Study on the characteristics of the materials and manufacturing quality to shrapnel-type couplings properties

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Abstract. With the development and application for the ultra-precision machinery industries and smart machinery have become prosperous. The precision transmission sub-system is an important part of the precision machinery equipment and smart machinery industries. Then shrapnel-type coupling is an important part of the precision transmission system. In the shrapnel-type couplings with high precision, high reliability, and high efficiency. The design of shrapnel-type couplings needs to correct and improved in the manufacturing with very high-precision inspection equipment, and expert measurement technology. The high quality of shrapnel-type couplings, materials and manufacturing qualities are the main factor for high precision, high reliability, and high efficiency. This paper will be a depth study of the body materials and manufacturing qualities of shrapnel-type couplings. The inner hole contact surfaces of the shrapnel-type couplings to connect between each other connecter tested the properties of the coupling via toque-torque angle testing equipment with changing the shrapnel-type couplings body materials and manufacturing different roughness of inner hole. The key characteristics that affect the torsional rigidity and failure torque of the coupling grasped are found out using the self-developed toque-twist angle testing machine. The body of the shrapnel-type couplings made with 7075 aluminium alloy and 6061 aluminium alloy. Through experiments, we can understand the influence of different materials bodies on the torsional rigidity and failure moment of the shrapnel-type couplings. From experimental results, that 7075 aluminium alloy is better than 6061 aluminium alloy of torsional rigidity or failure moment. As the inner hole surface roughness of the shrapnel-type couplings smaller has a high failure torque of coupling.

1. Introduction
With the demand on the precision transmission sub-system is an important part of the precision machinery equipment and smart machinery industries, the shrapnel-type coupling is a critical part of the precision transmission system. The aluminum alloy body gives its high strength and corrosion resistance. Importantly, the centerpiece has a single flexible disk acts as a vibration damper to absorb impact, this design can enhance the torsional rigidity of the shrapnel-type couplings. In angular deviation circumstances, couplings will calibrate in between the shaft, shrapnel-type couplings have excellent performance in high-speed conditions. On the other hand, the design of shrapnel-type couplings needs to correct and improved in manufacturing with very high-precision inspection equipment, and expert measurement technology.

Belloli et al. [1] investigated the Messina bridge structural analysis review the structural strength’s dynamic response of the embarkation and the ambient vibration, analyzing the natural frequency of the
structure to prevent structural resonance directed to massive hazards. Reddy and Sekhar [2] utilizing the Fourier analysis method to calculating acceleration and twisting force, investigate the damage condition of the axis and bearing using dynamic response analysis all with time and displacement, Therefore, the natural frequency of the structure and number can early detect before the equipment un-normal situation, this information can maintenance machine and reducing manufacture cost. The Nabeya Bi-tech Kaisha America LLC [3] is a well-known global manufacturer of design couplings, the company researches the dynamic response of the elastic couplings in vibrant conditions. Although the elastic couplings have a higher rigidity, the results show the couplings can’t provide enough damping capability which may cause the resonance of the system. The Ruland manufacturing co., Inc. [4] used an encoder and test the damage of the couplings to prevent future failure, this paper suggests first changing the back-back angular contact bearing to face-face installation can optimize the overall structure design and enhance strength support. Second, replacing the elastic couplings made of 2024 aluminum alloy with the encoder couplings made of 7075 aluminum alloy can provide a much higher flexural intensity also extend the longevity of the couplings. Perez et al. [5] research the flexible shaft couplings primarily made of aluminum alloy. This paper used the ultra-cryogenic treatment (-196°C) in-process to control the inside retained austenite, also improve the dimensional stability of the couplings. Hmida et al. [6] used the model of Nelson and Crandall to analyze the rigid couplings and elastic couplings, discussed the influence of using elastic couplings, and the correlation of the natural frequencies for the couplings. Sawalhi et al. [7] measured the couplings bending stiffness and used a vibration test rig to present the simulation model, the experiment shows the axial speed of the acceleration vibration signal is increases lower and higher harmonics. Similar behavior on low-frequency modulation was reported in the measured signal. Druker et al. [8] research the manufacturing process for the coupling, investigated the weldability and the formability of the metal sheet. Welding can influence the shape memory properties of the material and this method will recover 83% diametrical expansion of the coupling.

