Journal of Materials Processing Technology 214 (2014) 2095–2101

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Strength of spline joints assembled by forming

Kenji Hirota[a,*], Kazuhiko Kitamura[b], Yoshihiko Ukai[c], Keiichi Matsunaga[d]

[a] *Department of Materials Science and Engineering, Kyushu Institute of Technology, Kitakyushu, Fukuoka 804-8550, Japan*
[b] *Department of Mechanical Engineering, Nagoya Institute of Technology, Nagoya, Aichi 466-8555, Japan*
[c] *Toyota Motor Corporation, Toyota, Aichi 471-8571, Japan*
[d] *MEG Inc., Anjo, Aichi 446-0052, Japan*

ARTICLE INFO

Article history:
Received 28 June 2013
Received in revised form 20 January 2014
Accepted 2 February 2014
Available online 12 February 2014

Keywords:
Spline joint
Torsional strength
Assembly by forming

ABSTRACT

In this paper, a new assembling method of spline joints that enables tight fitting in a simple manner by allowing slight plastic deformation at the spline teeth was introduced. Experiments were carried out for the spline joints of medium carbon steel varying the overlap zone between the male and the female spline teeth. Axial joining strength was increased with increase in the overlap length due to the residual compressive stress by forming. The joint by the proposed method also showed higher torsional strength than the conventional joint. Improvement in the torsional strength was explained based on the deformation and hardness distribution around the spline teeth. With respect to the shape of overlap zone, better results were obtained when using the specimen having a uniform overlap length along the axial direction.

1. Introduction

Spline-hub connections are reliable mechanical joints for torque transmission and widely applied to automotive parts. Since these joints are mostly subject to cyclic loading, the evaluation of fatigue strength has been a main concern. Shen et al. (2013) developed a plain-fretting fatigue unified prediction model and discussed the plain and fretting fatigue performance of involute spline shaft-hub connection teeth. It is generally said that increase in residual compressive stress at the interface of the joint is effective to improve the fatigue strength. Miyazawa et al. (2011) combined a press fit joint with a spline-joint and demonstrated that the joint proposed showed higher torsional fretting strength than conventional spline-joints. Nigrelli and Pasta (2007) evaluated the residual stress induced around the hole by split-sleeve cold expansion for the purpose of assessment of fatigue life.

Joining by forming is also advantageous for improving the fatigue strength and has various excellent features of no heat influence and resulting thermal deformation, high productivity and joinability of dissimilar materials. Spot joining methods such as clinching and self-piercing riveting are the typical examples and many attempts have been made for the sheet metal parts in which spot welding can not be applied. Abe et al. (2012) reported the possibility of joining high strength steel and aluminum alloy sheets by mechanical clinching.

Joining of a shaft and a disk-like part by forming has also been tried. Kanamaru et al. (1984) created a mechanical shaft-disk connection by forging the disk in such way that the material of the disk fills the grooves on the shaft. Alves and Martins (2013) developed a single stroke mechanical joining process to fix sheet panels to tubular profiles and applied it to automotive parts. Egami et al. (1997) developed a new manufacturing method for serration joints: a serration joint was obtained by pushing a serrated shaft into the hole of a mating part so that the serrations of the shaft shave the hole surface. In this method, the serrated shaft acts as a shaving tool and hence the shaft should be much harder than the hole. This process was applied to join a cam plate to a shaft and the joint obtained exhibited enough torsional fatigue strength. The authors proposed a similar method for serration joints by using cold forward extrusion: Kitamura et al. (2012) summarized the joining mechanism and optimum conditions to achieve high torsional strength and Hirota et al. (2012) investigated the effect of the shape of serrations and the rigidity of the disk on the joining strength. However, this method cannot be applied to such joints that the male and the female parts are made of the same material. In order to overcome the problem, a new method was proposed in this study. Through the experiments varying the amount of deformation, spline joints of medium carbon

---

* Corresponding author at: Department of Materials Science and Engineering, Kyushu Institute of Technology, 1-1, Sensui-cho, Tobata-ku, Kitakyushu, Fukuoka 804-8550, Japan. Tel.: +81 93 884 3369; fax: +81 93 884 3369.
E-mail address: hirota@post.matsc.kyutech.ac.jp (K. Hirota).

http://dx.doi.org/10.1016/j.jmatprotec.2014.02.007
0924-0136/

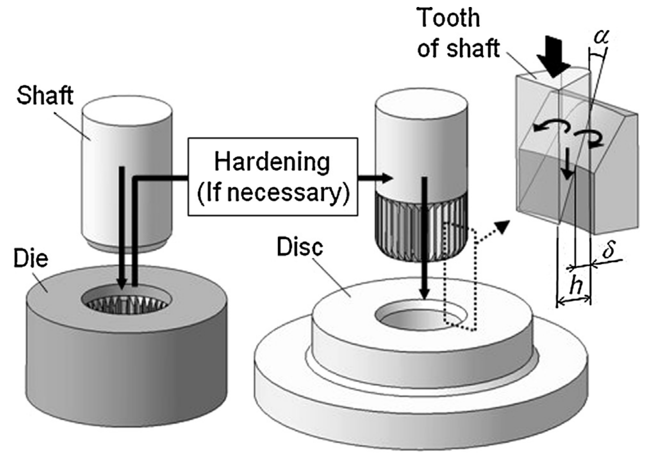

Fig. 1. Schematic of assembling method of serration joint by forming.

steel were successfully assembled and showed higher torsional strength than a conventional joint not accompanied by plastic deformation.

