Punching of Aluminum-clad Stainless Steel and Stainless Steel-clad Aluminum Material

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1. Introduction

It is no doubt that the progress of science and technology has been promoting the development of new material such as clad materials, plastics, ceramics, etc.

The new materials are expected to be used more often in the future, because they will be more advantageous than conventional materials such as steel, aluminum etc. There are many kinds of new materials. The clad material, two or more distinct metals or alloys that are metallurgically bonded together, will especially become of major interest for the reasons mentioned below. It is possible to design the machine parts: to select the clad material: to get many combinations by the information based on the known data.

However, the clad materials have some problems. That is to say, the machinability of the clad material depends upon the different yield points and work hardenability of the component materials. The bonding strength of the clad material also deeply influences the strength and machinability of it. Although not much data has been compiled regarding the clad materials, much is already known regarding the components which make up the clad material. For this reason, it would be relatively easy for a clad material to be selected to design machine parts, and because of its various kinds of characteristics, it would be adaptable for many purposes.

This study deals with the punching mechanism of Al-clad SS and SS-clad Al material. (They refer herein after to the Aluminum-clad Stainless Steel and Stainless Steel-clad Aluminum material, respectively.) The Al-clad SS and the SS-clad Al materials are widely used for automobile production.[1-1] The punching process should be indispensable work in the maching of clad materials at that automobile factory.

2. Clad Material

The Al-clad SS and the SS-clad Al materials selected in this paper are widely used for automobile's parts, because of high durability, much weight reduction, well corrosion control, good appearance, and etc. "How clad materials are made?" is mentioned below.[2-1)] The clad material can be made by several processes. Prior to continuous roll bonding process, the individual strips of metal are extensively cleared to provide contaminant free surfaces. And passed through a high pressure rolling mill. Subsequent thermal treat is then done to induce diffusion, improve bond strength, and provide stress relief for further cold working operation. Finally, finishing operations are performed such as rolling, annealing, edge trimming, slitting and cutting.

Table 2. 1 The Strength and the Thickness of Specimens

		Ultimate Tensile Strength			Thickness	
Al-clad SS		22.6 ksi	156 MPa	15.9 kgf/mm^2	0.1208 in.	3.068 mm
	Al 1100	12.3	84.7	8.6	0.054 ×2 (44.7×2)%	1.37×2
	SS 304	111.5	793	80.9	0.0128 (10.6%)	0.33
SS-clad Al		36.0	268	25.3	0.111	2.82
	SS 304	99.0	683	69.7	0.0155×2 (13.9×2)%	0.39×2
	Al 1100	13.6	93.7	9.6	0.08 (72.2%)	2.03

Table 2. 1 shows the strength and the thickness of clad sheets. The punching experiment of monolithic metals which correspond to the clad metals, Aluminum

Table 2. 2 Composition of Aluminum 1100

Al	Cu	etc
99.00%	0.12%	bal

Table 2. 3 Composition of Stainless Steel 304

Cr	Ni	C	Mn	Si	P	S	Fe
18.07%	8.14%	0.053%	1.46%	0.40%	0.028%	0.013%	71.84%

1100 and Stainless Steel 304 are done. The composition of Al 1100 and SS 304 are shown in Table 2. 2 and 2. 3.

3. Mixture Rule

An empirical rule of mixture is often used to predict the properties of laminates. The rule of mixtures averaging technique has been applied to both continuos fiiamentary composites and sheet materials.[3-1), 3-2)] Predictions agree well with observations, except at low strains, where differences in flow stress and elastic modulus of the components give rise to non-eligible multiaxial stress states. Although the rule of mixtures can be used to obtain accurate estimates of composite stress-strain curves from component stress-strain curves, a similar area-weighted average cannot be used to predict uniform tensile elongation.[3-1), 3-3)] However, predictions based on the maximum load condition for stability in monolithic materials have been shown to agree very well with filamentary composite data[3-4), 3-5)] as well. The phenomena of localization and fracture of sandwich sheet composites under tensile loading remain largely unexplored.

4. Experiment

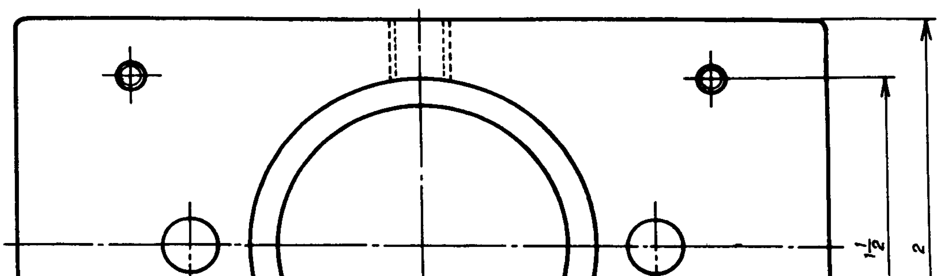
4. 1 Apparatus

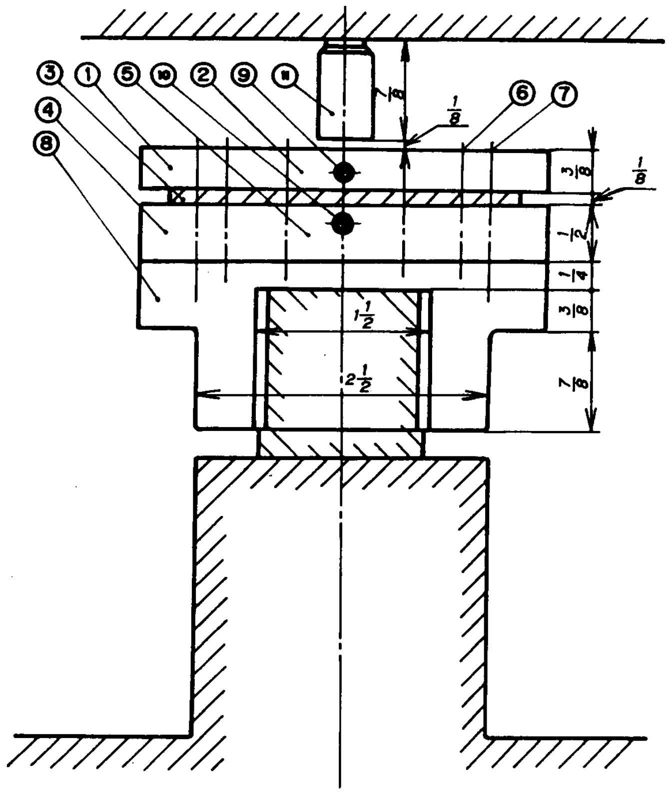
Figs. 4. 1.–4. 5 show the geometry of punching tools. Tables 4. 1–4. 3 show the dimension ot the tools. The high speed steel (air hardened A2, Rc55–60) are used.

The equipment used in this punching experiment is the "Dake Servo Hydraulic Press" (Maximum Load 50 klb (22.7 ton, 222.5 kN, Dake Corporation)).