The rotating-blade couplings with longitudinally ribbed turbulators are commonly used in four-wheel-drive vehicles, Yeh et al. [9] research the thermal characteristics of the couplings. With longitudinal rib, roughened walls can prevent temperature increases, extend the lifespan of the couplings, and protect the four-wheel-drive system. Guo et al. [10] studied the failure analyses of the DY08 aluminum alloy elastic couplings by tested with different analyses, research found out the fatigue fracture failure was caused by a machining defect on the inside surface of the coupling, which was the reason that caused the crack generation. Wu et al.[11] research the elastic couplings in misalignment condition used the numerical simulation, results indicated in certain situations the vibration response of rotor system might be linear, different variety and amplitude can affect vibrations by reaction moment.

The aforementioned studies of couplings from a performance standpoint were mostly surrounded the damping capability and analysis of the hazard. From a materials science perspective, different material properties can influence the performance of the couplings. Therefore, this paper research the influence of different materials bodies on the torsional rigidity and failure moment of the shrapnel-type couplings.

2. Experimental theory

2.1. Torsional rigidity
Torsional stiffness is the differential of torque to twist angle, which can be expressed as an equation (1).

\[ K(\theta) = \frac{dT}{d\theta} \]  

In equation (1), T and K represent the torsional moment and the torsional rigidity, respectively. It is important when K is linear the K is constant. When the torque and the twist angle are linear, K is a constant. But when the relation of torsion and the twist angle are nonlinear, K is the differential of the torsion function to the twist angle.
2.2. **Multiple regression**

In this paper, multiple regression is used to discuss the relationship between the dependent and the multiple independent variables or predictor variables.

\[
y = a_n x_i^n + a_{n-1} x_i^{n-1} + \cdots + a x_i + a_0, \ i=A, B, C, \ldots
\]

Equation (2), \( y \) is the dependent variable, \( x \) is the independent variable. \( A, B, C, \ldots \) is variable factors, \( i \) is the number of variable factors. \( n \) is the power of regression.

2.3. **Coefficient of determination**

This paper used the coefficient of determination to analyze the curve-fitting of the equation of multiple regression.

\[
\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i
\]

In the above equation, \( \bar{y} \) is the observed data and \( n \) values marked \( y_1, \ldots, y_n \).

The variability of the data can be calculated from \( SS_{tot} \) and \( SS_{res} \).

\[
SS_{tot} = \sum_i \left( y_i - \bar{y} \right)^2
\]

Total sum of squares, \( SS_{tot} \), is related to the total variation of the relationship between twist angle and torque.

\[
SS_{res} = \sum_i \left( y_i - f_i \right)^2 = \sum_i e_i^2
\]

where \( SS_{res} \) is the residual sum of squares, related to the unexplained variation.

\[
R^2 = 1 - \frac{SS_{res}}{SS_{tot}}
\]

In equation (5) \( R^2 \) is a statistic to show information about the goodness of fit for the model. Therefore, the coefficient of determination is measure the fit for the prediction data and the test data. The \( R^2 \) variable is in between 0–1, when its value is 1 indicated the unexplained variation approaching to zero. Therefore, the multiple regression equation is very reliable.

2.4. **Coefficient of variation**

\[
C.V. = \frac{\sigma}{\mu}
\]

To represent the repeatability of the test sample results, in equation (7) standard deviation \( \sigma \) and average value \( \mu \) are calculated to coefficient of variation (C.V.).

3. **Experiment device and sample**

3.1. **The shrapnel-type coupling**

The shrapnel-type coupling produced by GMT GLOBAL INC. was used in this study. Figure 1 presents the drawing and dimension of this coupling. The main body is made of A7075 duralumin and thought ultra-cryogenic treatment in -196°C temperature. In this case, it can improve quality, durability, and increase organizational uniformity of the coupling. Its securing screw is use hexagon socket bolt; the shrapnel part is made of SUS301 stainless steel; the insert pin is made of the SUS303 stainless steel. Used the method of securing to tightening the coupling, the mandrel is secure in place because screw-
in the bolts can decrease the shrink slit. This method is easy to attach, teardown, and reduces the damage of the axle mandrel.

