Response of shrink fitted assemblies to the dynamic torsion

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Abstract. Product design is mostly centered around design of different contact pairs. Among contact pairs, interference fit pair is widely used. Design of interference fits, involves not only dimensional interference, but also condition of interface between mating surfaces. Factors such as texture of interface, hardness of interface material and also physical properties of contacting materials influence the functional characteristics of interference shrink fitted assemblies. In actual practice most of such joints are subjected to dynamic loading. Data on torsion response is only limited. So that, detailed investigation on the influence of dimensional interference, contact length and interfacial properties (electroless nickel coating) on torsion capacity of interference fitted assemblies has been carried out. The response of interference fitted assemblies to dynamic torsion load has been evaluated, using L-9 Orthogonal array of experimental conditions to bring down the number of experiments. The results are analysed using analysis of variance (ANOVA) to find out the individual effects of parameter on dynamic loading. The Torque load carrying capacity of the shrink fitted assemblies is improved by electroless nickel coating. This could be attributed to the increase in actual contact area and tenacity of Nickel plating and presence of strong molecular bonds between the mating parts chosen for the assemblies. But the selection of interference, contact length and hardness of mating parts play a vital role in deciding the performance of these joints. The results clearly indicate that the dynamic performance of the assemblies could be improved by suitably selecting the materials keeping in mind the above factors. It is also found from the ANOVA results that the assemblies with (hardness) coated interlayer performed better. Interference and contact length also has influence on the strength but in this case their influence is not very significant. An expression is obtained using regression analysis, which gives relationship between the parameters. A result obtained from regression analysis is closer to the experimental values.

Key words: Shrink fitted assembly, Electroless nickel coating, L-9 Orthogonal array and ANOVA analysis.

1. Introduction
Interference fitted joints are found to be suitable in mechanical assemblies as they ensure good load carrying capacity as a result of an intimate contact between the mating parts. The load carrying capacity depends on the physical dimensions, the material characteristics and surface conditions of mating parts. The coefficient of friction, a factor influencing the interface condition, is influenced by many factors such as the roundness, straightness of the shaft and bore and also their surface roughness. The method of assembly plays an important role in deciding the strength of interference fitted assemblies.

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The effect of the assembly techniques on the qualities of interference fitted assemblies were assessed by Andreev.et.al. The study was carried out by investigating the metallography of the contact zone and the physical and mechanical conditions of the mating surfaces. The method of heating and cooling was suggested by fitting a thin walled bush to a bearing house. The results of experiments conducted to investigate the shrink fit assembly of wheel pair for a narrow gauge diesel locomotive showed the supremacy of shrink fit assembly method. A method has been suggested by Andreev.et.al for dismantling of interference fit joints during the repair of machinery and rectification of errors committed during assembly. A procedure was developed by Andreev.et.al for the design of interference fitted joint in which a provision has been made to minimize the material required ensuring working capacity of the assembly at higher and varying temperature. An attempt was made by Berniker to calculate the change in strength when the interference fitted assemblies are subjected to rotation. Oxidation is another effective method of increasing the load carrying capacity of tapered interference fit joints and is reported by Bobrovnikov, et.al in their work. Firsov,et.al have developed a calculation procedure to select the optimum interferences for large press fit joints. The strength of the shaft journals carrying antifriction bearing races is increased by plating and controlling the hardness of plating. The strength and the breakdown mechanism of press fitted joints under cyclic loading were investigated by Kobrin. Ramachandran and Radhakrishman have reported an increase in load carrying capacity with an improvement in finish of mating surfaces in general. Surface strengthening is another effective method of increasing the axial load carrying capacity of shrink fitted assemblies and is reported by Ramamoorthy, et.,al.,in their work. Sawin concluded that the interference fitted assemblies with polished and ground surfaces can carry higher loads than those with rough turned surfaces. The influence of the amount of interference on the fatigue strength was also studied by Balatkii and Mclekhov and showed that an increase in interference decreases the endurance of shafts. It has been reported that adhesion or mechanical bonding and diffusion between mating parts take place at elevated temperature in case of heat-treated assemblies. The use of soft coatings like zinc or copper is also recommended by Vinogradov in press fit joints. Soft coating protects the surface against break-down. The joint was subjected to cyclic loading with increasing amplitudes of flexural stress till the failure of the joint.

