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Research on the Rolling Process of Rotational-type Components
(2nd Report, Profile-shaping Process in the Rolling of Some Rotational
Components Having Functional Features such as Screw and Gears)*

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By means of experimental rolling of screw-like and gear-like components, shapes which blank cylinders come to develop in a process are observed in detail and processes of forming their functional profiles are examined.

In order to realize the characteristics of deformation, a method was taken in which experimental processes were examined comparatively by establishing a model process under some simple assumptions accepted as plausible. By this means, chief controlling factors of the process have been pointed out. A distortion observable in the cross-sectional figure of a workpiece is important. This distortion which affects considerably the forming of profile features cannot completely be represented by the proposed model. It is also important to realize that the material undergoes different cumulative amounts of reduction according to its peripheral position occupied when the rolling starts.

1. Introduction

The components-rolling, so called in this paper, means the rolling process of forming screw thread or gear by rolling a workpiece. Although there are a number of rolled goods sold in market, in general, a rolled product cannot always have satisfactory form and quality due to its particular deformation mechanism. In order to clarify the deformation in components-rolling exhaustively and to find a solution to troublesome problems peculiar to this process, a series of experimental studies have been carried out.

In the preceding report, cases of plain cylinders being rolled between plain flat dies were dealt with, and fundamental phenomena observed commonly to all the components-rolling were fully clarified⁽¹⁾.

In this paper, the forming procedure of a component having specific profile such as screw thread or gear teeth will be treated.

First, a method of composing a deformation model of rolling will be proposed to give a criterion for the actual deformation. The composition is originally based on some simple accepted assumptions which are plausible. By comparing the actual deformation with this model, points of importance in considering the process were revealed. A point worth notice is a dis-

tortion peculiar and common to the rolling. When such a distortion is once brought about in the cross sectional figure, it will be retained and brought eventually into the finished parts. This paper deals principally with the influence of this distortion on the forming mechanism of the profile features (screw thread and gear teeth). Though, in this research, specimens for screw or for gear do not give exactly the form of a male screw or of a spur gear, hereafter they will be referred to simply as "the screw" or as "the gear", and their specific profile portions will be inclusively represented by a term "feature".

2. Method of experiment and conditions

A sketch of the test rig is shown in

Fig.1 Tool arrangement for components-rolling.

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Table 1 Experimental conditions.

dies	blank material	products	other conditions
flat dies for the screw, lead angle: $8=0^\circ$, pitch: 2mm	diameter: 16.52mm length: 50mm	Aluminium A1050F	lubricant: not used rolling speed: 5.3mm/s temperature: $(20 \pm 1)^\circ\text{C}$
flat dies for the gear, lead angle: $8=90^\circ$, pitch: 2mm pressure angle: 30°	diameter: 16.68mm length: 50mm		
		screw-like component effective diameter: 16.438mm	
		gear-like component diameter of pitch circle: 16.553mm	

Fig.2 The profile feature of the dies.

Fig.4 Flow stress-strain curve for A1050F aluminium.

Fig.1. Rolling method is the same as the one in the preceding report in which two blank cylinders were rolled simultaneously. This time, however, the pressure-pin method formerly employed for measuring die pressure should be abandoned because of the specific profile of the workpiece. So, it was decided to detect the normal component of force acting on the die face by the wire strain gauges attached on the tie-rods. In spite of the evident ability of this testing device, details of the load measuring system as well as the examination of the rolling force will be left to the next report.

Two pairs of forming dies are provided with a profile feature of triangular ridges which are common to both the screw and the gear except the lead angle of 0° in the former in contrast with 90° in the latter. The cross section of the dies' feature has an old standard form of metric thread of a 2 mm pitch as shown in Fig.2.

The specifications of tools, material used, and the other conditions are tabulated in Table 1.

Fig.3 shows the details of inlet part of the die whose proportion is in accord with the practice in the production line. This inlet ramp of the working face of the outside dies determines the amount of die penetration per each half revolution of the blank. In this case, the inlet chamfer can give a revolution of 0.64 before the workpiece reaches the parallel portion of the

Fig.3 Details of the inlet part of die.

die. Therefore, the specimen as a whole completes a full reduction after revolving an amount of 1.14, as this ultimate reduction is given by a constant clearance between parallel parts of dies. For this reason, only the phenomena during initial 1.5 revolutions will be described in this paper, though 5 to 7 revolutions are generally needed for completion of a practical process.

Specimens are cut from commercially pure aluminium bars of the specification A1050F (proof stress = 6.69 kgf/mm^2), their stress-strain curve by a well-lubricated compression test is given in Fig.4.

Profiles of deformed components were measured by a toolmakers' microscope with a precision angular dividing attachment and a tracer-type form tester, and deviations of the equivalent effective diameters of a half-rolled product from the final effective diameter aimed at were measured by a floating micrometer with two appropriate cylinders.

