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International Journal of Pressure Vessels and Piping 79 (2002) 807–818
INTERNATIONAL JOURNAL OF Pressure Vessels and Piping
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The effect of material difference and flange nominal size on the sealing performance of new gasketless flanges

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Received 9 April 2002; revised 30 August 2002; accepted 20 September 2002

Abstract

This paper deals with a new seal system between flange joints without using a gasket. This gasketless flange includes a groove and an annular lip that is machined in one of the flange rings which when removed being in contact with the other flange to form a seal line when the flanges are assembled. In this study, firstly, fundamental dimensions are examined for unplasticized polyvinyl chloride (PVC-U JIS) to obtain the best sealing performance. Then, the effects of material difference and flange nominal size upon the sealing performance of the new gasketless flange are investigated for two types of materials, 0.25% carbon steel (S25C JIS) and PVC-U. It is found that the critical internal pressure at which leakage appears is mainly controlled by the maximum stress at the annular lip for each material even if the flange nominal sizes are different. The gasketless flange made by PVC-U shows the higher critical internal pressure compared with the case of S25C if the same clamping forces are applied. The effect of stress relaxation for PVC-U on the sealing performance is also considered. Then, it may be concluded that this PVC-U gasketless flange as well as S25C has good sealing performance.

Keywords: Fixing element; Coupling; Machine element; Contact problem; Pipe flange; Sealing performance

1. Introduction

In a flanged joint, it is always necessary to select a suitable gasket depending on the kind of fluid, the pressure and the temperature. However, even though suitable gaskets are chosen, their sealing performance usually deteriorates over the years. Therefore, maintenance to repair leaks and/or replace gaskets is required. This paper deals with a new seal system between two flanges without using gaskets [1]. Fig. 1(a) shows the system that includes a groove and an annular lip that is machined in one of the flangings which when removed being in contact with the other flange to form a seal line when the flanges are assembled [2,3]. Fig. 1(b) shows a kind of gasket using the equivalent seal system. This new gasket is named *superseal*, which is to be inserted between the flanges instead of conventional gaskets.

In a previous paper [4], the fundamental dimensions of this system were investigated for a popular flange nominal size 50 A (JIS [5], see Table 2) made by 0.25% carbon steel (S25C JIS). Through experimental and finite element method (FEM) analyses, the following conclusions were made:

1. FEM analyses indicates that the maximum stress in the z-direction at the contact zone $\sigma_{z\max} \approx -1200$ MPa with a suitable plastic zone size is necessary for the pressure of 4.9 MPa.
2. It may be concluded that desirable dimensions are thickness (5 mm) and the depth of the groove (13 mm) for the deformed area of the flange 50 A made by S25C.
3. Helium leak testing indicates that the gasketless flange based on most desirable model B has a lower leak rate, and better sealing performance than conventional gaskets.

However, in Ref. [4], there is no discussion about the effect of flange nominal size different from 50 A upon the sealing performance. Moreover, several industrial plants, such as soda, plating, paper, and pulp cannot use metal pipes if they treat corrosive fluids. In this study, therefore, several gasketless flanges and superseals are prepared with varying flange nominal size and materials to investigate the general sealing mechanism through experiment and FEM analyses.

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PII: S0308-0161(02)00103-5

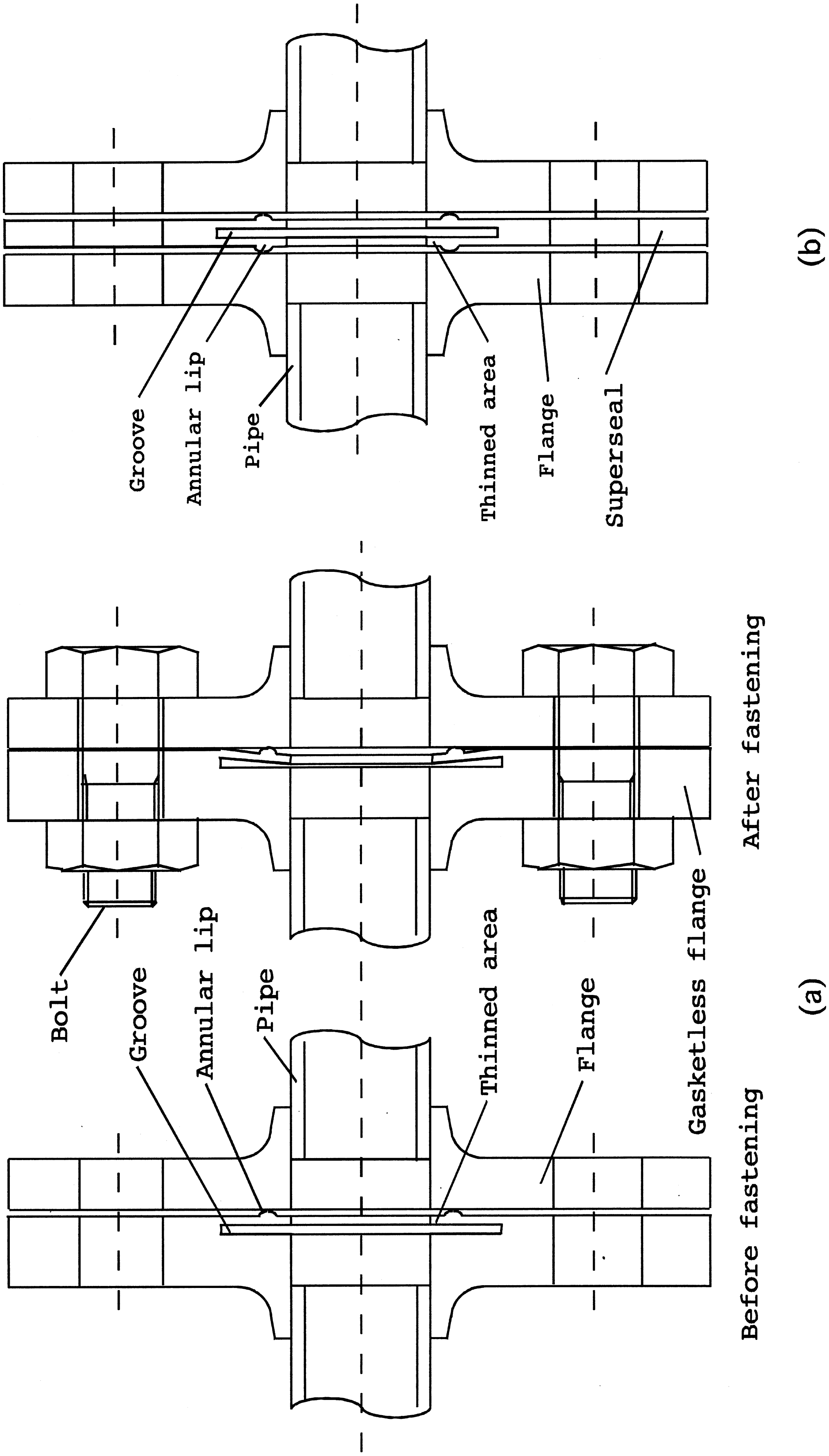

Fig. 1. (a) Gasket-less flange and (b) a kind of gasket named superseal.

