EFFECT OF SHARP EDGED STEP ON THE PERFORMANCE OF STRAIGHT WALLED RECTANGULAR DIFFUSER

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ABSTRACT

The aim of the present work is to investigate the effect of an upstream facing sharp edged step mounted at diffuser inlet on its pressure recovery factor. Experiments were carried out on 9 diffusers with 3 different angles and 3 different area ratios, each one of them was tested with 4 different step depths. The results however showed that the step has different effects on diffuser behaviour. The combined effects of the step showed that: 1 - The displacement thickness at diffuser inlet decreases by using a step, 2 - The pressure recovery factor can be increased by 40 % by using a proper step depth, 3- The proper step depth depends on diffuser geometry.

INTRODUCTION

The diffuser is one of the most important components of turbomachinery, in which a portion of the kinetic energy is converted into pressure energy. This conversion process is usually associated with losses due to the medium viscosity and velocity gradient in the boundary layer, which develops rapidly in a decelerating flow. The boundary layer can finally separate from the wall before diffuser outlet causing excessive losses. The growth of boundary layer thickness can increase so that the actual flow area decreases and may cause flow acceleration. The most important parameters that affect the flow in the diffuser can be generally classified into geometrical and aerodynamic parameters. The most important researches were carried out in references [1,2,3,4] on the effect of geometrical parameters as the area ratio, diffuser angle, wall curvature, and length to breadth ratio on the performance of the diffuser. To study the effect of aerodynamic parameters it is required to control the flow inside the diffuser. The flow control devices fall into two categories, namely: "active" and "passive", the first one of which includes; boundary layer suction and blowing control method. Although significant gain in diffuser performance was possible with the aid of these methods the many practical difficulties involved have limited their application [5]. Passive flow control devices function as a result of energy absorbed from the main air stream to energize the flow in the boundary layer. The screen devices are very effective in producing a more uniform velocity distribution. Radial splitters were applied to produce a mixing process which improves the pressure recovery factor (PRF) in wide angled conical diffusers [5]. The flow can also be divided into two halves in order to diminish the boundary layer thickness, but this method is associated with great losses. It was also proved that an initial moderate swirl has an improving effect on the (PRF) [6,7,8]. The diffuser performance is also deteriorated with increasing the shear region of the inlet main flow [9].

In the present work a new passive method is investigated, in which an upstream facing sharp edged step is mounted at the diffuser inlet. The formed eddies behind this step transmit a portion of momentum from the main stream to the flow involved in the boundary layer, and that can lead to a decrease in the velocity gradient in this layer, and hence decrease the shear region of the inlet main flow. The eddies formed behind the step will cause also losses [10,11]. The combined effect of the step is to be investigated in this work. It is intended that the formed eddies behind this step would energize the flow in the boundary layer and thus minimize the boundary layer thickness at diffuser inlet.

NOMENCLATURE

b	Diffuser depth	mm
c	Axial velocity	m/s
C_p	Pressure recovery factor	

C_s	Step loss coefficient	
L	Diffuser length	mm
P	Static pressure	N/M^2
q	Dynamic pressure	N/M^2
R	Air constant	J/Kg K
R_e	Reynolds number at diffuser inlet, and based on the mean velocity	
S	Step depth	mm
T	Temperature	K
W	Diffuser width	mm
γ	Ratio of specific heat	
δ	Boundary layer thickness at diffuser inlet	mm
δ^*	Boundary layer displacement thickness	mm
at	diffuser inlet $= \int_0^{\delta}(1 - \frac{C}{C_{max}})dy$	
θ	Diffuser divergence angle	deg

Subscripts

i	Diffuser inlet (before the step)
max	Maximum
o	Diffuser outlet
t	Total (stagnation)
1	Diffuser inlet (after the step)

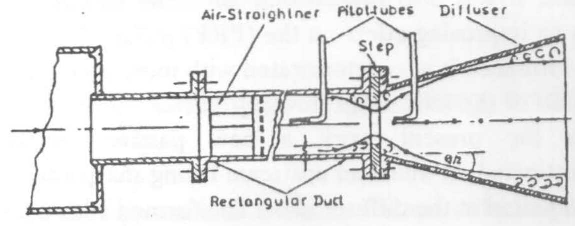

Figure 1. Schematic diagram of the test rig.