2. Mechanical joint assembled by forming

2.1. Assembling of serration joint by forming

In the production of spline joints or serration joints, precise machining, which is time and cost consuming, is required to achieve a tight fit tolerance for enough fatigue strength. The authors developed a new method to obtain a tight-fit serration joint with high productivity. The procedure of the process is illustrated in Fig. 1. A shaft having serrated portion at one end and a disk with a hole at the center are prepared. The serration is given to the shaft by forward extrusion and hardened by carburizing and quenching if the disk is as hard as the shaft. The diameter of the hole is determined so that the overlap ratio of the tooth and the hole δ/h is equal to about 0.5. Next, the shaft is pushed into the hole up to the end of the serrated zone, where each tooth of the serration is indented on the surface of the hole and a mechanical engagement is created in the circumferential direction between the shaft and the disk. Thus, tight fitting is achieved in a simple operation due to the residual compressive stress by indenting. Kitamura et al. (2012) and Hirota et al. (2012) reported the optimum conditions for the lead angle α and the overlap ratio δ/h to achieve high torsional strength.

2.2. Assembling of spline joint by forming

The method in Fig. 1 has a limitation for the combination of materials to obtain a successful joint, i.e. the teeth of serrations should be approximately three times harder than the hole surface, otherwise the serrations collapse and no mechanical engagement is formed. In this paper, a new method was proposed to overcome the limitation. Dimensions of the spline-disk joint targeted in this study are illustrated in Fig. 2(a). A straight sided spline (designation: 6 × 18 × 22, ISO 14-1982) is provided with the shaft, while the mating teeth in the hole are designed so that a part of the tooth overlaps by β per side against the tooth of the shaft. As the external spline is pushed into the internal spline, either or both of the teeth deform at the overlap zone and the spline joint tightly fitted by the residual stress on the resulting interface is obtained. This method will be applicable between the same materials since the amount of deformation is much less compared with the previous method as shown in Fig. 1. A constant gap of 0.2 mm is given at the miner diameter of the spline so that the material deformed at the overlap zone escapes to the gap. Contrarily, no gap (with a tolerance of 0.02 mm) is given at the major diameter to assure the coaxiality and the perpendicularity of the disk to the shaft in assembling.

In this method, the overlap length is considered to be the most important factor for the assembling load and the strength of the joint and hence, varied in two ways as shown in Fig. 2(b). The type I specimen has straight tooth sides and the overlap length is uniform along the axial direction, while the type II specimen has tapered tooth sides and the overlap length increases along the axial direction. The parameter sets in the experiments are summarized in Table 1, where test cases 5 and 6 are used for comparison at approximately the same overlap length ($\beta \cong \beta'$) between different types of disk specimens and case 7 as a reference sample of the conventional spline joint.

Both the shaft and disk were made of medium carbon steel containing 0.45 wt% C (S45C (JIS)) and the spline teeth were processed by wire electro discharge machining. Since fitting is achieved by plastic deformation in this method, the manufacturing tolerance for tooth dimensions will be rather relaxed compared with that for conventional spline joints. Therefore, the teeth can be processed by forward extrusion and machine finishing of the major diameter and the type II specimens were designed based on such a processing method.

The shaft and the disk were set on a die set as shown in Fig. 2(c), where the coaxiality and the position of the teeth in the circumferential direction were adjusted by the chamfers at the shaft and the hole edges, and two positioning pins, respectively. The die set was loaded by a hydraulic press at a rate of 5 mm/s and the shaft was pushed into the disk to the depth of 4 mm, where load-stroke data were measured by means of a strain gauge load cell (capacity: 200 kN) and a contact type displacement sensor (ranges: 0–10 mm). The assembled joints were subjected to strength tests. The axial strength was evaluated with the load to withdraw the shaft from the disk by using the same die set system for assembling. A torsion test was carried out as follows: both ends of the joint were fixed on the testing machine with bolts and the shaft side of the joint was rotated, where torque-torsional angle data were measured by means of a torque meter (capacity: 1kN· m) and a rotary encoder (resolution: 0.1°) as shown in Fig. 2(d).

3. Results and discussions

3.1. Deformation behavior in assembling

Assembling was carried out at the cases 1–4 of Table 1 and the load-stroke curves were obtained as shown in Fig. 3. The curves for type I specimens showed a logarithmic increase, meanwhile those for type II specimens an exponential increase. In order to compare the load between the type I and II specimens, the maximum overlap length is calculated for the type II specimens according to the following equation: $\beta' = L \tan\theta$, where L and θ are the engaged length and the tapered angle of the tooth side, respectively. Referring to the values of β and β' as listed in Table 1, assembling load seems to obey the order of the overlap length.

Fig. 4 shows the appearance of the spline teeth observed after disassembling the joint. The overlap zone of the teeth was deformed and the step was formed as indicated by the arrows. In all cases, neither fracturing nor adhesion was observed and the deformation of the teeth was remarkable when β or θ was large. In the type I specimens, both teeth of the shaft and the disk deformed evenly and the step was formed on the shaft side. On the contrary in the type II specimens, deformation was only found on the disk: the overlap zone of the disk seems to be shaved by the shaft tooth and accumulate toward the assembling direction.