3.2. The mandrel
Figure 2 shows the mandrel used for this study. It was designed to simulate the drive end and the driven end for coupling. Material is SCM 440 alloy steel, with HRC 58–62, and the surface roughness average around 0.3μm.

![Figure 1. The structure of the shrapnel-type coupling.](image1)

![Figure 2. The photograph of the Mandrel.](image2)

3.3. The main body of the aluminum alloy

3.3.1. 6061 aluminum alloy. The 6061 aluminum alloy is great on structural strength and corrosion resistivity; it contents aluminum (Al), magnesium (Mg), and silicon (Si) elements. With a density of 2.71 g/cm³ and tensile strength of around 125 MPa. T6 temper aluminum had through precipitation hardening processing, heat treatment, cool down, and artificial age-hardening, etc. This alloy will have 2 to 5 times the strength and tensile strength will reach 310 MPa. This alloy is primarily used on cars, boats, and aircraft material because it has excellent welding capability, also costs lower than the 7000 series aluminum alloy.

3.3.2. 7075 aluminum alloy. The 7075 aluminum alloy has more intensity, machinability, tension strength, and better scale stability, it contains Aluminum (Al), Zinc (Zn), Magnesium (Mg), Silicon (Si), and Copper (Cu) elements. With a density of 2.71g/cm³ and tensile strength of around 276 MPa. The weld ability of this aluminum is not ideal because the alloy contained carbon elements and has less corrosion resistance, this alloy is commonly used in military and aviation. In this paper select A7075 aluminum alloy went through T6 Heat treatment for the test sample, its tensile strength will reach 538MPa.

3.4. The coupling torsion tester
Figure 3 shows the coupling horizontal torsion tester designed for the special fixture, apply to the pore size of couplings range from 2mm to 30mm diameter. With angle encoder and torque meter to calculate the maximum torsion, also investigate the relationship between the angle of twist and failure torque. The main purpose of testing couplings is to demonstrate the relationship between the torsional of the threaded fastener and the axial force, data points can output to graph then export to the monitor display, this paper used the information for the follow-up analysis.

![Figure 3. The photograph of the coupling horizontal torsion tester.](image3)
3.5. Automatic image measuring instrument
Auto-4030 automatic image measuring instrument is used produced by JIMDANDY TECHNOLOGY Co., Ltd. To improve the machining accuracy of the product, the instrument inspects the surface condition using a high magnification lens to draw a geometric figure. Also, combine with AutoCAD to input the part drawing and the system will improve accuracy up to 0.1 μm, it can fully automatically inspect screening to reduce labor cost and inspection time.

3.6. Torque wrench
A 120QLK torque wrench, produced by Nakamura Mfg. Co., Ltd, was used in this study. The pre-set torque wrench use range from 3.92~11.76 N-m, torque wrench applied to the locking torque of the spindle set screws.

3.7. Surface roughness profile tester
A surface roughness profile tester FORMTRACER SV-C4500 SERIES, produced by Mitutoyo Co., was used in this research. It can measure the surface geometry and calculate the surface roughness of the object. The specification of the Z1 contour measurement range is 60mm, the Z1 contour resolution is 0.02 μm, the roughness of the Z1 measurement range is 800/80/8 μm, the roughness of the Z1 resolution is 0.1 μ maximum, and operation force of the probe is 0.75mN.

3.8. Multi-function adjustable plinths
The paper used the multi-function adjustable plinths to adjust mandrel angle, collocation with the platform of the testing machine to adjust the radial direction and axial displacement of the coupling.

4. Results and discussion

4.1. The influence on the coupling torsional behavior of the material
Consider the application used of the material is very important. The paper chooses two common industry-used 7075 aluminum alloy and the 6061 aluminum alloy. The 6061 aluminum alloy had a lower cost and great corrosion resistivity can easily preservation; the 7075 aluminum alloy had the highest strength in the aluminum alloy series but it was more expensive to manufacturing and difficult to store. Shrapnel-type couplings mainly used material are the above two aluminum alloy and stainless steel. To demonstrate the material characteristics of the two aluminum alloys, this paper will test the couplings by choosing two different materials and research the influences on the product performance.