From the above observations by various researchers on the strength of interference fitted assemblies, it is clear that mostly work has been carried out on axial loosening strength of shrink fitted assemblies and available literature on torque bearing capacity is limited. Hence, the present study is concerned with torque capacity of interference fit assembly and subjected to different interfacial condition.

2. Objectives
In this study the mechanism of strength improvement combined and individual effects of physical parameters and plating of shrink fitted assemblies are analysed using L-9 orthogonal array and ANOVA analysis. Based on the experimental data, an empirical model for estimating the strength of shrink fitted assemblies under (torque) dynamic loading is developed using regression analysis.

3. Method of assembly

3.1. Shrink fit
Instead of heating the female part (hub) like in expansion fit, this method involves cooling the male part (shaft) so that it fits the assembly is allowed to reach the room temperature. The cooling temperature for the shaft to have zero interference can be obtained from the equation.

\[
t' + t_0 = \frac{\Delta}{d} \frac{1}{\alpha_1 \cdot 1000}
\]
t’ - Cooling temperature, °C

\( t_0 \) - Working environment, °C

\( \Delta \) - Interference of the joint, µm

\( d \) - Diameter of the joint, mm

\( \alpha_1 \) - Linear coefficient of contraction for the shaft material, µm/m/°C

The cooling temperature can be attained by using dry ice (-80°C), liquid nitrogen (-196°C) or liquid oxygen (-184°C).

4. L-9 Orthogonal array

L-9 Orthogonal array is known as a Taguchi’s orthogonal array. In this study, the total numbers of experiments were selected based on the number of parameters that influence the load carrying capacity of interference fitted joints and also the number of levels of variation for each of these parameters. Three parameters were identified and three level variations were used. Normally 3\(^3\) experiments are required where the setting of various parameters (required to be studied) is changed from one experiment to another. Conducting matrix experiments using special matrices, called orthogonal array, allows the effects of several parameters to be determined efficiently using 9 experiments and is an important technique in robust-design. It gives more reliable estimates of factor effects with less number of experiments when compared to the traditional methods.

| Test case | Parameter-1 | Parameter-2 | Parameter-3 |
|-----------|-------------|-------------|-------------|
| 1         | 1           | 1           | 1           |
| 2         | 1           | 2           | 2           |
| 3         | 1           | 3           | 3           |
| 4         | 2           | 1           | 2           |
| 5         | 2           | 2           | 3           |
| 6         | 2           | 3           | 1           |
| 7         | 3           | 1           | 3           |
| 8         | 3           | 2           | 1           |
| 9         | 3           | 3           | 2           |

The design of experiments for L-9 orthogonal array is shown in table-1 and based on this table contact lengths, hardness and interferences are selected for the experiments.

5. Experimental setup

Nine components with different combinations as per the L-9 orthogonal array were selected for experimental purpose and typical test specimen and its dimensions are shown in Figures 1a-1c. The dynamic testing was conducted in an actuator machine (Figure 2) under constant load mode.
Special fixture was fabricated for holding the component in this machine, which is shown in Figure 3. Component is fixed into the fixture and a small arm is fitted on the shaft, which is fixed for the actuator and then 35 kg (constant) dynamic load with a frequency of 1 Hz (cycles per second) is applied. The duration before failure of assemblies under dynamic loading was noted and table 2 gives typical values obtained from experiments.

**Figure 1a.** Typical test Specimen with assembled and dismantled conditions.

**Figure 1b.** General dimensions of bush.

**Figure 1c.** General dimensions of shaft.

Special fixture was fabricated for holding the component in this machine, which is shown in Figure 3. Component is fixed into the fixture and a small arm is fitted on the shaft, which is fixed for the actuator and then 35 kg (constant) dynamic load with a frequency of 1 Hz (cycles per second) is applied. The duration before failure of assemblies under dynamic loading was noted and table 2 gives typical values obtained from experiments.

**Figure 2.** Actuator with strain gauge indicator used for Dynamic load testing.

**Figure 3.** Actuator with proving ring.
5.1. Method of analysis
In the present study, experiments were specially designed and conducted in order to develop an expression
to estimate the strength including all the important factors. For such an estimation two methods are used
and the details are presented in the following sections.