Figure 2. General view of the test rig.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus consists of a constant speed radial fan with a mass flow rate of 0.224 Kg/sec. A honey comb air flow straighteners composed of square cells is mounted in the approach duct to minimize swirling flow conditions. This is followed by a square duct of 55*55 mm cross-section and 600 mm length to ensure an axial flow at diffuser inlet. At mid point of this duct a Pilot tube was mounted to measure the total pressure. The velocity distribution at diffuser inlet was carried out with a single hole Pilot tube of 0.5 mm inside diameter connected with a substantially designed traversing mechanism of one mm pitch. A general layout and a photograph of the test rig are shown in Figures (1 and (2)) respectively. The static pressure distribution along the diffuser was measured through 4 small taps of 0.8 mm diameter each at consequent cross sections. The axial distance between two adjacent static holes was 55 mm, the pressure taps are connected to a vertical U tube water manometer. Experiments were carried out on 3 groups of diffusers with length to breadth ratio L/W = 4,6,8, with different wall angles $\theta/2$ of 3,5,7 deg, each one of them was tested by using 4 different step depths (0,3,4,5 mm). The inlet square cross section of all diffusers are of 55x55 mm. In the experiments, the centerline air velocity at diffuser inlet was kept unaltered to provide a Reynolds number of $2.2*10^5$. Velocity distribution at inlet is measured to calculate the equivalent boundary layer thickness for each step, also the static pressure distribution along the diffuser was measured to calculate the "PRF". Figure (3) demonstrates the flow pattern around a sharp edge, after Batchelor [12], while Figure (4) is a definition sketch of the flow inside a diffuser.

Figure 3. Flow around a sharp edge [12].

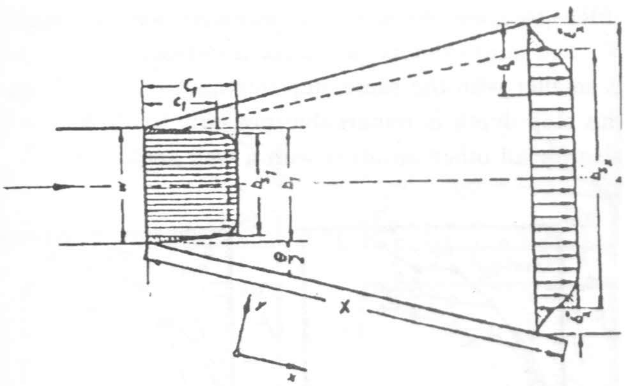

Figure 4. Flow pattern inside the diffuser.

The obtained experimental results of the diffuser were used to calculate the diffuser parameters according to the following mathematical expressions:

$$\delta^* = \int_0^\sigma \left(1 - \frac{C}{C_{max}}\right) dy, \qquad \text{where:}$$

$$C = \sqrt{\left(\frac{2\gamma}{\gamma - 1}\right) . R_{air} . T_t\left[1 - \left(\frac{P}{P_t}\right)^{0.2857}\right]},$$

The pressure recovery factor "C_{px}" at any section, X can generally be expressed by:

$$C_{px} = \frac{\frac{1}{bx}\int_{b_x} P_x .db - \frac{1}{b_i}\int_{b_i} P_i . db}{\frac{1}{b_i}\int_{b_i} q_i . db}$$

For unswirled flow the static pressure can be considered constant over the diffuser cross-section [13]. The performed measurement gives the last equation of "C_{PX}" a suitable criterion for evaluation of the tested diffusers.

RESULTS AND DISCUSSIONS

The experimental results showing the effect of step depth on displacement thickness δ^* for different types of diffusers are illustrated in Figure (5). The magnitude of δ^* decreases rapidly by increasing the step depth until s=3 mm., after that the curves deflect with a small positive gradient. The point of deflection thus represents the optimum step depth (the step depth for minimum displacement thickness).