This paper includes the hardness test of the two aluminum alloys, the result of Figure 4 and Table 1 indicate the 7075 aluminum alloy hardness value is HRB 91.5 and the 6061 aluminum alloy value is HRB 65. The hardness value on both alloys had an obvious difference, indicate the 7000 series aluminum alloy has a better strength capability.

Figure 5 is the angle of twist and failure torque of the 7075 aluminum alloy test sample, using a 6 N·m locking spindle screw to secure the coupling. The maximum angle of twist for the test sample is 6.458×10⁻⁴ rad. Table 3 shows the failure torque value of test sample No.1 is 28.332 N·m, test sample No.2 is 28.592 N·m, test sample No.3 is 28.369 N·m, and three sample failure torque average around 28.431 N·m. Table 2 shows both the coefficient of determination approaching 1, Table 3 coefficient of variation is very similar indicated great reliability of the 7075 aluminum alloy sample.

Figure 6 is the angle of twist and failure torque of the 6061 aluminum alloy test sample, using a 6 N·m locking spindle screw to secure the coupling. The maximum angle of twist for the test sample is 4.189×10⁻⁴ rad. Table 5 shows the failure torque value of test sample No.1 is 18.774 N·m, test sample No.2 is 19.228 N·m, test sample No.3 is 19.134 N·m, and three sample failure torque average around 19.045 N·m. Table 4 shows both the coefficient of determination approaching 1, the coefficient of variation is identical and proves the great reliability of the 6061 aluminum alloy sample. In Table 5 are the failure torque data of the 6061 aluminum alloy.
Figure 4. Aluminum alloy hardness test.

Figure 5. The relationship between the angle of twist and failure torque of the 7075 aluminum alloy coupling.

Table 1. Different aluminum alloy hardness test (HRB).

| aluminum alloy | 7075 | 6061 |
|----------------|------|------|
| Sample 1       | 91.1 | 64.9 |
| Sample 2       | 91.4 | 65.3 |
| Sample 3       | 91.6 | 64.6 |
| Sample 4       | 91.4 | 65.1 |
| Sample 5       | 91.8 | 65.3 |
| Average        | 91.5 | 65.0 |
| C.V. (%)       | 0.3  | 0.5  |

Table 2. The Torsional rigidity calculation and the coefficient of determination.

| If torque greater than 14.34 Nm | If torque less than or equal to 14.34 Nm |
|---------------------------------|------------------------------------------|
| \( K \left( \frac{N \cdot m}{rad} \right) = -4.86 \times 10^8 \theta (rad) + 5.6151 \times 10^5 \) | \( K \left( \frac{N \cdot m}{rad} \right) = 58348 \) |
| \( R^2 = 0.999 \) | \( R^2 = 0.993 \) |

Table 3. The failure torque data of the 7075 aluminum alloy.

| Sample | Failure torque (N/m) |
|--------|----------------------|
| 1      | 28.332               |
| 2      | 28.592               |
| 3      | 28.369               |
| Average| 28.431               |
| C.V. (%) | 0.494               |

Table 4. The Torsional rigidity calculation and the coefficient of determination.

| If torque greater than 10.94 Nm | If torque less than or equal to 10.94 Nm |
|---------------------------------|------------------------------------------|
| \( K \left( \frac{N \cdot m}{rad} \right) = -9.440 \times 10^7 \theta (rad) + 6.268 \times 10^5 \) | \( K \left( \frac{N \cdot m}{rad} \right) = 56306 \) |
| \( R^2 = 0.999 \) | \( R^2 = 0.993 \) |
Table 5. The failure torque data of the 6061 aluminum alloy.

| Sample | Failure torque (N\(\cdot\)m) |
|--------|-----------------------------|
| 1      | 18.774                      |
| 2      | 19.228                      |
| 3      | 19.134                      |
| Average| 19.045                      |
| C.V. (%)| 1.256                      |

Figure 7 shows the coupling made of 7075 aluminum alloy has a failure torque average of 28.431 N\(\cdot\)m, it is more superior to the 6061 aluminum alloy average of 19.045 N\(\cdot\)m. Both failure torque difference around 9.39 N\(\cdot\)m. In conjunction with the couplings made of 6061 aluminum alloy has an angle of twist of 0.024°. Table 6 indicated the torsional rigidity of the 7075 aluminum alloy is higher than the 6061 aluminum alloy.