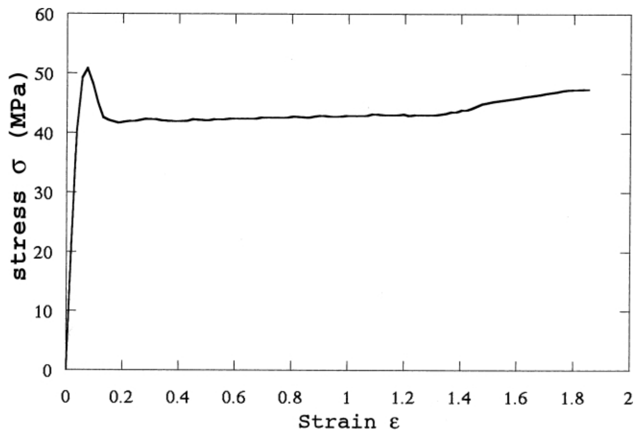

Fig. 2. Stress–strain relation of PVC-U JIS.

2. Fundamental dimensions for PVC-U

2.1. Materials used

In the previous study [4], suitable dimensions for a gasketless flange were obtained for 0.25% carbon steel (S25C JIS) and for the popular flange nominal size 50 A. In a similar way, in this study, first, for unplasticized polyvinyl chloride (PVC-U JIS) and for the size 50 A, suitable dimension will be investigated. Then, the sealing performance is compared with the case of S25C. Fig. 2 indicates the stress–strain relation of this material obtained by the authors using a test specimen with a diameter 10 mm. Table 1 shows the material properties of PVC-U given by Mitsubishi Chemical. In this study, test specimens are prepared through machining thick plates. Since it is difficult to obtain very thick plates for PVC-U, in these experiments only superseals as shown in Fig. 1(b) are used and they are inserted between the conventional flanges made by PVC-U.

2.2. Experimental method for water leak testing

In this study, first, a popular flange nominal size 50 A is taken as an example; then, the fundamental dimensions are examined. Three types of superseals are prepared, where thickness of deformed area $h = 4$ mm, 8 mm, and ∞ (see Table 2 and Fig. 3(a)).

Here, $h = \infty$ has the meaning of no groove, $g = 0$ in Fig. 3(a). By comparing the results through water leak testing, we may find how sealing is achieved by self-energized action on the annular lip. Fig. 4 shows the experimental equipment for water leak testing. Before an internal pressure is applied by a water-hydraulic pump, the flanges are clamped using M16 (JIS). The testing time is 10 min for each pressure level. Then, if no leakage and no pressure drop are found, the testing pressure level is increased. Finally, the critical pressure for leakage p_{cr} is obtained. Fig. 5 shows the relationship between the clamping force $\pi l_b q$ and the critical internal pressure for leakage p_{cr} obtained from the experiment. Although this relation was obtained several times repeating assembly and disassembly, no difference was observed. In other words, in contrast to the case of S25C [4], no effect of plastic deformation is observed for PVC-U. Also, the FEM analyses presented in Section 2.3 indicate that a small

Table 1
Physical and mechanical properties for PVC-U JIS

	Physical properties Specific weight	Hardness	Coefficient of water absorption (%)			
Measurement method	JIS K 7112	JIS K 7202	ASTM D 570			
PVC-U	1.47	R-119	0.03			
	Mechanical properties Tensile strength [MPa (kgf/mm^2)]	Elongation (%)	Strength for bending [MPa (kgf/mm^2)]	Elasticity for bending [MPa (kgf/mm^2)]	Young's modulus [MPa (kgf/mm^2)]	Izod impact strength [kJ/m^2 (kgf cm/m^2)]
Measurement method	JIS K 6745	JIS K 6745	JIS K 7203	JIS K 7203	ASTM D 638	JIS K 6745
PVC-U	57 (5.8)	114	94 (9.6)	3300 (340)	2940 (300)	5.0 (5.1)

Table 2
Dimensions of superseals for PVC-U (mm)

Size 50 A	a	b	c	d	e	f	g	h	i	R_j	R_k	l	l_b
$h = 4$ mm	155.0	120.0	86.5	70.0	60.0	11	3	4	0.2	1.5	3.5	13.25	28
$h = 8$ mm	155.0	120.0	86.5	70.0	60.0	19	3	8	0.2	1.5	3.5	13.25	28
$h = \infty$	155.0	120.0	–	70.0	60.0	11	0	∞	0.2	–	3.5	–	28