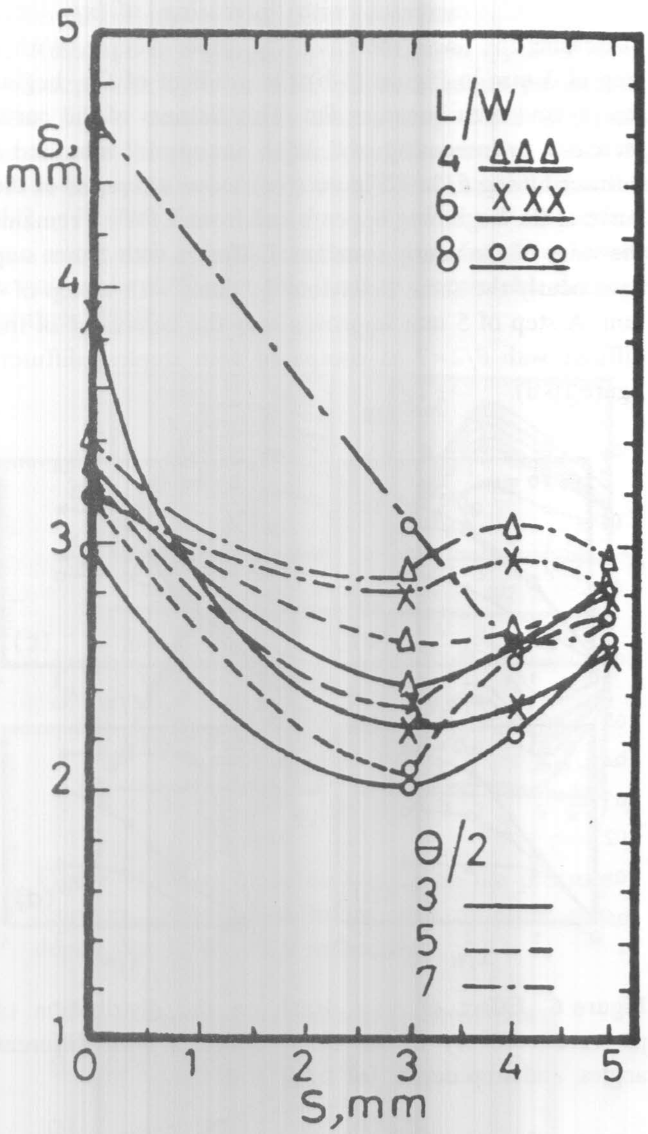

Figure 5. Effect of step depth on the displacement thickness.

The behaviour of "PRF" for 3 diffusers having L/W 4,6,8 is represented in diagrams. A diagram for each step depth is drawn between the "PRF" and dimensionless length x/w with the diffuser angle $\theta/2$ as a separate parameter, so that we can see the effect of the diffuser angle on its behaviour. Relation between "PRF" and "$\theta/2$" was also drawn with L/w as a separate parameter.

THE PRESSURE RECOVERY FACTOR "PRF"

Behaviour of diffusers with L/W = 4

Figure (6) represents the relation between C_{px} and X/W. In Figure (6-a) where the step is equal to zero the value of C_p increases with increasing of x/w. On decreasing the angle increases Cp_x more steeply. With a step of 3 mm in Figure (6-b) the gradient of Cp_x begins steeply and then becomes flat. This flatness of the curve increases by increasing of θ. With a step of 4 mm. and a diffuser having $\theta/2=7$ Figure (6-c) more steepness of the curve at the beginning appears and from X/W=1 remains the value of Cp nearly constant. Diffusers with 5 mm step gave nearly the same behaviour as those with a step of 4 mm. A step of 5 mm improves only the behaviour of the diffuser with $\theta/2=7$ as compared with stepless diffuser, figure (6-d).

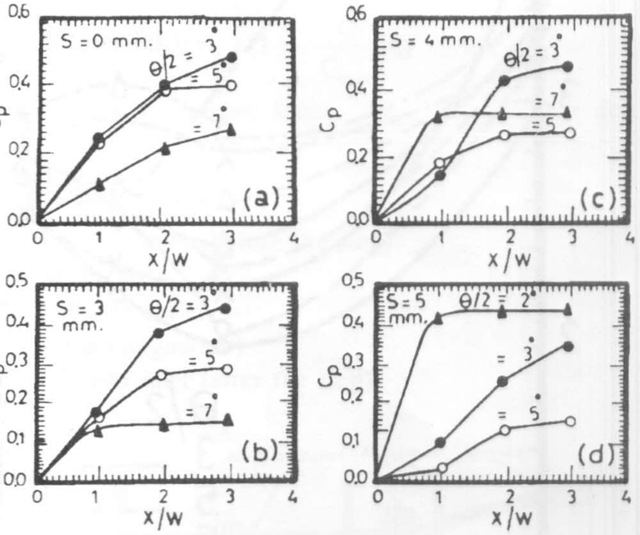

Figure 6. Effect of step depth on the distribution of pressure recovery factor along diffusers with different angles, and step depth, for L/W = 4.