3. Configuration of workpieces in rolling

Fig.5(a) shows circumferential distributions of effective diameters measured along a groove generated in 'the screw' by two-wire method. Since the curves in this figure represent merely deviations from the final value of an ideal effective diameter, the realistic configuration typical of rolling should be the one schematically illustrated in Fig.6. It appears to have something in common with the cross sections of plain cylinders being rolled between flat dies as shown in the preceding report. Though a deviation in effective diameters decreases with the number of turns, a roundness deviation in effective diameter stands at more than 0.2 mm even after initial 1.5 revolutions*.

* As would be seen in the preceding report, we could notice also such a peculiar configuration of the cross-sectional profile of a screw thread sold in the market, in which the number of turns seems to be 6 - 7 rev..

Fig. 5(a) Peripheral distribution of effective diameters in the screw.

Fig. 5(b) Peripheral distribution of pitch diameters in the gear.

CO : Center of the bite

Fig. 6 General material configuration typical of a rolling.

(a) 0.5 rev.

(b) 0.75 rev.

(c) 1.0 rev.

Fig. 7 Peripheral distribution of minor and major diameters in the screw.

(a) 0.5 rev.

(b) 0.75 rev.

(c) 1.0 rev.

Fig. 8 Peripheral distribution of root and tip cylinders in the gear.

Fig. 5(b) shows deviations in the pitch diameter of the gear, which are measured by the over-pin method. These deviations seem to be the same in nature as those in effective diameter.

In order to have the circumferential profile on the whole in the screw, a workpiece rolled halfway was taken out and mounted between centers of a circular dividing attachment of toolmakers' microscope. Thus the diameters of the root and the crest at any peripheral position could

be measured by means of the stage micrometer of the microscope. The results obtained at three stages can be plotted as shown in Fig. 7. Deviations of the root diameters (black points) from a circle are evident with consequent variation in the height of thread (radial distance from a white point to a black one).

In the case of the gear, the halfway-rolled workpiece was mounted directly on the stage-glass of the microscope so that its axis coincided with the rotating axis

Fig.11 Process models of the screw.

assumptions.

(1) Total length of a specimen does not change throughout the process.

(2) A meridian plane of symmetry which passes middle of a tooth width or a space width remains a plane during a process.

(3) Central angle between the neighbouring meridian planes mentioned above keeps a constant value, and the tool engages with involute tooth form of the specimen properly.

(4) Tip surface of the tooth piles up in the space of the die profile retaining a cylindrical form.

In fact, the calculated values of piling up under a constant penetration of dies showed little difference between the screw and the gear.

6. Comparison of the experimental process with the model, and discussion

As the model might be supposed to give a copy-book deformation, by comparison of the experimentals with this model we can easily get an idea of how unexpectedly a real material behaves.

Turning to Fig.7 again, two kinked fine lines show the circumferential root and crest lines by the model drawn to make a comparison with the experimentals, where the full line represents the root and the broken line the crest. It will be seen that the agreement in the root diameter, between black points and full lines, is fairly good at the initial stage of 0.5 rev. (Fig.7(a)). As the rolling goes on, however, the actual root diameter becomes far larger than the model diameter except at the center of bite C as will be seen in Fig.7(b). Since a penetration is always accompanied by a lateral expansion of the core as a whole, the experimental root diameter shown in Fig.7(c) becomes considerably larger than the models'. Moreover, the actual height of threads obtained is shorter on the whole than the models' except in certain portions in (a). According to the model the crest should pile up rapidly near the bite center due to the rapid sinking at the root, but the actual piling up is quite moderate. So, undoubtedly some of the assumptions in section 5, so far

Fig.12 Profile curve at the bitten portion of a cross section through a root of a screw.

Fig.13 Stereo-graphical view of a thread profile.

accepted by many investigators in considering the deformation mechanics of components-rolling, cannot be said to hold for further analyses.

An examination of three dimensional pattern of the metal flow in the specimens and its effects on the forces required will be reported in the next paper, so, in view of only the deformation we will give here some comments on the assumptions.

Assumption (1) is said to be practically correct: the reason will be given in the next report⁽²⁾ where the so called 'split plug' method is applied for detailed strain analysis.

Assumption (2) is incorrect in the strict sense (Fig.3(b) and Fig.4 in the preceding report⁽¹⁾), but even when the distortion of the meridian plane exists to some degree, it is thought that this distortion will scarcely affect the behavior of piling up of the thread ridges. The form tester record gave such a profile curve at the bitten portion of a cross section through a root as in Fig.12, and it is evident that no bulging at the inlet side did occur.

Assumption (3) is unrealistic, because the difference between the observations and the process models will never be understood unless we assume that the material undergoes plastic deformation as a whole.

Assumption (4) is correct except at the initial stage of the rolling. Fig.13 shows a stereo-graphical view of a thread profile recorded by a form tester, in which we can see a localized piling-up at the beginning stage of bite, and this would bring about an under-estimation of the major

Fig.14 Gear tooth forms.