4. 2 Test Condition

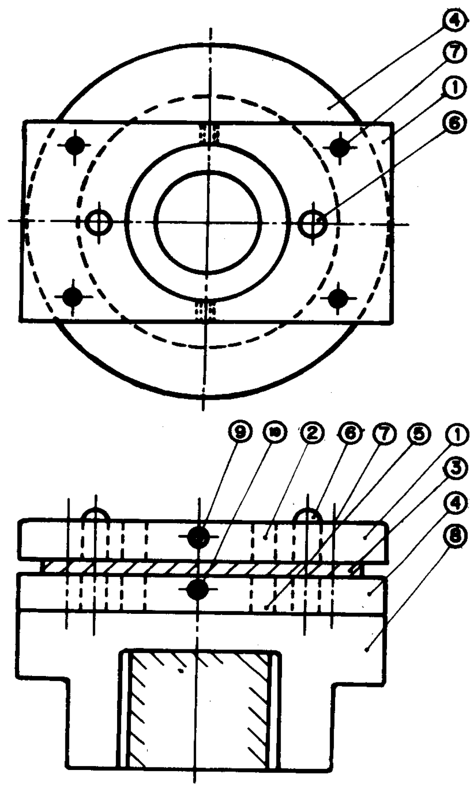
Table 4. 4 shows the experimental conditions. The percentage radial clearances are 10.5, 17.5 & 28% for each punch diameter respectively. They are relatively high because the purpose of the punching process is to make a hole. Generally speaking, the punching process has a relative higher percentage radial clearance





① Die holding plate ② Upper die ③ Plate (Specimen) ④ Die holder ⑤ Die
⑥ Guide pin ⑦ Screw ⑧ Die set holder ⑨, ⑩ Die fixing screw ⑪ Punch

Fig. 4. 1 Schematic Diagram of Punching Apparatus



① Die holding plate ② Upper die ③ Plate (Specimen) ④ Die holding ⑤ Die
⑥ Guide pin ⑦ Screw ⑧ Die set holder ⑨, ⑩ Die fixing screw

Fig. 4. 2 Diagrammatic Arrangement of Axi-symmetric Punching

Table 4. 3 The Dimension of the Lower Die

Lower Die (A2)

D_p	d_d	d_c	L_d	L_{dh}	L_{dl}
1" (25.4 mm)	1+C" (25.4+C mm)	1 1/8"(28.6 mm)			
5/8" (15.9 mm)	5/8+C" (15.9+C mm)	6/8"(19.1 mm)	3/8" (9.5 mm)	2/8" (6.4 mm)	1/8" (3.2 mm)
3/8" (9.5 mm)	3/8+C" (9.5+C mm)	4/8"(12.7 mm)			

$C=D_p \times 7/100$ $D_h=1\ 1/2$ in (38.1 mm) (all the same)

Table 4. 4 Experimental Conditions

Punch Diameter (in.)	3/8 (9.5 mm), 5/8 (15.9 mm), 1 (25.4 mm)
Clearence (%)	10.5, 17.5, 28.0
Tool Material	High Speed Steel, A2 (Air Hardened, R_c 55~60)
Punching Speed (in./min)	10.14 (257.6 mm/min, less than)
Lubricant	MoS_2

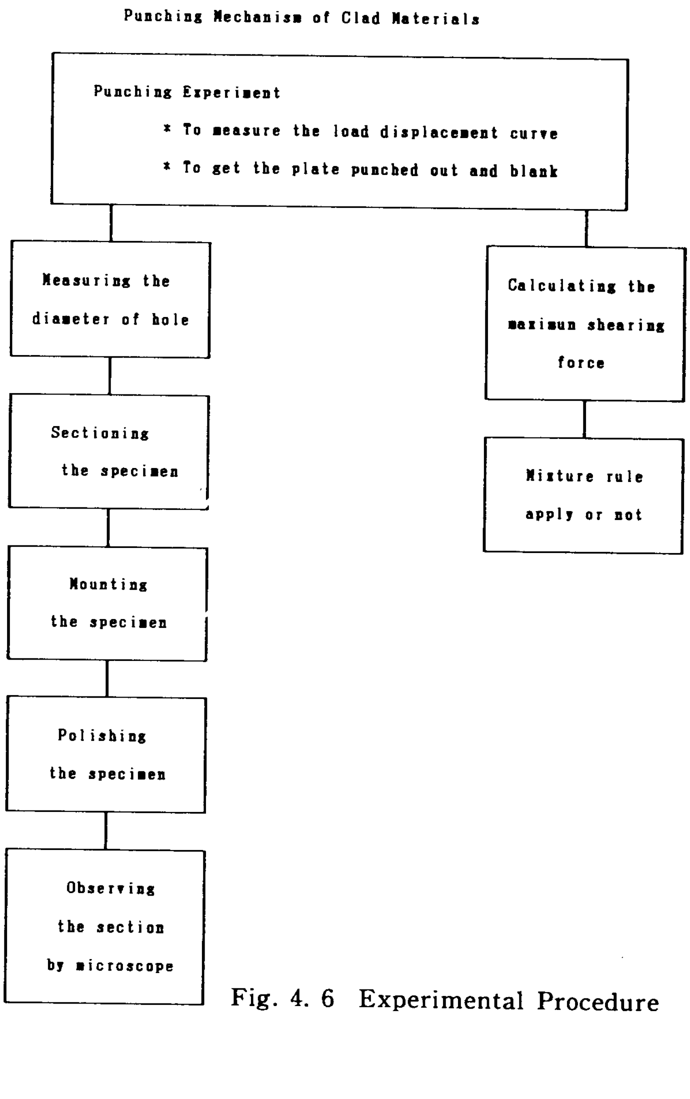


Fig. 4. 6 Experimental Procedure

measured by optical microscope which has two direction micrometers. And specimens are mounted by bakelite resin to polish and observe the section. The punching process is sometimes stopped half-way to investigate the punching mechanism of clad material.

5. Results and Discussion

5. 1 Maximum Shearing Stress and Mixture Rule

Fig. 5. 1 shows the maximum shearing stress of four kinds of materials with three different kinds of punch diameters and ultimate tensile strength. The maximum shearing stress calculated from the expeiment in each punch diameter is less

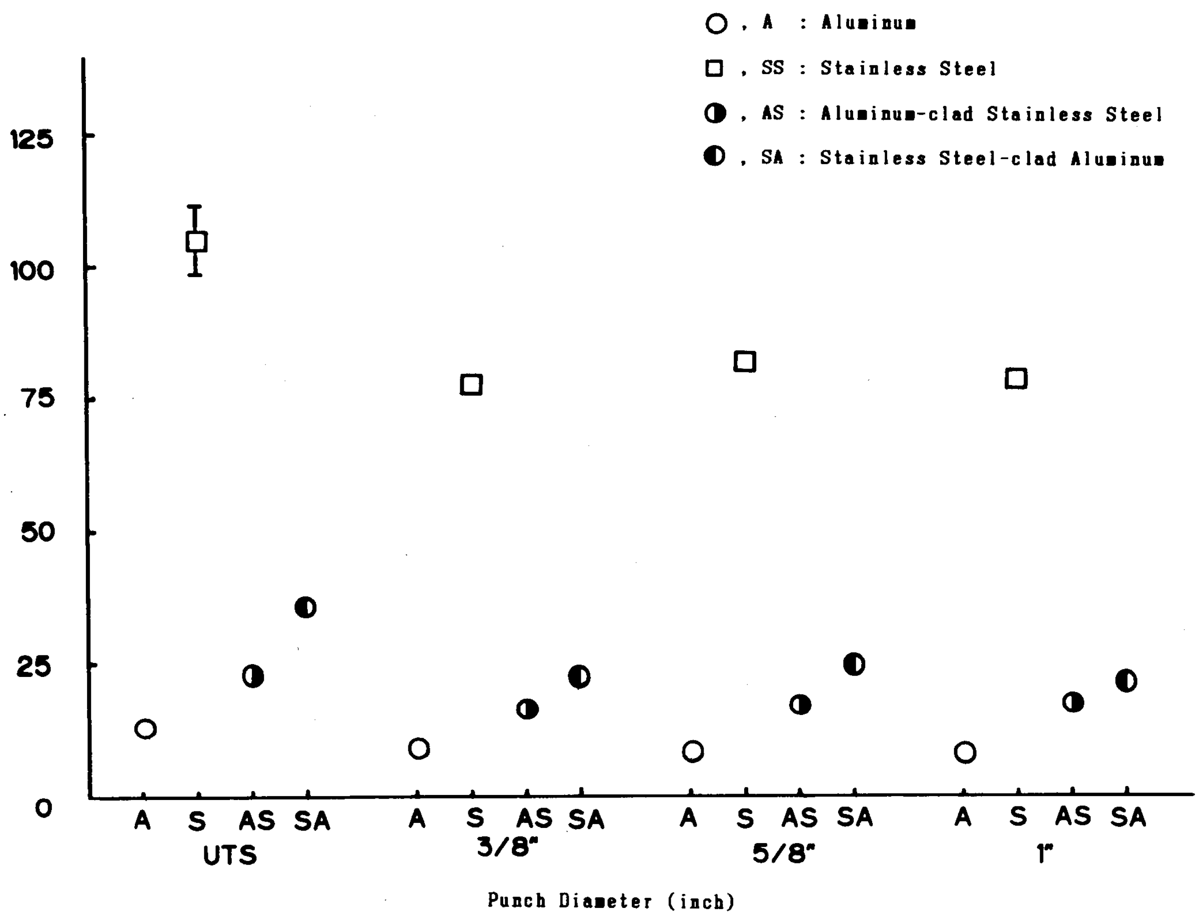


Fig. 5. 1 Ultimate Tensile Strength and Maximum Shearing Stress of Each Material in Each Punch Diameter