Behaviour of diffusers with L/W = 6

Figure (7) shows the behaviour of diffusers with L/W = 6. The curves are qualitatively similar to those with L/W = 4, but with increasing values of "Cp_x". The improvement of "PRF" is remarkable when a step of 3 mm depth and $\theta/2 = 3^o$ was used however this step depth has a negative effect on the diffuser with $\theta/2 = 7^o$.

Behaviour of diffusers with L/W = 8

The diffusers with L/W = 8 represent the largest tested diffusers. The increase in diffuser length lead to an improvement in diffuser "PRF". Figure (8) shows the behaviour of these diffusers. A step of 3 mm improved the "PRF" by about 40 % for the diffusers with wall angle of 3^o. The improvement in Cp for a diffuser with $\theta/2 = 5^o$ is smaller with the same step depth. A negative effect of this step depth is remarkable not only for L/W = 8 but also for all other diffusers with a wall angle $\theta/2 = 7^o$.

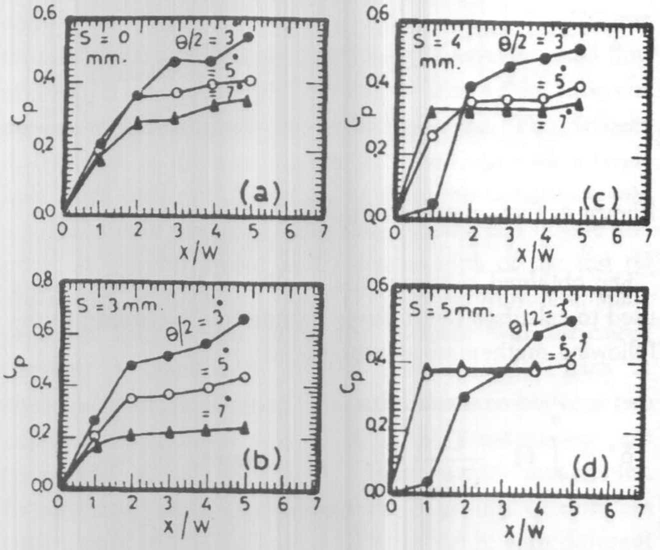

Figure 7. Effect of step depth on the distribution of pressure recovery factor along diffusers with different angles, and step depths, for L/W = 6.

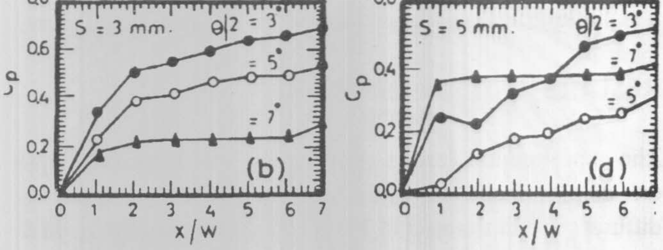

Figure 8. Effect of step depth on the distribution of pressure recovery factor along diffusers with different angles, and step depth, for L/W = 8.

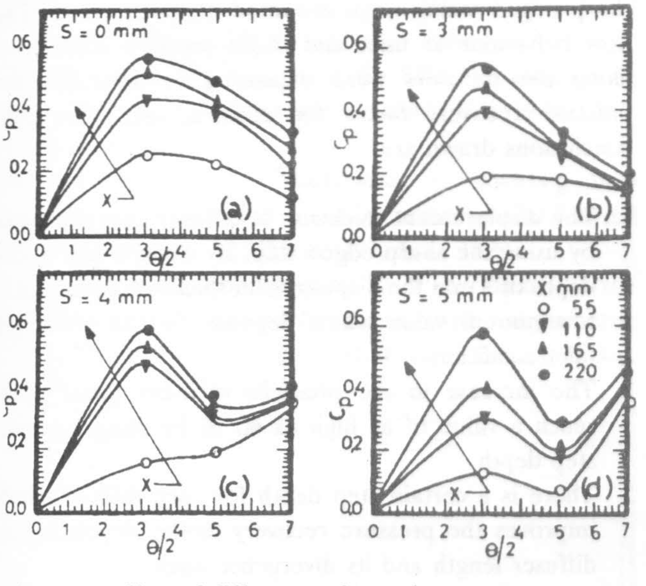

Figure 9. Effect of diffuser angle on the pressure recovery factor for diffusers with different step depths, for L/W = 4.