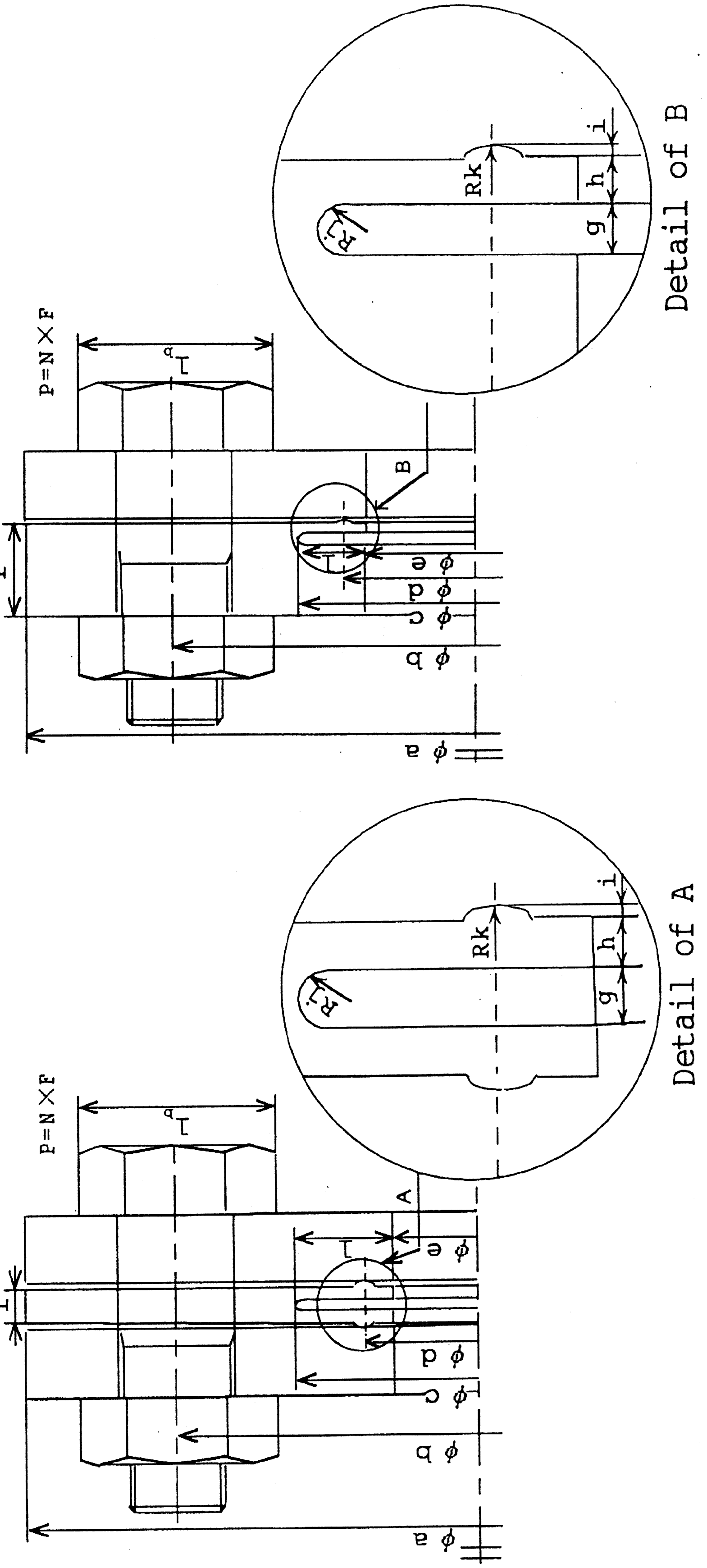

Fig. 3. Dimensions of (a) superseals for PVC-U and (b) gasketless flanges for S25C.

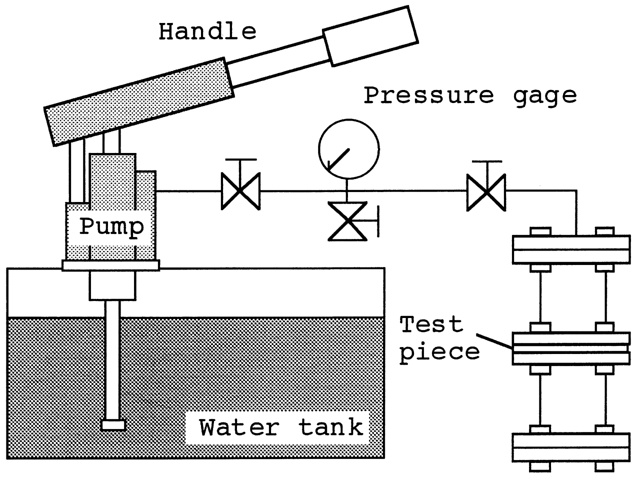

Fig. 4. Experimental equipment for water leak testing.

plastic zone appears only for $h = \infty$ near the top of the contact area. In this case, the joint may have arrived at a shakedown condition. From Fig. 5, it is found that $h = 8$ mm has the best sealing performance for the material PVC-U and the nominal size 50 A.

2.3. Analytical method and results

Fig. 6 indicates a typical finite element mesh that uses four node axisymmetric elements and frictionless contact. The total number of elements is between 2624 and 2961 and the total number of nodes is between 2816 and 3173. The stress–strain relations are indicated in Fig. 7 in comparison with S25C. The clamping force is estimated from the torque applied to the bolts on the basis of JIS B 1084 [5]. This force is applied to the model assuming an equivalent axisymmetric uniform distribution load.

Fig. 8 shows the relationship between the clamping force $\pi l_b q$ and the maximum normal stresses in the z-direction $\sigma_{z\max}$ for PVC-U. With increasing thickness of the deformed area, the value of $\sigma_{z\max}$ increases. Although usually larger values of $\sigma_{z\max}$ have better sealing performance [4], $h = \infty$,

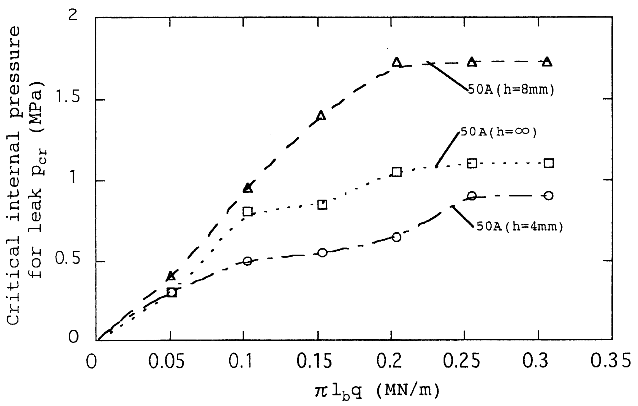

Fig. 5. Clamping force vs. critical internal pressure for leakage.

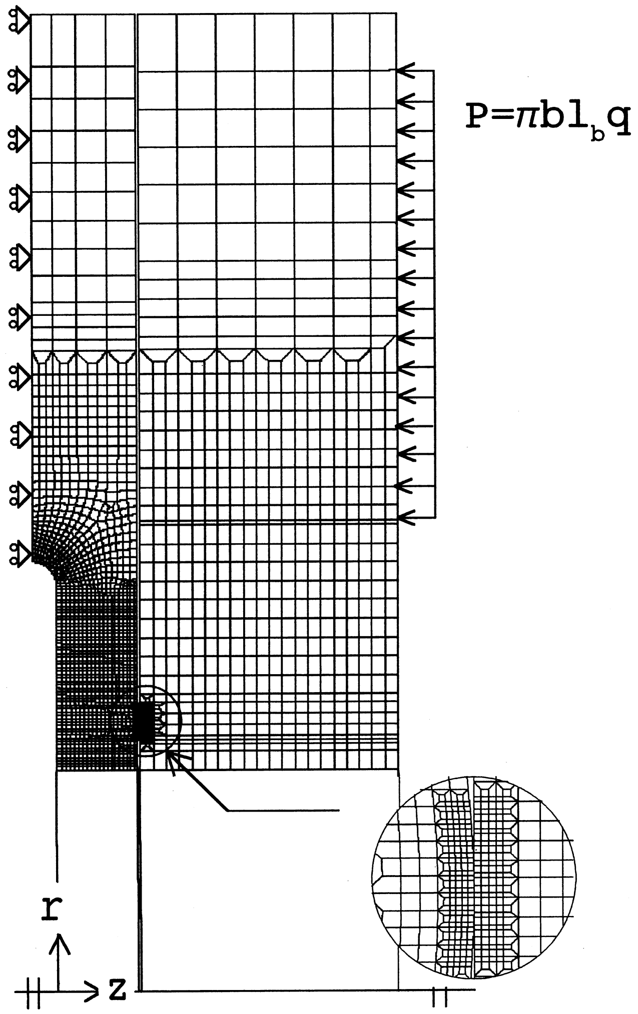

Fig. 6. Finite element mesh.