than the ultimate tensile strength of each of them. There is not much difference in the maximum shearing stresses of each punch diameter. But a little difference in Stainless Steel and SS-clad Al can be recognised.

Table 5. 1 shows the maximum shearing stresses predicted by mixture rule to compare with the maximum shearing stress calculated from the experiment. In this

Table 5-1 The Maximum Shearing Stress predicted by Mixture Rule for Each Punch compared to Experimental Value

Material	Maximum Shearing Stress			
	Punch Diameter			By Literature[5-1]
	3/8"	5/8"	1"	
Al (Al 1100)	9.5 ksi (6.7 kgf/mm²)	9.3 ksi (6.6 kgf/mm²)	8.7 ksi (6.1 kgf/mm²)	9~11 kgf/mm²
SS (SUS 304)	78.1 ksi (54.9 kgf/mm²)	82.6 ksi (58.1 kgf/mm²)	79.1 ksi (55.6 kgf/mm²)	52~56 kgf/mm²
Al-clad SS	17.3 ksi (12.2 kgf/mm²)	17.7 ksi (12.5 kgf/mm²)	17.4 ksi (12.2 kgf/mm²)	—
Al-clad SS calculated by Mixture Rule	16.6 ksi (11.6 kgf/mm²)	16.7 ksi (11.7 kgf/mm²)	16.2 ksi (11.2 kgf/mm²)	—
SS-clad Al	22.7 ksi (16.0 kgf/mm²)	24.9 ksi (17.5 kgf/mm²)	21.5 ksi (15.1 kgf/mm²)	—
SS-clad Al calculated by Mixture Rule	25.7 kgi (18.0 kgf/mm²)	26.6 ksi (18.6 kgf/mm²)	25.4 ksi (17.8 kgf/mm²)	—

case these stresses calculated by the method which are based on each maximum shearing stress in the punching of component monolithic materials.

The maximum shearing stresses of Al-clad SS materials calculated by the experiment are 17.3 ksi (12.2 kgf/mm², 119.6 MPa) for 3/8", 17.7 ksi (12.5 kgf/mm², 122.5 MPa) for 5/8", and 17.4 ksi (12.2 kgf/mm², 119.7 MPa) for 1". And the maximum shearing stresses calcuiated by mixture rule are 16.6 ksi (11.6 kgf/mm², 113.7 MPa) for 3/8", 16.7 ksi (11.7 kgf/mm², 114.7 MPa) for 5/8", and 16.2 ksi (11.2 kgf/mm², 109.8 MPa) for 1". Differences between them are −4.9% for 3/8", −6.4% for 5/8", and −8.2% for 1".

The maximum shearing stresses of SS-clad Al materials calculated by the experiment are 22.7 ksi (16.0 kgf/mm², 156.8 MPa) for 3/8", 24.9 ksi (17.5 kgf/mm², 171.5 MPa) for 5/8", and 21.5 ksi (15.1 kgf/mm², 148.0 MPa) for 1". And the maximum shearing stresses calculated by mixture rule are 25.7 ksi (18.0 kgf/mm², 176.4 MPa) for 3/8", 26.6 ksi (18.6 kgf/mm², 182.3 MPa) for 5/8", and 25.4 ksi (17.8 kgf/mm², 174.4MPa) for 1". Differences are 12.5% for 3/8", 6.3% for 5/8", and 17.8% for 1".

The difference in Al-clad SS material is less than that in SS-clad Al material. The reason why Al-clad SS material has less difference between them than SS-clad Al material may be the shape of punch force-punch displacement curve. A little differences in both of them are due to the bonding strength which is not obtained in any papers, the different work hardenablity of each component material and etc.

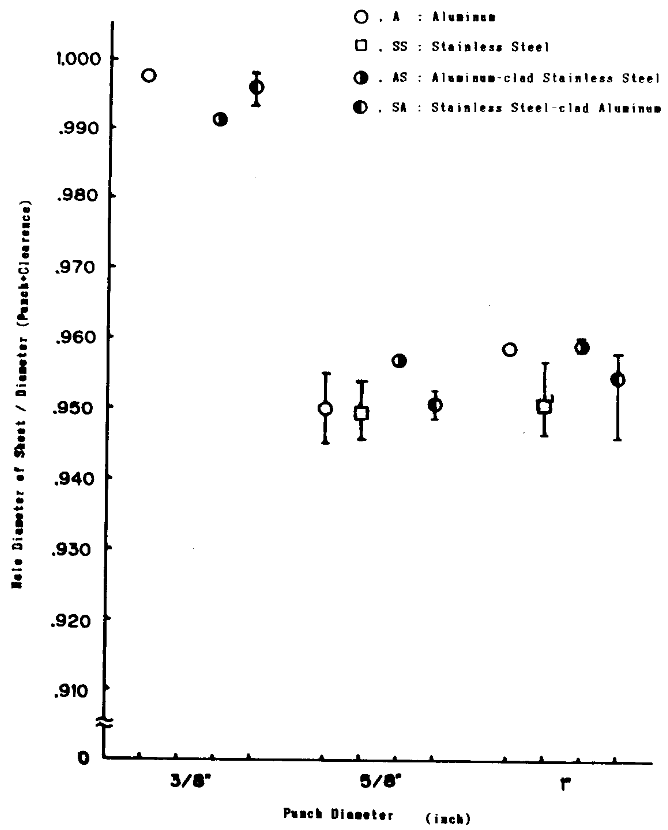


Fig. 5. 2 Ratio of Sheet Diameter to Punch Diameter

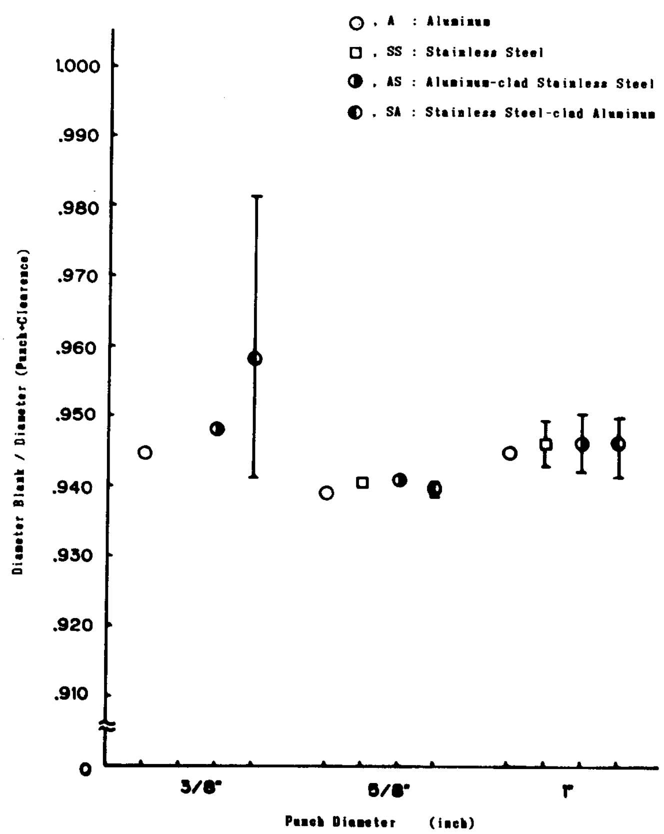


Fig. 5. 3 Ratio of Blank Diameter to Punch Diameter

5. 2 Measurement of Hole Diameter

Figs. 5. 2 and 5. 3 show the measurement of the hole diameters. Fig. 5. 2 shows that the hole of the 3/8" diameter punch in the sheet is distinctly better than those of the other sizes. That better hole depends upon the small clearence. The 5/8" hole and the 1" hole have nearly the same tendency in sheet to punch diameter ratio values, even though a difference in clearence can be found. In all the diameters of blanks, except SS-clad Al material, a prominent difference in size cannot be found. Morever, the difference of the diameter of hole and blank except for the aluminum blank does not depend upon the kind of material.