4.2. The inner hole surface roughness influence the torsional behavior of the coupling

This chapter discusses the inner hole surface roughness of the coupling. Studies the difference in the clamping effect by investigating two different surface roughness samples in Figure 8, it is the average surface roughness of the drive shaft and the driven shaft of the sample A and B before and after the test. Figure 9 and Figure 10 are the micrographs of the surface roughness after the test. The more detailed surface roughness data of the test sample A and B are shown in Table 7.

Table 7. The surface roughness of the test sample (\(\mu\)m).

| Group | Sample | Location   | Before | After |
|-------|--------|------------|--------|-------|
| A     | Sample 1| Driving shaft | 0.103  | 0.108 |
|       | Sample 2| Driving shaft | 0.111  | 0.101 |
|       | Sample 2| Driven shaft  | 0.137  | 0.206 |
Table 8. Torsional rigidity data of the group A.

| Sample | Failure torque (Nm) |
|--------|---------------------|
| 1      | 16.442              |
| 2      | 16.555              |
| 3      | 16.791              |
| Average| 16.596              |
| C.V.(%)| 1.072               |

Figure 8. Average surface roughness of the test sample.  
Figure 9. The surface roughness of the sample A.  
Figure 10. The surface roughness of the sample B.

Figure 11 is the angle of twist and failure torque of group A. The maximum angle of twist for this group is $2.967 \times 10^{-4}$ rad. Table 8 shows the failure torque value of group A. No.1 is 16.442 N·m, test sample No.2 is 16.555 N·m, test sample No.3 is 16.791 N·m, and three sample failure torque average around 16.596 N·m.

Figure 12 is the angle of twist and failure torque of group B. The maximum angle of twist for this group is $2.269 \times 10^{-4}$ rad. Table 9 shows the failure torque value of group B. No.1 is 13.221 N·m, test sample No.2 is 13.418 N·m, test sample No.3 is 13.042 N·m, and three sample failure torque average around 13.227 N·m.
Figure 11. The relationship between the angle of twist and failure torque of the group A.

Table 9. Failure torque data of the group B.

| Sample | Failure torque (Nm) |
|--------|---------------------|
| 1      | 13.221              |
| 2      | 13.418              |
| 3      | 13.042              |
| Average| 13.227              |
| C.V. (%)| 1.420               |

Figure 12. The relationship between the angle of twist and failure torque of the group B.

Figure 13 shows the difference between two different surface roughness, the sample A failure torque is 16.59 N.m and the sample B failure torque is 13.22 N.m. Finer surface finishing can provide better clamping force and the difference between the two is 3.37 N.m; choose the angle of twist on the test sample B is 2.27×10^{-4} rad to calculate the torsional rigidity. The Table 10 is shows Failure torque data of the groups.

Figure 13. The relationship between the angle of twist and failure torque of the coupling inner hole surface roughness.

The chapter contains data and information to show the importance of the quality of the inner hole surface. Through finish machining to achieve the optimal surface smoothness and have a larger contact surface with the shaft and the mandrel, enhance the clamping force between the inner hole and the mandrel.

Table 10. Failure torque data of the group.

| Group | Angle of twist (rad) | Failure torque (Nm) |
|-------|----------------------|---------------------|
| A     | 2.967×10^{-4}       | 16.596              |
| B     | 2.268×10^{-4}       | 13.227              |
5. Conclusion
Industry commonly used 6061 aluminum alloy and 7075 aluminum alloy because it had a significant impact on the performance standpoint of the coupling. From experimental results, 7075 aluminum alloy in torsion rigidity and failure torque category is better than 6061 aluminum alloy but the manufacturing cost is more expensive. Therefore, consider the material needs to base on the cost-performance ratio. The coupling inner surface roughness closer to the mandrel surface roughness avenger around 0.3μm was better, the inner surface roughness of the test sample was 0.101 μm. Failure torque was greater than the test sample coupling had an inner surface roughness of 0.101 μm, because a larger surface contact with the shaft and the mandrel to enhances the clamping force.

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