has worse performance than $h = 8$ mm. Because flanges are actually clamped by using four bolts and there is no groove for $h = \infty$, it seems difficult to form a uniform contact line in the circumference between the annular lips and the other flanges. From the comparison among the results of $h =$ 4 mm, 8 mm, and ∞, it may be concluded that the thickness $h = 8$ mm is most desirable for the material PVC-U and the nominal size 50 A. On the other hand, in Ref. [4], from the comparison among the results of $h = 3$ mm, 5 mm, and ∞, it was found that $h = 5$ mm is the best for material S25C and nominal size 50 A.

3. Effect of flange nominal size and material difference on the sealing performance of gasketless flanges

In the above discussion, suitable dimensions are investigated for PVC-U in comparison with S25C when the flange nominal size is 50 A. However, it is important to know the effect of flange nominal size on the sealing performance. In this study, therefore, for the size of 250 A

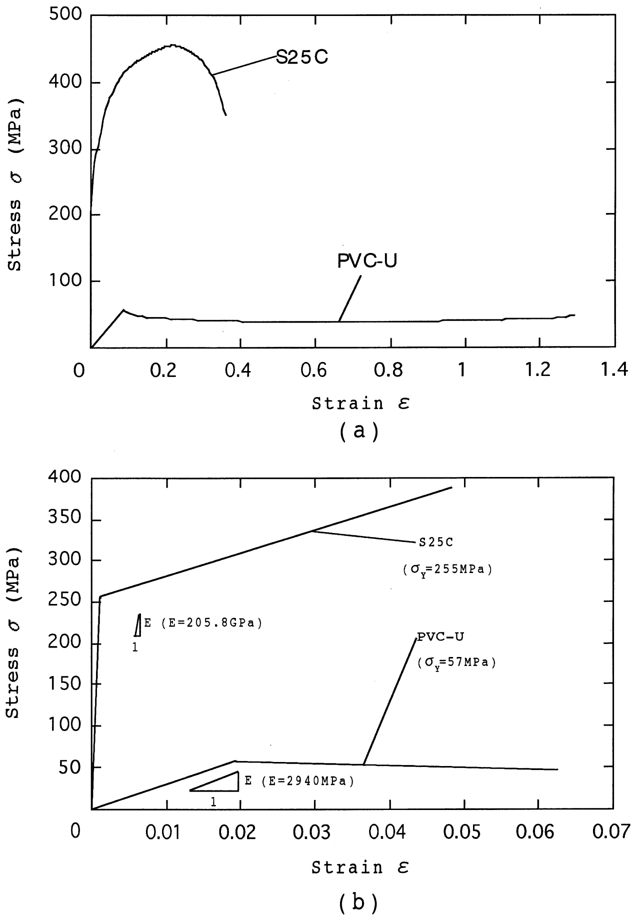

Fig. 7. Stress–strain relations used for (a) S25C and PVC-U and (b) FEM analyses.

[6], superseals made by PVC-U and gasketless flanges made by S25C are prepared, and their sealing performance will be compared with the cases of 50 A using water leak testing. In the analysis of S25C, gasketless flanges are replaced by superseals that have the same dimensions because there is almost no difference between the results [4].

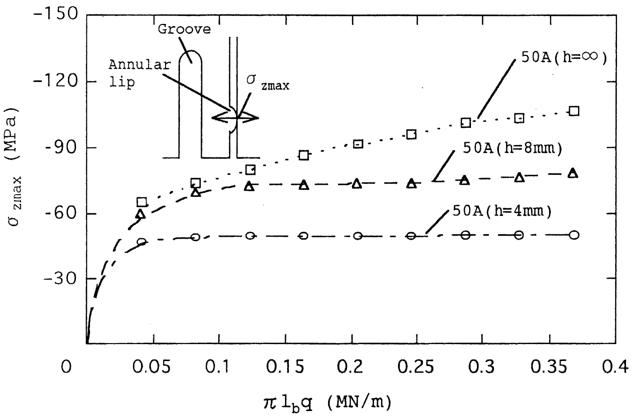

Fig. 8. Clamping force vs. maximum normal stresses for PVC-U.

3.1. Experimental study and results

Table 3(a) with Fig. 3(a) indicates dimensions used for PVC-U, and Table 3(b) with Fig. 3(b) showing dimensions for S25C. In this study, the best dimensions $h = 8$ and 5 mm, which were obtained for 50 A, are applied for the size 250 A; then, the effect of the flange nominal size is investigated. The flanges are clamped using four bolts of M16 (JIS) for 50 A, and 12 bolts of M22 (JIS) for 250 A. Fig. 9 shows the relationship between the clamping force $\pi l_b q$ and the critical internal pressure for leakage, p_{cr} obtained from the experiment. For both PVC-U and S25C, the larger flange nominal sizes decrease the critical internal pressure, p_{cr}. Under the same clamping forces, PVC-U has lower values of p_{cr} compared to S25C. For 50 A of PVC-U, $p_{cr} = 1.7$ MPa = constant when $\pi l_b q \geqq 0.2$ MN/m, and $p_{cr} = 0.4$ MPa = constant for 250 A of PVC-U. This is because the deformation of thinned area is finished if the clamping force is large enough, similar to the case of S25C [4].

3.2. Analytical study and results

Fig. 10 shows the relationship between the clamping force $\pi l_b q$ and the maximum normal stresses in the z-direction $\sigma_{z\max}$ for PVC-U. With increasing flange nominal size, the value of $\sigma_{z\max}$ decreases under the same clamping forces $\pi l_b q$ $(= P/b)$. As shown in Appendix, the rigidity of the flange decreases with increasing flange nominal size. Under the same clamping force and size, S25C has higher values of $\sigma_{z\max}$ than PVC-U because of the higher rigidity.