5. 3 Observations of the Specimen

Sheet Figs. 5. 4 thru 5. 7 show the sheets of Aluminum, Stainless Steel, Al-clad SS, and SS-clad Al materials which are punched out. Fig. 5. 4 points out that it, the Aluminum, is not smooth since it exhibits a jogged surface near the exit point of the punch. Fig. 5. 5 shows that the punched surface of the Stainless Steel is not perpendicular. It exhibits much distortion in a localized region near the punching surface. The Al-clad SS sheets inward concavity does not start at the edge but rather at a small distance from the edge. This is because the distortion zone is very pronounced, as in Fig. 5. 6.

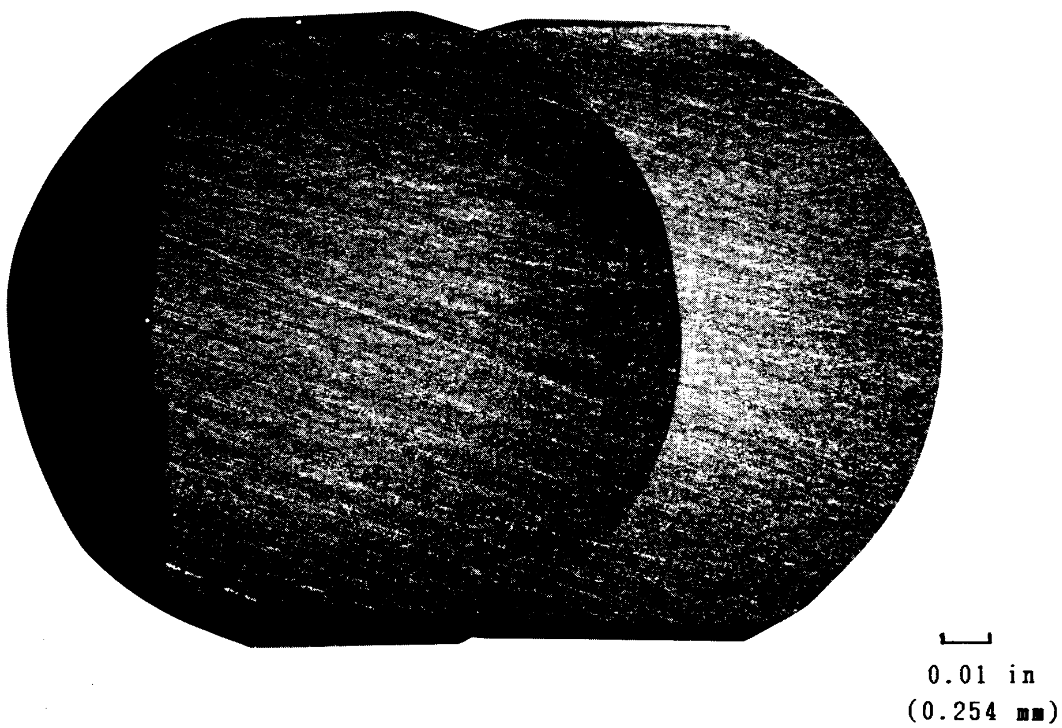
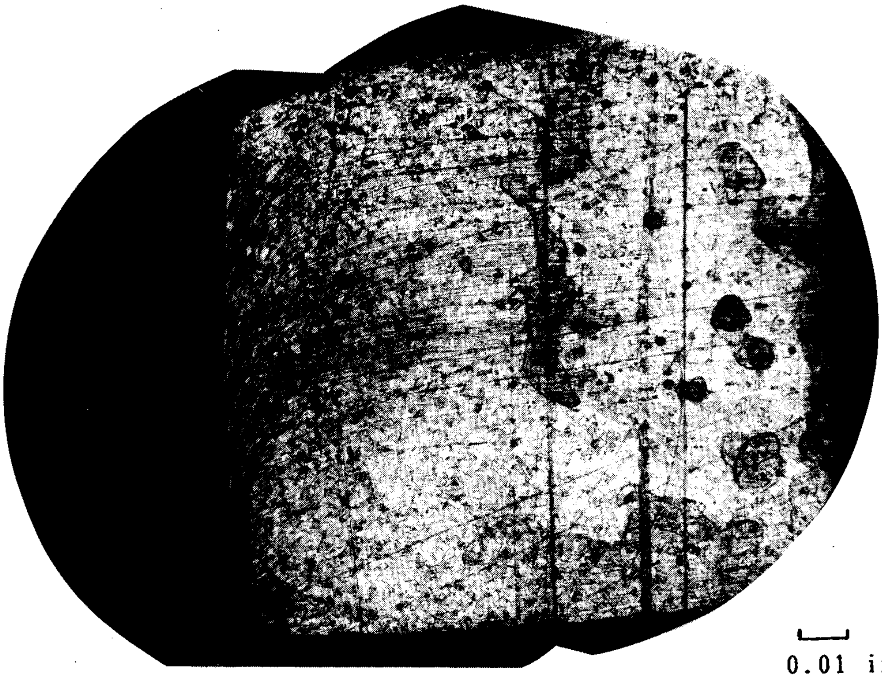
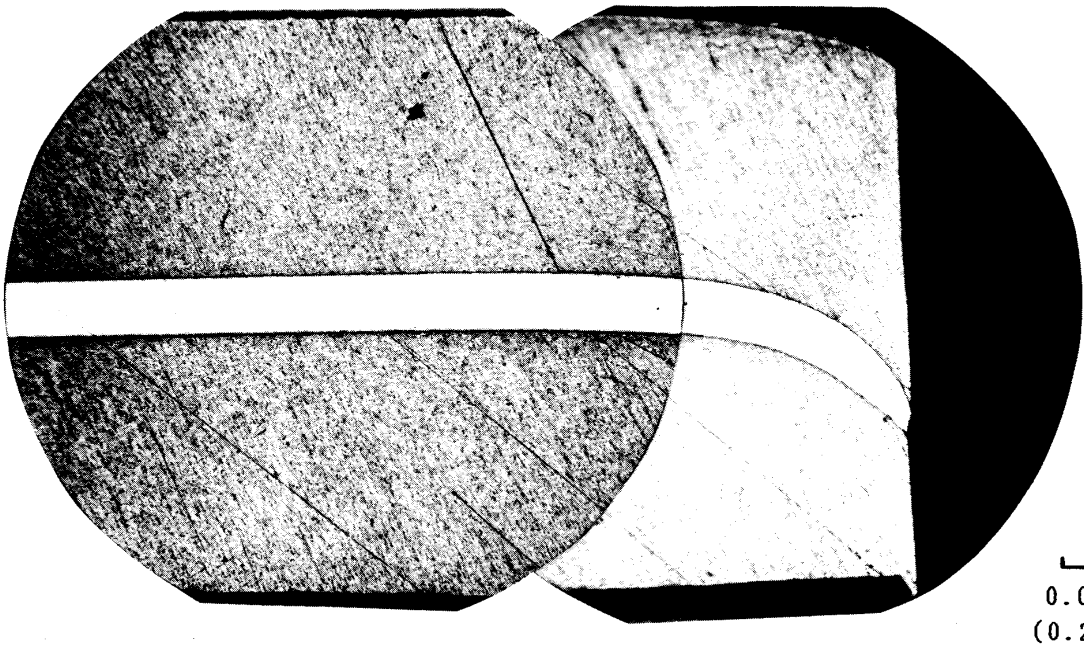