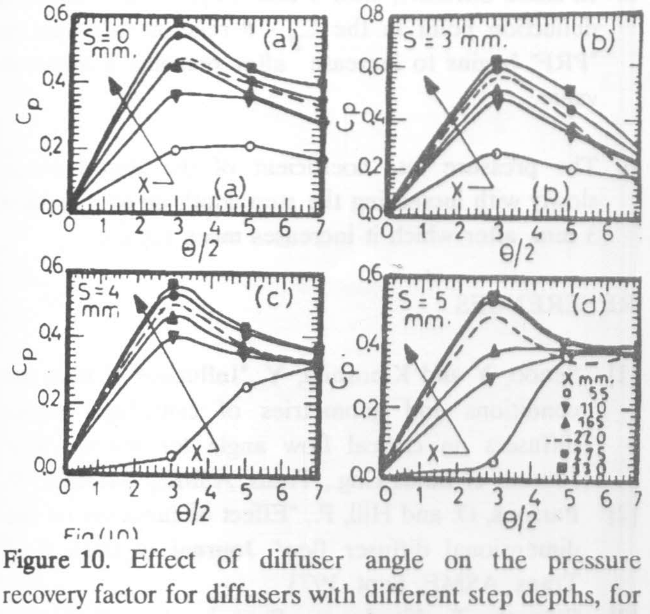

Fig.(10)

Figure 10. Effect of diffuser angle on the pressure recovery factor for diffusers with different step depths, for L/W = 6,8 respectively.

The relation between θ/2 and Cp is represented in diagrams (9,10,11) with the axial distance "X" as a separate parameter and for the same last groups in order to clarify the effect of the wall angle on the PRF. The trend of all curves is almost the same. The "PRF" increases firstly with θ/2 until it becomes equal to 3°. In some diffusers which have a step of 5 mm. depth there is a deflection point at which the "PRF" begins to increase again. The shortest diffusers with X = 55 mm showed in some cases a different behaviour. The effect of stepdepth on the "PRF" is illustrated in Figure (12) for different types of tested diffusers with L/W = 4 & θ/2 as separate parameters. This figure demonstrates that a step depth of 3 mm represents the proper depth for diffusers with θ/2 = 3°, while it qualitatively increases to 5mm. for diffusers with θ/2 = 7°. This figure also shows that it is not advisable to use a step with a depth less than 3 mm. for diffusers with a wall angle of 7° since this leads to a noticeable decrease in their "PRF".

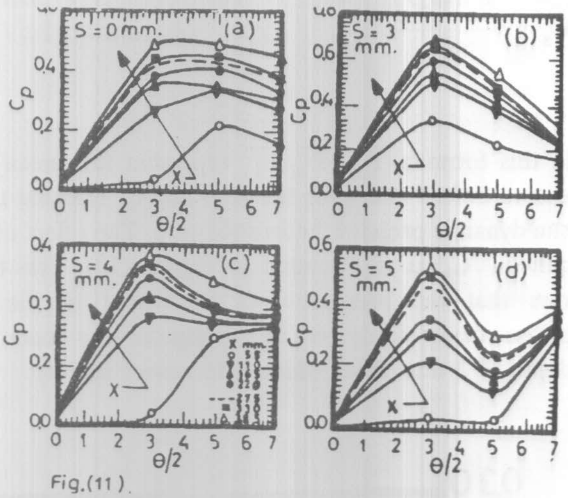

Fig.(11)

Figure 11.Effect of diffuser angle on the pressure recovery factor for diffusers with different step depths, for L/W = 6,8 respectively.