Fig.15 Feature-forming-ratio.

Fig.16 Specification of the typical profile.

Fig.17 Actual passage of rolling of some points on a specimen (screw).

diameter by the process model shown in Fig. 7(a).

Fig.8 gives similar analyses on the gear**. In the gear, though the general tendency was similar to the screw, the observed root cylinder came closer to the

** In the experiment on gear, die working space was set a little narrower than the nominal value intentionally.

model in Fig.(c). The tip cylinder observed was smaller than the model. Comparison of the gear tooth forms between the ideal and an observed one is made in Fig. 14. As will be seen from Fig.8 and Fig.14, in case of the gear not only the assumption (3) but also (4) seems incorrect.

Referring to Figs.7 and 8, we can see how the height of the thread or the tooth grows with the number of turns. Fig.15

Fig.18 Distortion of the core.

gives this development by so to say the feature-forming-ratio $\phi = h/h_f$ against the number of turns of component, where h is the current height of a thread or of a tooth, and h_f the final must-height. As illustrated in Fig.16, the h values, both in the process models and the observed results, vary with the circumferential position. Thus, the feature-forming-ratios observed should be represented for ranges between $h_{\max}/h_f$ and $h_{\min}/h_f$ as vertical lines shown in Fig.15. In the case of the screw (Fig.(a)), as well as the gear (Fig.(b)), observed feature-forming-ratios appear to develop fairly more slowly than those of the process models, and this suggests that the central core of the components deforms plastically so as to have a share of the die penetration.

Supposing that Fig.16 shows the cross-sectional configuration of the screw when it has made a number of turns of 0.75, the material points C' and C'' are just passing through a spatially fixed point O in Fig. 10, and the points A' and A'' are beginning to contact with a die at the inlet side. Tracking these material points from the beginning of the process, current major and minor diameters corresponding to these points were measured. The results are shown by plots in Fig.17. This gives an aspect of the actual die penetration into a material in the case of the screw which was assumed to take an ideal form of $24^\circ\Pi$ $28^\circ\Pi$ in Fig.9. It should be noted that the diameters really increase for periods of 2 to 3 and 4 to 5 and so on. If we pay attention to the point of 0.75 rev., then we see that $h_{\max}$ is represented by the ordinate difference of $C_4'C_4''$ and $h_{\min}$ is given by that of $A_3'A_3''$.

According to Fig.16, a radial length of $C'C''$ which gives $h_{\max}$ at 0.75 rev. should become $h_{\min}$ after about 0.47 rev. when the situation becomes similar to $A'A''$ of the beginning of bite. But, if we assume that a height of the feature once attained does not change during the free revolution of about 0.5 after leaving the die, we can regard $h_{\max}$ of about half a

rev. before the referred stage as $h_{\min}$ at that stage. Points denoted by Δ (mark) in Fig.15 are thus plotted as guessed $h_{\min}$'s. It will be seen in the figure that in the screw, guessed points almost lie on the $h_{\min}/h_f$ curve, but in the gear, they are somewhat smaller than the observed values. In the latter case, it was observed that the rolling action to generate a tooth form was still effective in the receding side and this brought about a certain increase of the diameter.

Fig.18 shows the distortion of the core by the ratio $d_{\max}/d_{\min}$ of the maximum and the minimum of the root diameters. In the case of the screw (a), distortion observed is far larger than that expected from the process models, and a distortion once brought about in the cross section is difficult to vanish completely and it is brought eventually into the finished parts. In the case of the gear (b), a distortion observed seems to be similar to one of the process models, but the plastic kneading action in the tooth itself or around the root, as would be seen in Fig.3 (c) in the preceding report, will cause troublesome problems.

7. Conclusions

By means of experimental rolling of screw-like and gear-like components with profiled straight dies, shapes which blank cylinders come to develop in a process were observed in detail and processes of forming their functional features were fully examined.

The results obtained are summarized as follows:

(1) In the components-rolling, the process of the die penetration into a specimen is quite different from those seen in the strip rolling or other continuous processes. It is important to realize that the career of deformation varies from point to point in a specimen.

(2) Process models of rolling were proposed on the basis of some simple assumptions. Observed results did not agree

with those process models except at the initial stage of rolling, and this fact told us that the whole work material was really subjected to plastic deformation. Plastic deformation in the core part of the specimen appears to have considerable influence on the forming of profile features.

(3) Distorted figure in the cross section is brought into the finished parts and it seems to limit the accuracy of the products.

(4) Even though the occurrence of deformation in the core part delays the piling up of the feature to some degree, it brings about a more effective die penetration in the subsequent stage of rolling. So, even in the stage of smooth-out-rolling

the feature continues to pile up, which phenomenon was more remarkable in the case of the screw. On the results of this report, deformation and the rolling forces will be analyzed in the next report.

8. Acknowledgement

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