Fig. 5.4 Aluminum Sheet Section
P. D. (Punch Diameter)1 in (25.4 mm)



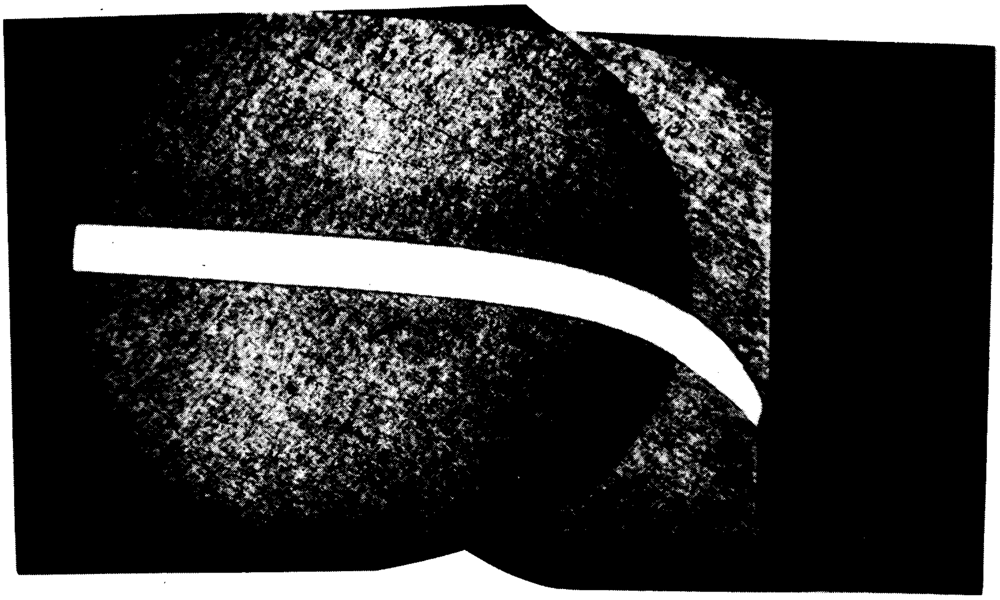
0.01 in
(0.254 mm)

Fig. 5.5 Stainless Steel Sheet Section
P. D. 3/8 in (9.5 mm)



0.01 in
(0.254 mm)

Fig. 5.6 Al-clad SS Sheet Section
P. D. 5/8 in (15.9 mm)



0.01 in
(0.254 mm)

Fig. 5.7 SS-clad Al Sheet Section
P. D. 5/8 in (15.9 mm)

In Fig. 5.7 SS-clad Al sheet section shows much doming in a localized region near the punched surface. Beyond this region there is no distortion while in Al-clad SS sheet distortion appeared over the entire surface. Because of elongation, the stainless steel section of Al-clad SS material becomes tapered near the punching surface. The curvature of the Stainless Steel in Al-clad SS material is greater than that of Aluminum in the punched material because the strain in the Aluminum is greater than that of the Stainless Steel. The stress applied to the Aluminum is greater than its fracture stress, but not so for the Stainless Steel. This situation allows the Stainless Steel section to elongate till fracture stress is reached, as can be seen in half-way specimens.

Blank Figs. 5.8 thru 5.11 show the sections of blanks of Aluminum, Stainless Steel, Al-clad SS, and SS-clad Al materials. Each specimen shows the different shape and size of deformation zone. Especially remarkable is the difference between the Al-clad SS and the SS-clad Al materials. That is to say, the deformation zone of SS-clad Al material could be found at the perimeter of the hole, while the Al-clad SS material has two different kinds of deformation zones which are doming and dishing. Much doming in the latter could be found. The blank section of monolithic

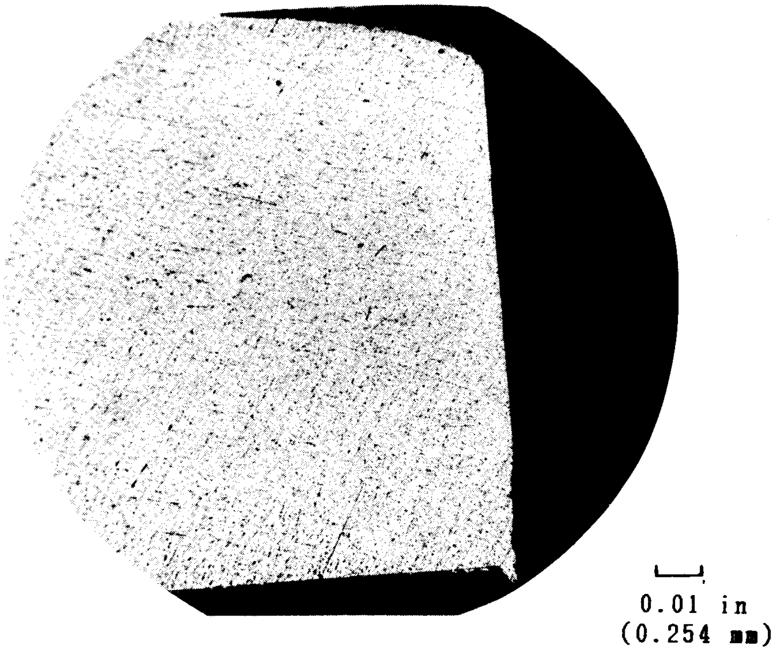


Fig. 5.8 Aluminum Blank Section
P. D. 5/8 in (15.9 mm)