Fig. 11(a) shows the state of von Mises equivalent stress for PVC-U in comparison with S25C in Fig. 11(b). Here, the same clamping force $\pi l_b q = 0.3$ MN/m is applied to the best dimensions of $h = 8$ mm for PVC-U, and of $h = 5$ mm for S25C. As shown in Fig. 11(a), the PVC-U does not have a plastic zone. On the other hand, as shown in Fig. 11(b), the S25C has certain amounts of plastic zone. The flexibility of PVC-U yields good sealing without a significant plastic zone size.

Fig. 12(a) shows the relationship between the critical internal pressure for leakage, p_{cr}, and maximum normal stresses in the z-direction $\sigma_{z\max}$ for PVC-U and S25C. As shown in Fig. 12(a) and (b), the critical internal pressure for leakage p_{cr} is controlled by the maximum normal stresses in the z-direction even if the flange materials are different. Fig. 12(b) shows the relation for S25C in comparison with PVC-U. Although PVC-U usually has small values of $\sigma_{z\max}$, PVC-U has higher and better values of p_{cr} than S25C under the same values of $\sigma_{z\max}$.

4. Effect of stress relaxation on the sealing performance of PVC-U superseal

In the above discussion, the critical internal pressure for leakage p_{cr} is controlled by the maximum normal stresses in

Table 3
Dimensions of (a) superseals for PVC-U (mm) and (b) gasketless flanges for S25C (mm)

Size (A)	a	b	c	d	e	f	g	h	i	R_j	R_k	l	l_b
(a) Superseals for PVC-U (mm)													
250	400.0	355.0	293.5	277.0	267.0	19	3	8	0.2	1.5	3.5	13.25	37
50	155.0	120.0	86.5	70.0	60.0	19	3	8	0.2	1.5	3.5	13.25	28
(b) Gasketless flanges for S25C (mm)													
250	400.0	355.0	295.5	275.5	269.5	36	3	5	0.2	1.5	4	13	37
50	155.0	120.0	87.1	67.1	61.1	24	3	5	0.2	1.5	4	13	28

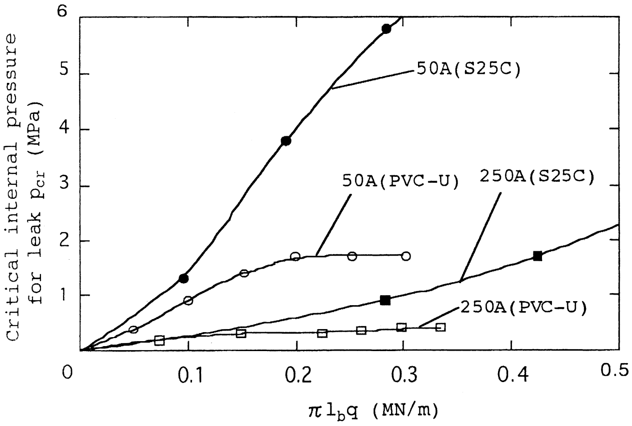

Fig. 9. Clamping force vs. critical internal pressure for leakage for PVC-U and S25C.

the z-direction $\sigma_{z\max}$. However, it is known that under fixed boundary conditions, for PVC-U stresses decrease as time passes due to stress relaxation. Therefore, it is necessary to consider the effect of stress relaxation on the sealing performance.

First, stress relaxation curves for PVC-U are obtained under fixed displacement when the initial stresses 9.8 and

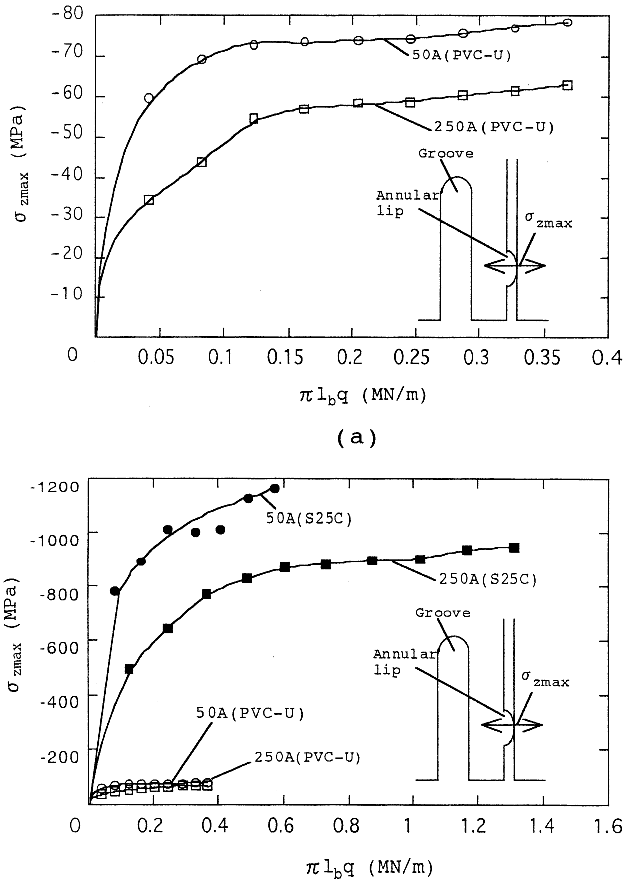

Fig. 10. Clamping force vs. maximum normal stresses for (a) PVC-U and (b) S25C in comparison with PVC-U.