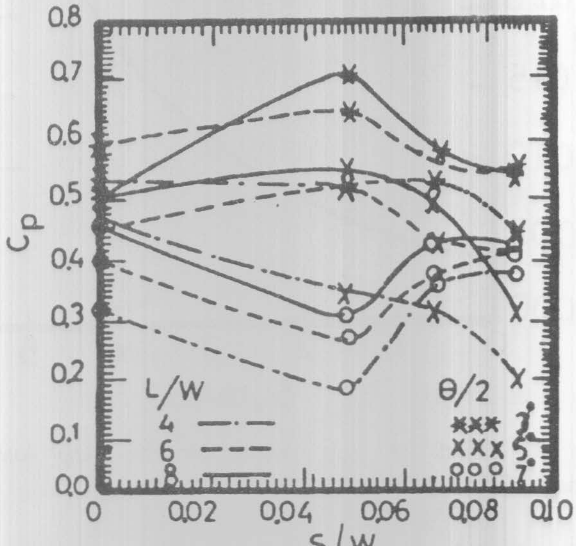

Figure 12. Effect of step depth on the pressure recovery factor.

Determination of step losses

It has been demonstrated that the "PFR" for all types of tested diffusers are affected by installing of a flow facing sharp edged step, it has also been noticed that not the performance of all diffusers has been improved, because of the mixing losses which occur due to the sudden contraction caused by this step. These losses can be expressed through a step loss coefficient "C_s", where:

$$C_s = \frac{\bar{P}_{ti} - \bar{P}_{t1}}{\bar{q}_i}$$

In this formula, $\bar{P}_{ti}$, $\bar{P}_{t1}$, $\bar{q}_i$ represent the mean total pressure before and after the step and $\bar{q}_i$ is equal to the mean dynamic pressure before the step. The effect of step depth on "C_s" is represented in Figure (13). This figure shows that the pressure loss coefficient of the step increases firstly slowly with increasing the step depth up to a depth of 3 mm. after which it increases rapidly.

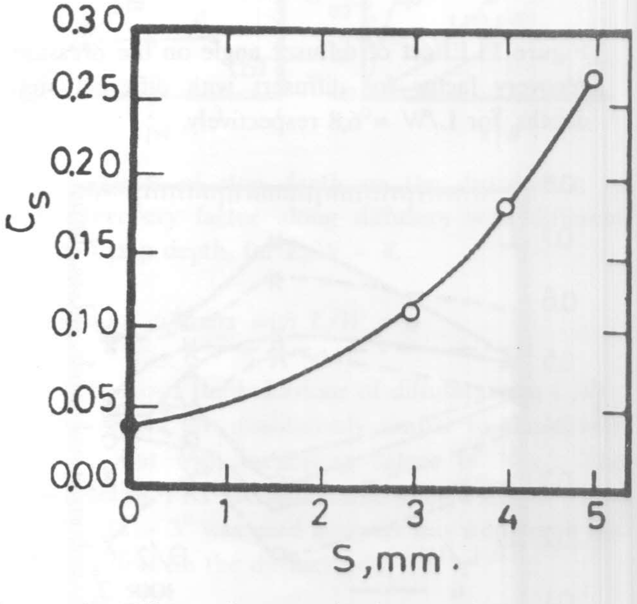

Figure 13. Effect of step depth on the step loss coefficient, (R_e = 2,2 x 10^5).

CONCLUSIONS

Nine rectangular diffusers with 3 different divergence angles and 3 different area ratios were tested with several sharp edged facing steps mounted at diffuser inlet. The flow behaviour at inlet and static pressure distribution along the diffusers were measured to determine the pressure recovery factor for each diffuser. The main conclusions drawn are:

1. The displacement thickness at diffuser inlet decreases by using the sharp edged step. By using a step with a depth of 3 mm the displacement thickness decreases to a minimum value which depends on the prescribed inlet conditions.
2. The increase in the pressure recovery factor could reach a value of as high as 40 % by using a proper step depth.
3. There is a certain step depth for each diffuser which improves the pressure recovery factor, depending on diffuser length and its divergence angle.
4. For diffusers with divergence angle equal to 14^o, it is not advisable to use a step with a depth less than 3 mm., since this deteriorates the "PRF" remarkably.
5. In some diffusers, with 5 mm step, there is a second deflection point in the C_p - θ relation at which the "PRF" begins to increase after reaching a minimum value.

6. The pressure loss coefficient of the step increases slowly with increasing the step depth up to a depth of 3 mm, after which it increases more rapidly.

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