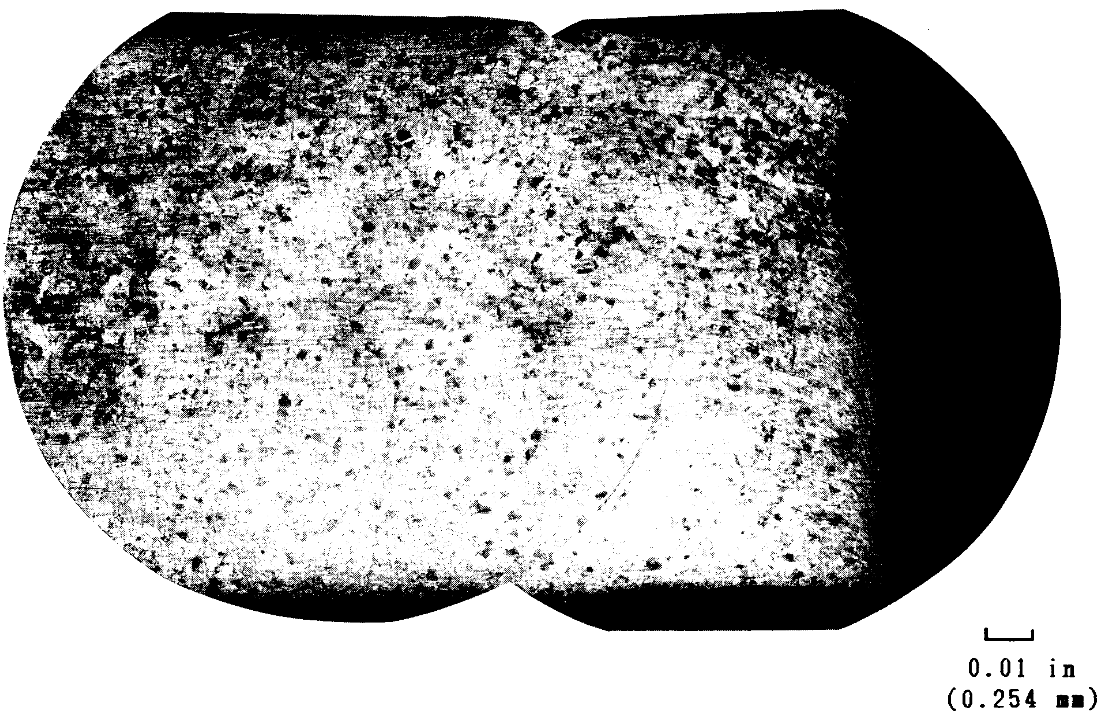
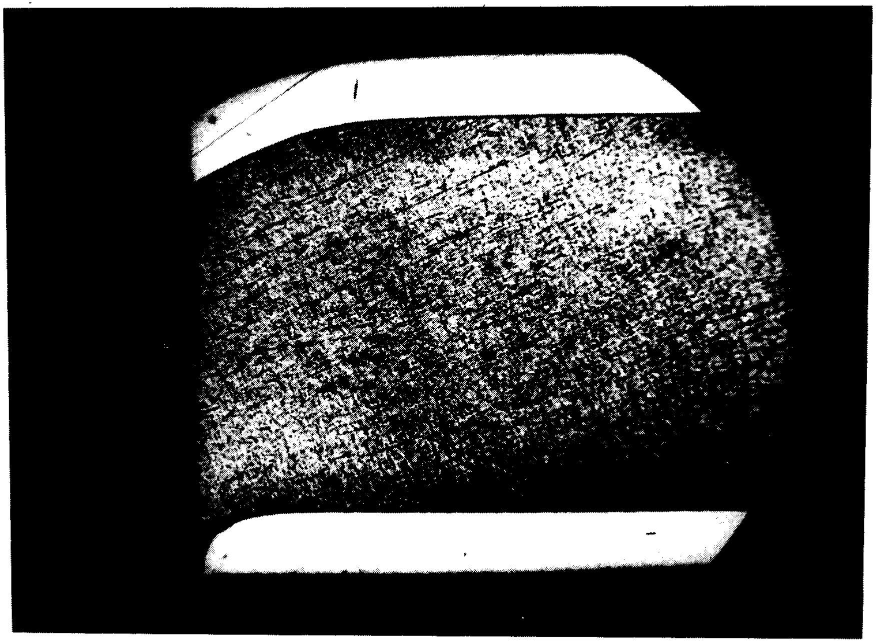
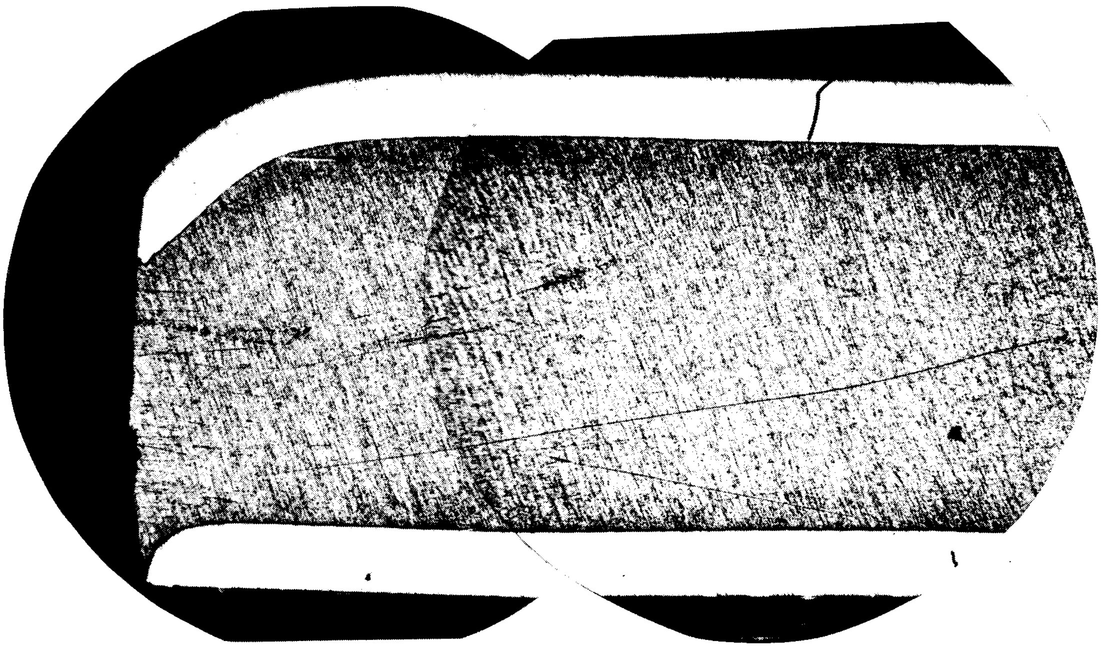


Fig. 5.9 Stainless Steel Blank Section
P. D. 5/8 in (15.9 mm)



0.01 in
(0.254 mm)

Fig. 5.10 Al-clad SS Blank Section
P. D. 5/8 in (15.9 mm)



0.01 in
(0.254 mm)

Fig. 5.11 SS-clad Al Blank Section
P. D. 1 in (25.4 mm)

Aluminum shows smoother and straighter surface than its sheet section counterpart. The other three materials do not have much difference between the sheet and blank section in appearence except in curvature. The curvature of doming of the blank in Stainless Steel, SS-clad Al, and Al-clad SS material is greater than that of the sheet. The separation of Aluminum from Steinless Steel in the punching experiment is closely related to the bonding strength. The two clad materials do not have the same tendencies for boundary seperation. A difference that exists between the two clad punched sheet sections is that in the Al-clad SS materiel the Aluminum is cleanly cut whereas in the SS-clad Al material the Aluminum has a cut with jogs. The monolithic materials exhibit a smoother surface on both sheet and blank sections than either clad materials show.

Figs. 5.12 and 5.13 show the sections of the half-way specimens of Aluminum. Fig. 5.14 shows the section of the half-way specimen of Staininless Steel. These figures distinctly show the difference in doming between Aluminum and Stainless Steel specimens.

Figs. 5.15 thru 5.18 show the processes of punching. The mechanism of the elongation of the Stainless Steel in clad material is schematicaly shown. After the