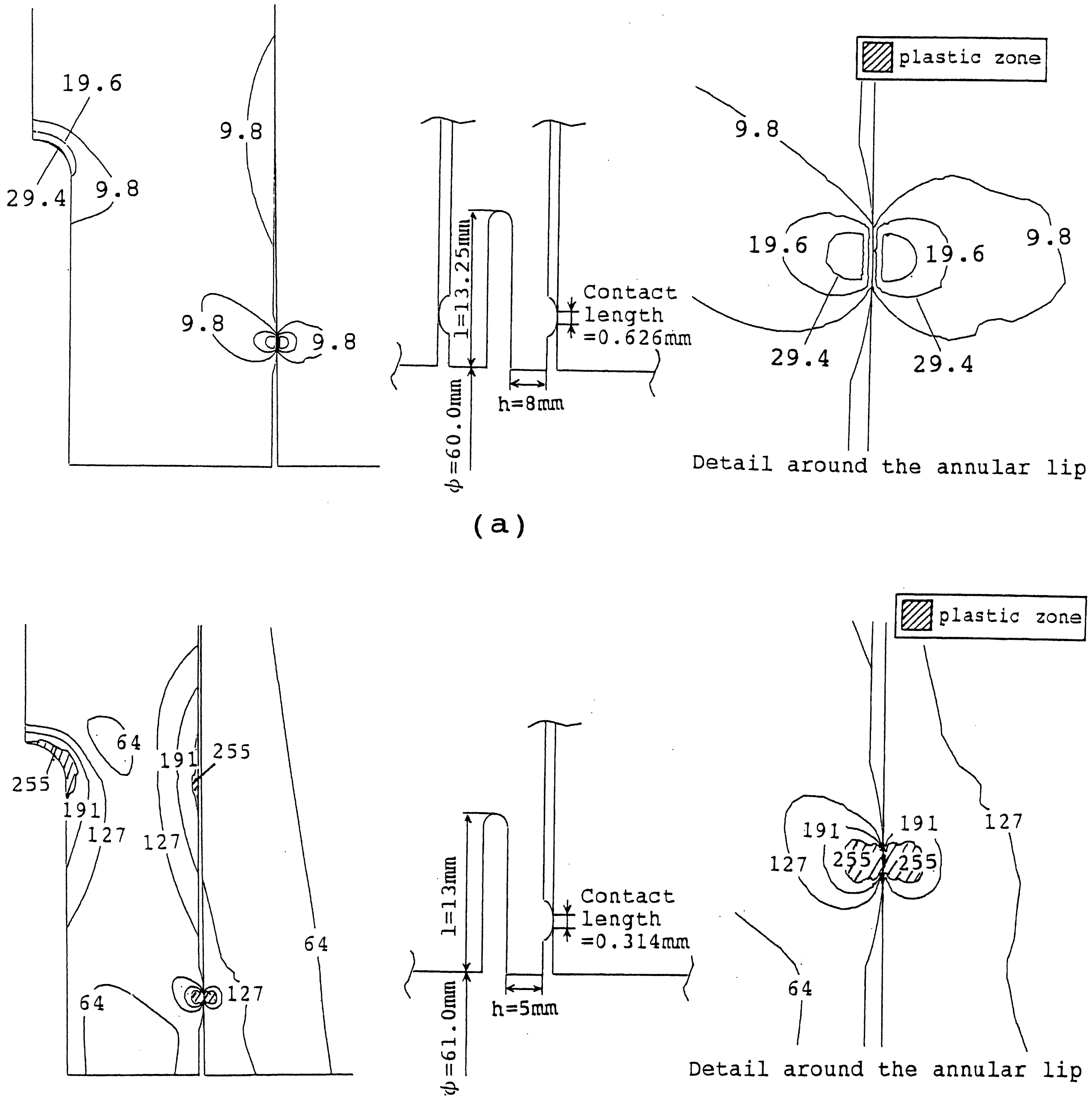

Fig. 11. von Mises equivalent stress σ_{eq} (MPa) for (a) the superseal for PVC-U and (b) the gasketless flanges for S25C.

24.5 MPa are applied (Fig. 11(a)). In this experiment, cylindrical specimens with diameter $d = 25$ mm and height $h = 50$ mm are used. Since stress relaxation curves for plastics depend on the load history before the initial stress is settled [7], a strain rate 200 μm/min, which is similar to the one when the flanges are clamped by bolts, is used to set up the initial stresses. Fig. 13 indicates the stress relaxation curves obtained.

For both cases of 9.8 and 24.5 MPa, the initial stresses decrease by 8.5% after 20 h. For the initial stress of 24.5 MPa, the stress becomes constant after 70 h reduced by 12%.

Next, the effect of stress relaxation on the sealing performance is investigated. In Section 3.2, the critical internal pressure was obtained by increasing the step by 0.05 MPa if no pressure drop is observed for 10 min under the previous pressure. Therefore, the effect of a longer testing time than 10 min is investigated by applying the maximum pressure with no leakage. The results are indicated in Fig. 14 as pressure–time curves.

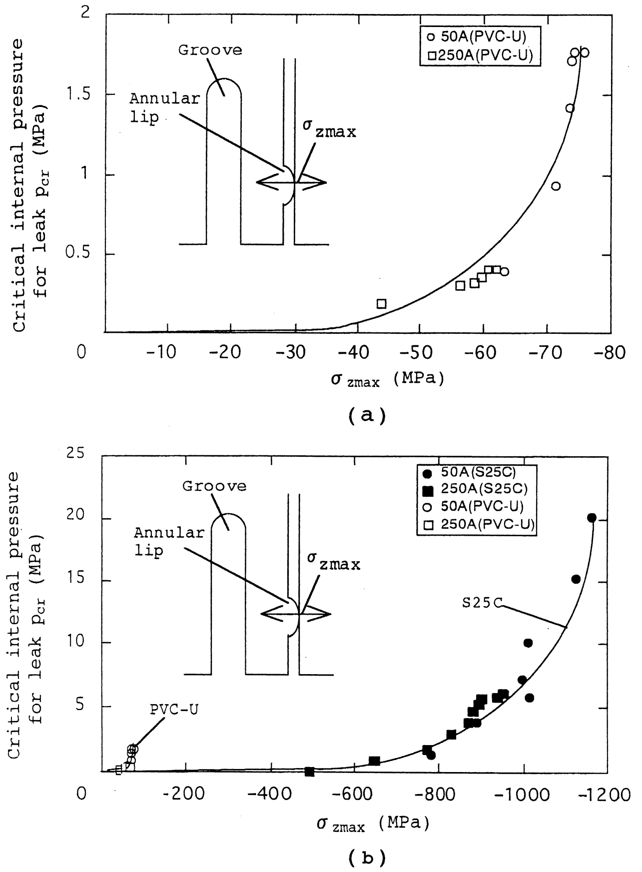

Fig. 12. Maximum normal stresses vs. critical internal pressure for leakage for (a) PVC-U and (b) S25C and PVC-U.