Table 2. Experimental results using Orthogonal Array.

| Test case | Contact length | Interference | Hardness - Hv | No of cycles |
|-----------|----------------|--------------|---------------|--------------|
| 1         | 10             | 17           | 180           | 396          |
| 2         | 10             | 20           | 250           | 450          |
| 3         | 10             | 23           | 420           | 583          |
| 4         | 15             | 17           | 250           | 426          |
| 5         | 15             | 20           | 420           | 522          |
| 6         | 15             | 23           | 180           | 468          |
| 7         | 20             | 17           | 420           | 600          |
| 8         | 20             | 20           | 180           | 438          |
| 9         | 20             | 23           | 250           | 474          |

5.1.1. ANOVA (Analysis of variance). The purpose of the analysis of variance (ANOVA) is to investigate
which design parameters significantly affect the quality characteristic. It can be seen that among the
parameters, hardness of mating interface is the most significant parameter while amount of interference
and contact length exerts more or less similar influence.

Table 3. ANOVA Results.

| source | DF | S     | V     | F     | S'     | ρ     |
|--------|----|-------|-------|-------|--------|-------|
| IF     | 2  | 2664.222 | 1332.111 | 1.4734 | 856.00 | 2.17  |
| Hv     | 2  | 32304.222 | 16152.111 | 17.8652 | 30496.00 | 77.33 |
| CL     | 2  | 2660.222 | 1330.111 | 1.4712 | 852.00 | 2.16  |
| (e)    | 2  | 1808.222 | 904.111 | 1.4712 | 7232.88 | 18.43 |
| Total  | 8  | 39436.88 | 4926.611 |       |        |       |

DF - Factor’s (or error’s) degrees of freedom
S - Factor variation (sum of square)
V - Factor variation, V=S/f (mean square)
F - Factor Variance ratio, F= V/Ve, where Ve is a pooled variance.
S’ - Factor pure variation, S’= S-Ve* f where f is degree of freedom within factors
ρ (rho) - Factor contribution ratio, ρ = S’ / ST 100% where ST is total variation
e - Pooled error
CL - Contact length
IF - Interference
Hv - Vickers’ hardness
From Table 3 and Figure 4, it is seen that if the contact length is considered at level 3, the interference at level 3 and hardness at level 3, the dynamic load carrying capacity of shrink fitted assemblies is maximum.

5.1.2. Estimation of strength using regression analysis. In the present study, regression analysis was used to assess the data and to develop an expression to estimate the strength. The equation obtained by the linear regression analysis is

\[ Y = A_1 + A_2 \text{CL} + A_3 \text{IF} + A_4 \text{Hv} \]  

\[ A_1 = 162.393 \]
\[ A_2 = 2.766 \]
\[ A_3 = 5.722 \]
\[ A_4 = 0.585 \]

\( Y \) - Dynamic-cycles  
\( \text{CL} \) - Contact length  
\( \text{IF} \) - Interference  
\( \text{Hv} \) - Vickers hardness

An expression is obtained by using regression analysis, which gives the relationship between the parameters. Results obtained from regression analysis are shown in Figure 5. It is seen that only for low (minimum level) fit condition there is a good relation i.e. the relation between torque capacity (dynamic – cycles) and fit condition is non-linear. It is also seen in the relatively lower order coefficient for hardness (A4) in the regression expression.
6. Results and discussion
The Torque load carrying capacity of the shrink fitted assemblies is improved by electroless nickel coating. But the selection of interference, contact length and hardness of mating parts play a vital role in deciding the performance of these joints. It was found from the ANOVA results that the assemblies with (hardness) coated interlayer performed better. The reasons for this improved performance are the increase in the actual contact area, hardness, the presence of strong molecular bonds and tenacity of Nickel layer. It was observed that the parameters like hardness, contact length and interference of mating parts, etc., as well influence the dynamic strength of the joint. Interference and contact length also has influence on the strength. But in this case their influence is not very significant. The results clearly indicate that the dynamic performance of the assemblies could be improved by suitably selecting the materials keeping the above factors in mind. An expression is obtained using regression analysis, which gives relationship between the parameters. A result obtained from regression analysis is closer to the experimental values. It was observed that the parameters like hardness, contact length, interference etc. of mating parts influence the dynamic strength of the joint.

7. Conclusion
Shrink fit assemblies with varying interface hardness were subjected to dynamic torque loading. It was found from the ANOVA results that the assemblies with (hardness) coated interlayer performed better. The reasons for this improved performance are the increase in the actual contact area, hardness, the presence of strong molecular bonds and tenacity of Nickel layer. Interference and contact length also has influence on the strength but in this case their influence is not very significant. Based on the experimental results an expression is obtained using regression analysis, which gives relationship between the parameters.

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