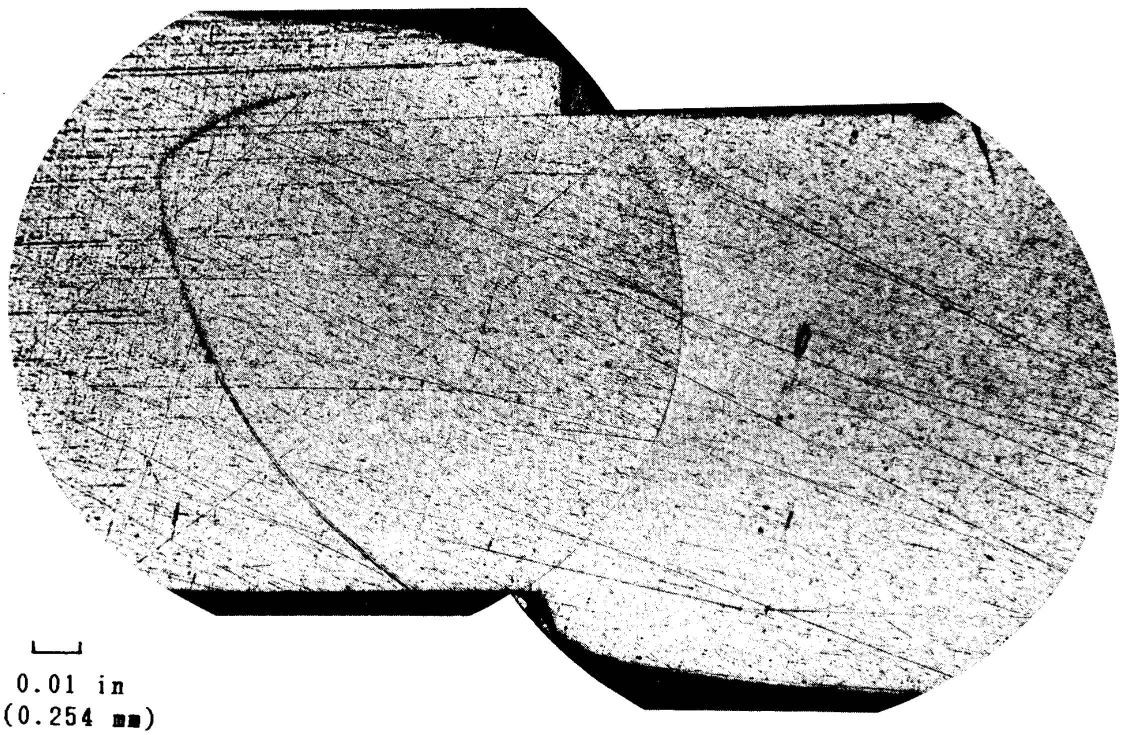


Fig. 5.12 Aluminum Half-Way Specimen Section
P. D. 1 in (25.4 mm) P. S. (Punch Stroke) 19%

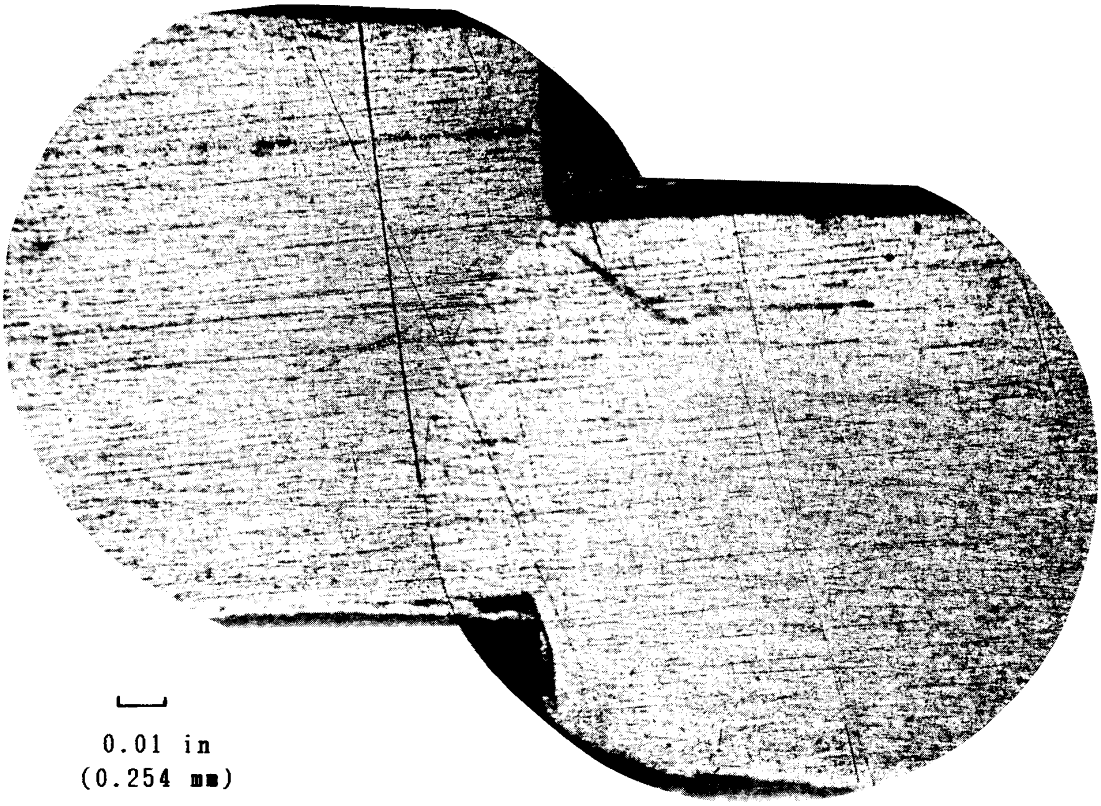


Fig. 5.13 Aluminum Half-Way Specimen Section
P. D. 5/8 in (15.9 mm) P. S. 37%

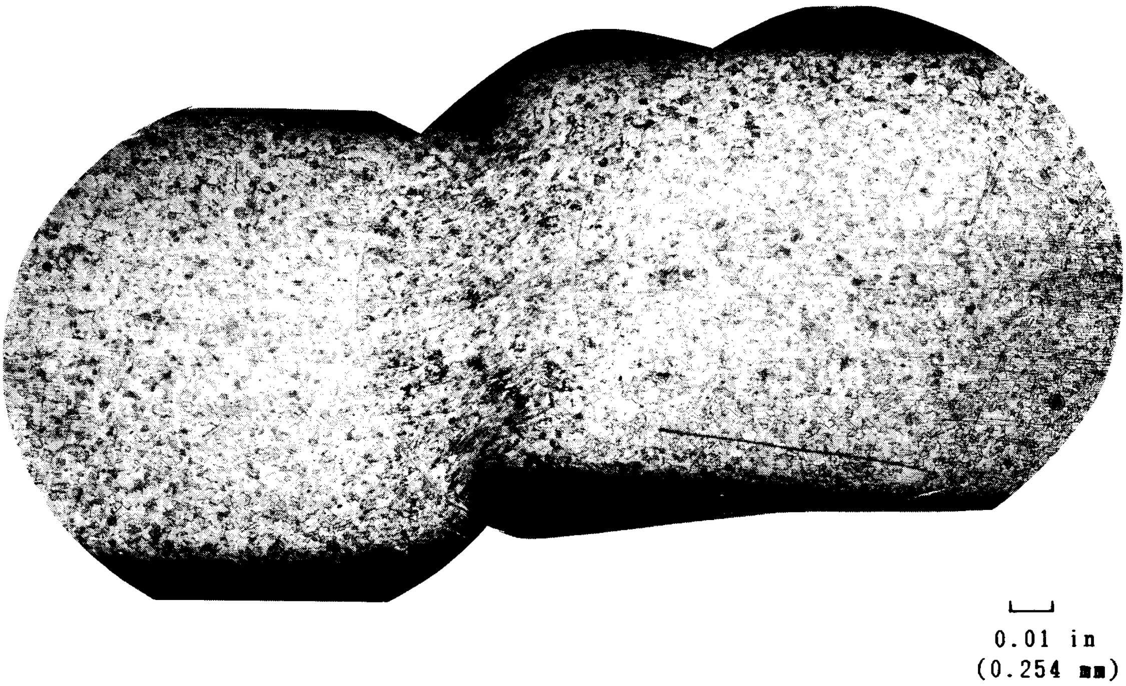


Fig. 5.14 Stainless Steel Half-Way Specimen Section
P. D. 1 in (25.4 mm) P. S. 18%