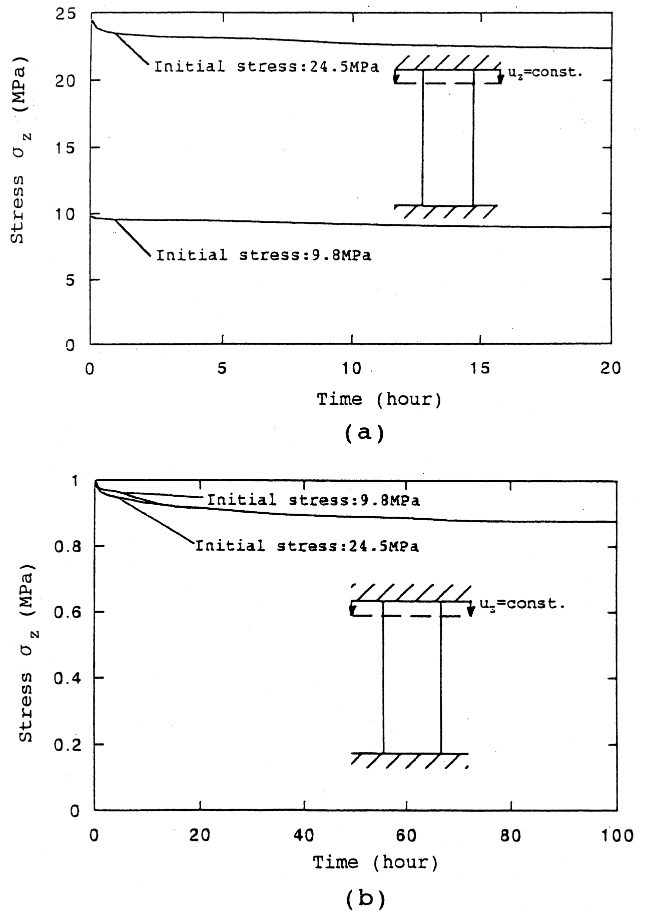

Fig. 13. Results of stress relaxation experiment (a) stress vs. time relation and (b) normalized stress vs. time relation.

For 50 A the pressure p decreases and becomes constant after 15 h, and for 250 A the pressure p decreases and becomes constant after 23 h. Further pressure drop is not observed until 100 h although it is not shown in the figure. These pressure drops are due to creep and expansion of the pipes and flanges, and are clearly different from the pressure drops when $p > p_{cr}$ is applied to the flanges with leakage.

Finally, the critical pressures p_{cr} obtained for 10 min testing time are also indicated in Fig. 14 as functions of time. As shown in the figure, p_{cr} is constant and independent of time. The effect of stress relaxation for PVC-U on the sealing performance can almost be neglected although the stress σ_{zmax} may decrease by about 10%.

To confirm the practical use, a PVC-U superseal with the size 50 A is also used at Mitsubishi Chemical Plant in Kurosaki, Japan. There, no leakage has been found for more than one and a half years under the following conditions:

Total clamping force: 12 KN ($\pi l_b q = 0.1$ MN/m).
Fluid used: hydrochloric acid.
Temperature used: room temperature
Pressure of fluid used: 0.49 MPa.

The authors think PVC-U superseals have enough life expectancy for industrial use from the results of the stress relaxation tests and this industrial application.

The stress relaxation tests and industrial application in this study and also other creep data of plastics [8,9] suggest that PVC-U superseals can be used for as many years as PVC-U pipes often used in industries.

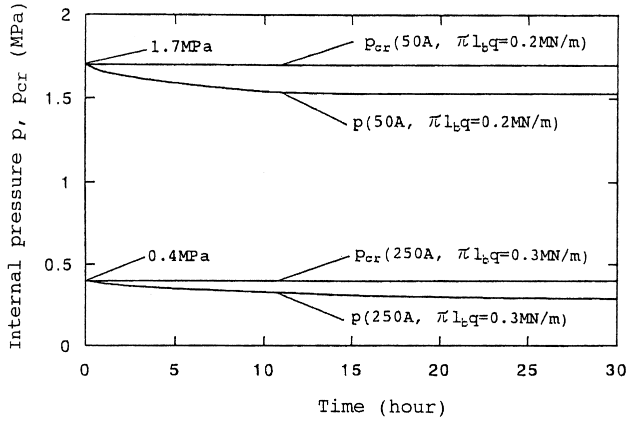

Fig. 14. Internal pressure vs. time relation.

5. Conclusions

Generally, the sealing performance of gaskets of flanged joints deteriorates after several years in service, and may result in leakage and eventually a need to replace the gaskets. In this paper, a new seal system is considered. In order to investigate the effects of material difference and flange nominal size, several gasketless flanges and superseals have been prepared. According to the experiment and FEM analysis, the following conclusions can be made:

1. Regarding superseal made by PVC-U with the size 50 A, from the comparison among the results of $h = 4$ mm, 8 mm, and ∞, it may be concluded that the thickness of deformation part $h = 8$ mm is the most desirable dimension. On the other hand, for S25C with size 50 A, $h = 5$ mm was the best dimension among the results of $h = 3$ mm, 5 mm, and ∞ [4].
2. From the results of the experiment and FEM analysis, for both S25C and PVC-U, the critical internal pressure for leakage p_{cr} is controlled by the maximum normal stresses in the z-direction $\sigma_{z\max}$.
3. For superseal made by PVC-U, it is difficult to obtain the higher $\sigma_{z\max}$. However, the higher critical internal pressure for leakage p_{cr} is obtained even under smaller values of $\sigma_{z\max}$ compared with the case of S25C. This is because PVC-U is flexible and easy to form a good seal line when the flanges are assembled.
4. The effect of stress relaxation for PVC-U on the sealing performance can almost be neglected although the stress $\sigma_{z\max}$ may decrease by about 10%.

Acknowledgements

The authors wish to express their thanks to former Professor Sadao Arai with Kyushu institute of Technology for his warmest advice about stress relaxation for PVC-U. The assistance and support given by the members of the research group, especially Prof. Hiroyuki Tanaka, Mr Ken-Ichiro Takeuchi, Mr Yasushi Takase, Kyushu Institute of Technology, and Mr Hiroshi Otsuji, President of Daiso Corporation, are greatly appreciated. This research has been partly supported by REFEC research fund.

