Aging
s	Shooting

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ACKNOWLEDGMENT

The authors would like to thank Kui Su, Xiaokun Ji, Dandan Liu and Pengfei Zhao for the special help in this study.