Appendix. FEM analysis for the effect of flange nominal size

In the previous study [4], the most suitable dimension of S25C gasketless flange with size 50 A was investigated by using water leak testing. Using the best dimension

Table A1
Dimension of analytical model (mm)

Size (A)	a	b	c	d	e	g	h	i	R_j	R_k	l	l_b
2000	2093.9	2058.9	2025.9	2006	2000	3	5	0.2	1.5	4	13	28
1000	1093.9	1058.9	1025.9	1006	1000	3	5	0.2	1.5	4	13	28
250	363.4	328.4	295.5	275.5	269.5	3	5	0.2	1.5	4	13	28
50	155.0	120.0	87.1	67.1	61.1	3	5	0.2	1.5	4	13	28
20	121.6	86.6	53.7	33.7	27.7	3	5	0.2	1.5	4	13	28

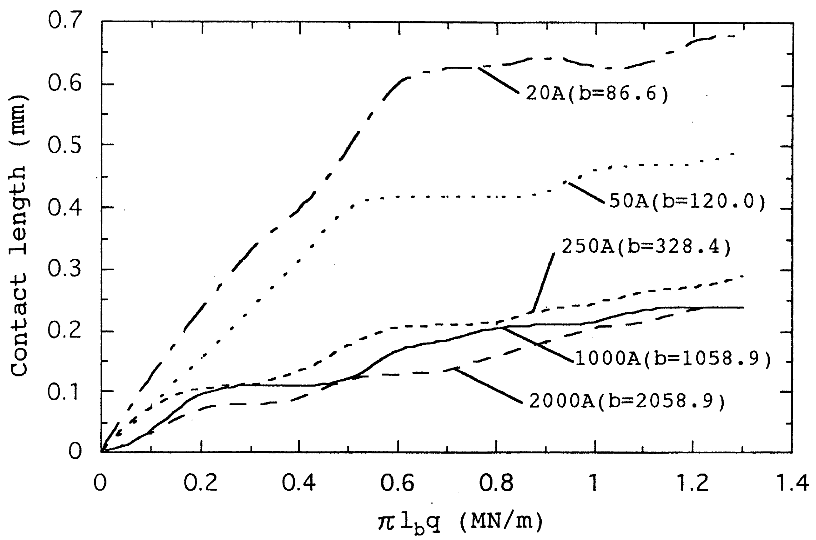

Fig. A1. Clamping force vs. contact length.

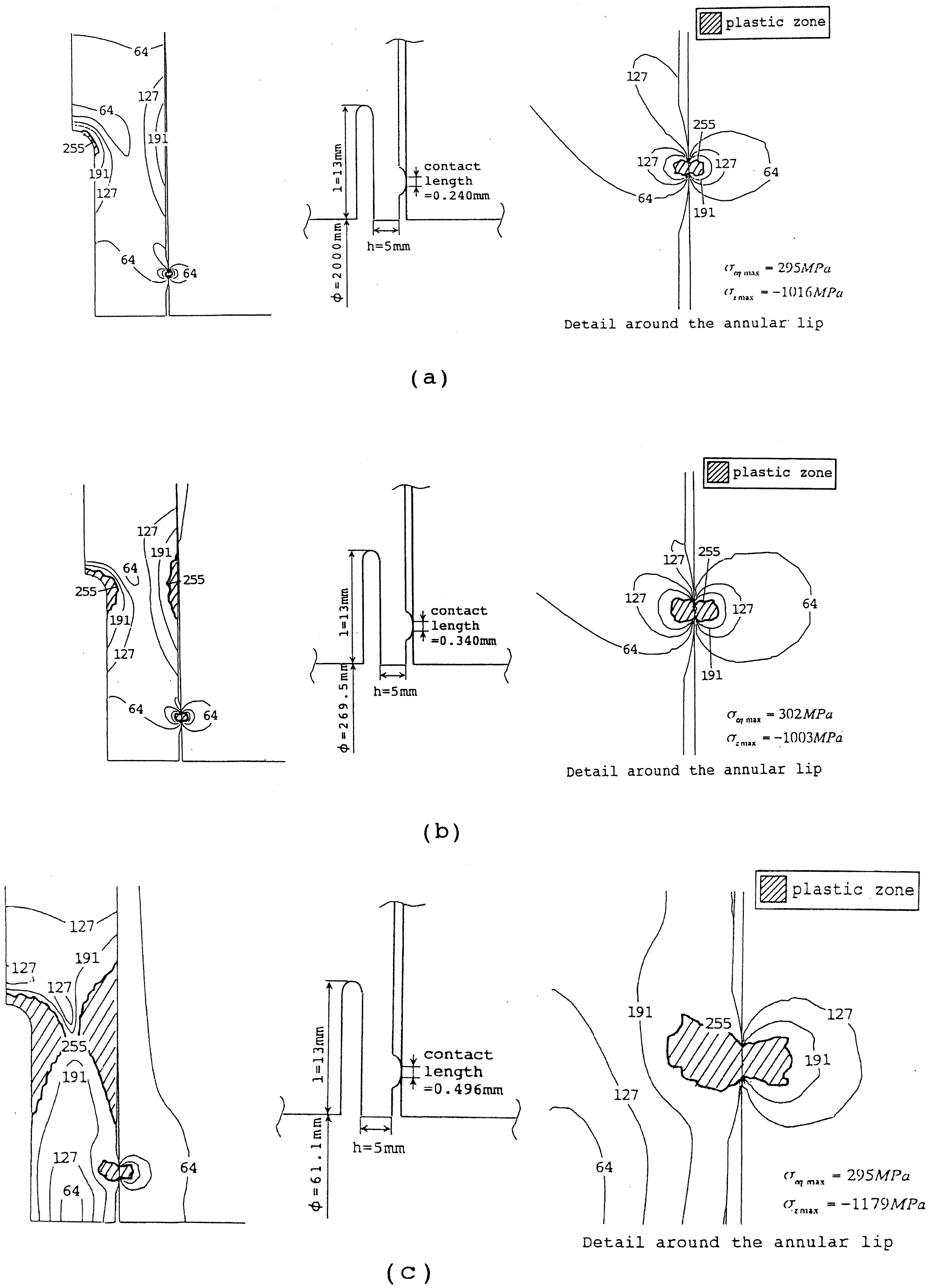

Fig. A2. von Mises equivalent stress σ_{eq} (MPa) for (a) 2000 A in Table 1 (clamping force $\pi l_b q = 1.29$ MN/m). (b) 250 A in Table 1 (clamping force $\pi l_b q = 1.29$ MN/m). (c) 50 A in Table 1 (clamping force $\pi l_b q = 1.29$ MN/m).

$h = 5$ mm obtained for 50 A, the effect of flange nominal size is investigated through the FEM analysis by varying the size from 20 to 2000 A [6]. The dimensions are shown in Table A1 with Fig. 3(b). Fig. A1 shows the relationship between the clamping force $\pi l_b q (= P/b)$ and the contact length. With increasing flange nominal size, the contact length decreases under the same clamping force $\pi l_b q$. Fig. A2(a)–(c) shows the von Mises equivalent stresses under the same clamping force $\pi l_b q = 1.29$ MN/m. With increasing flange size, both the value of $|\sigma_{z\max}|$ and the plastic zone size decrease because of the decreasing rigidity of the flange. To obtain the same sealing performance for the large flanges, it seems necessary to increase the rigidity of the deformed area by increasing the thickness of the deformed area, or decreasing the depth of the groove.

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