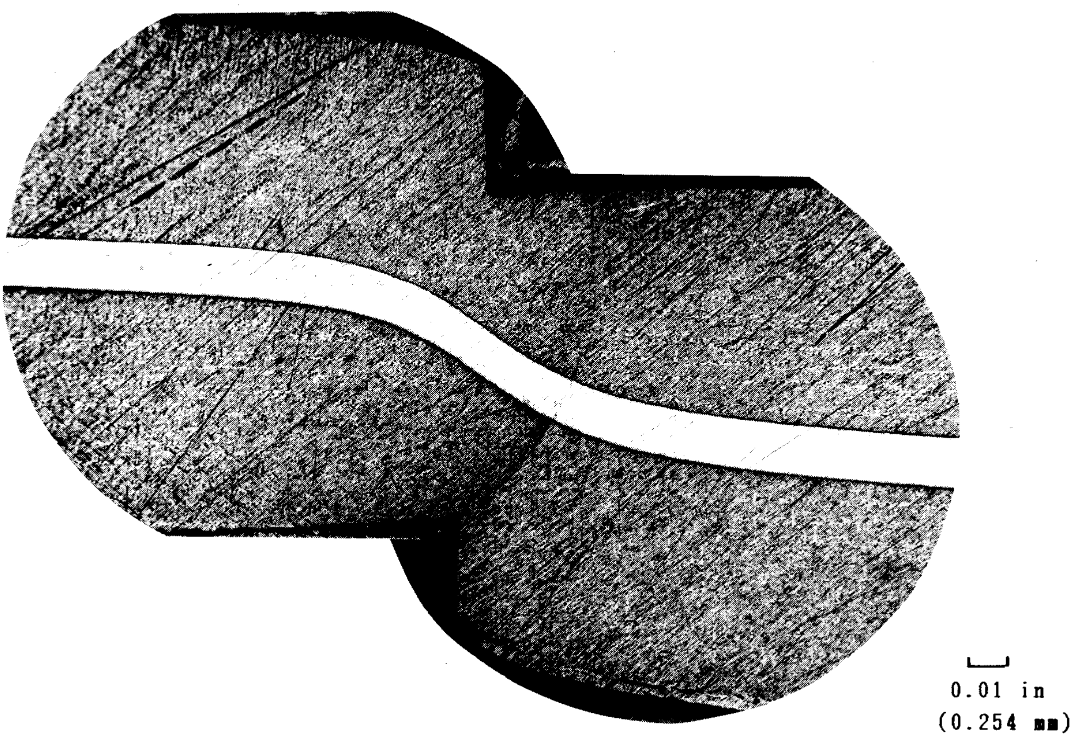


Fig. 5.15 Al-clad SS Half-Way Specimen Section
P.D. 5/8 in (15.9 mm) P.S. 34%

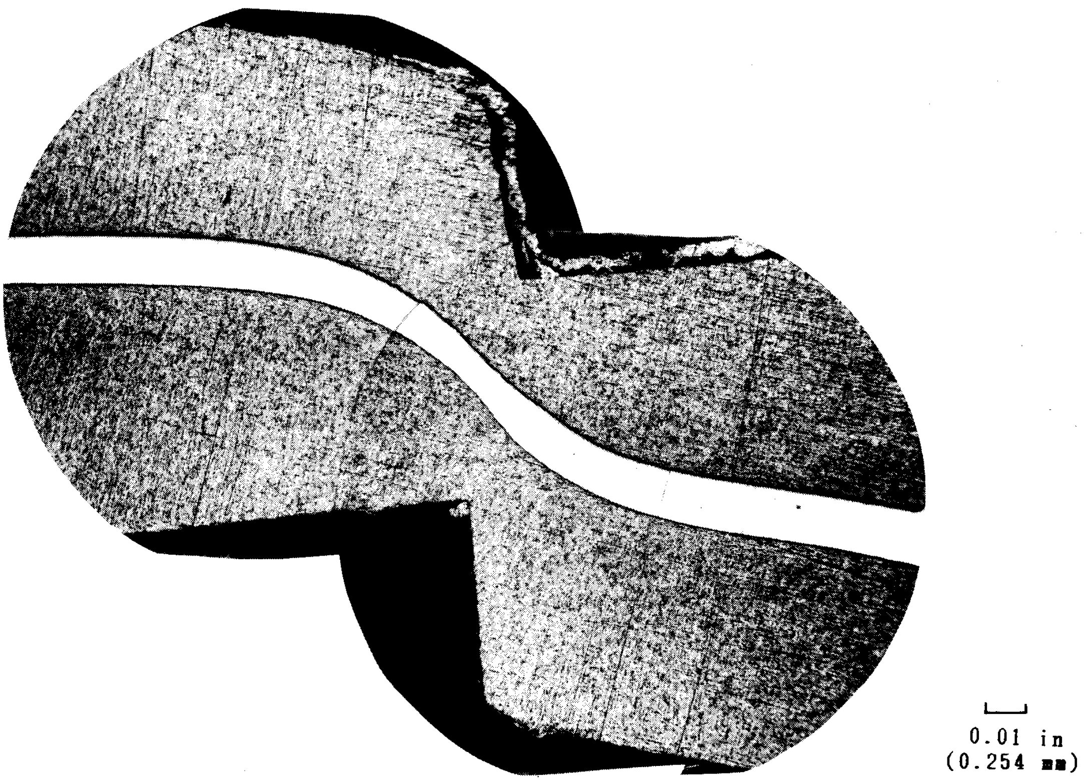


Fig. 5.16 Al-clad SS Half-Way Specimen Section
P.D. 3/8 in (9.5 mm) P.S. 56%

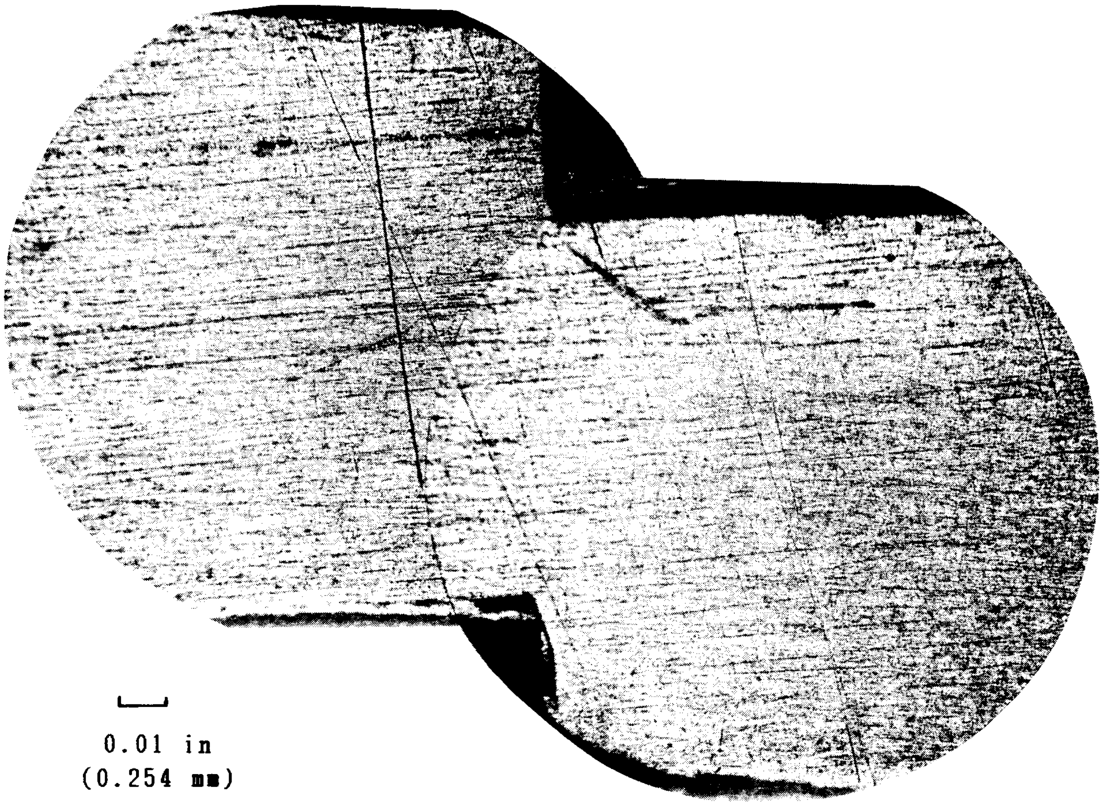


Fig. 5.13 Aluminum Half-Way Specimen Section
P.D. 5/8 in (15.9 mm) P.S. 37%

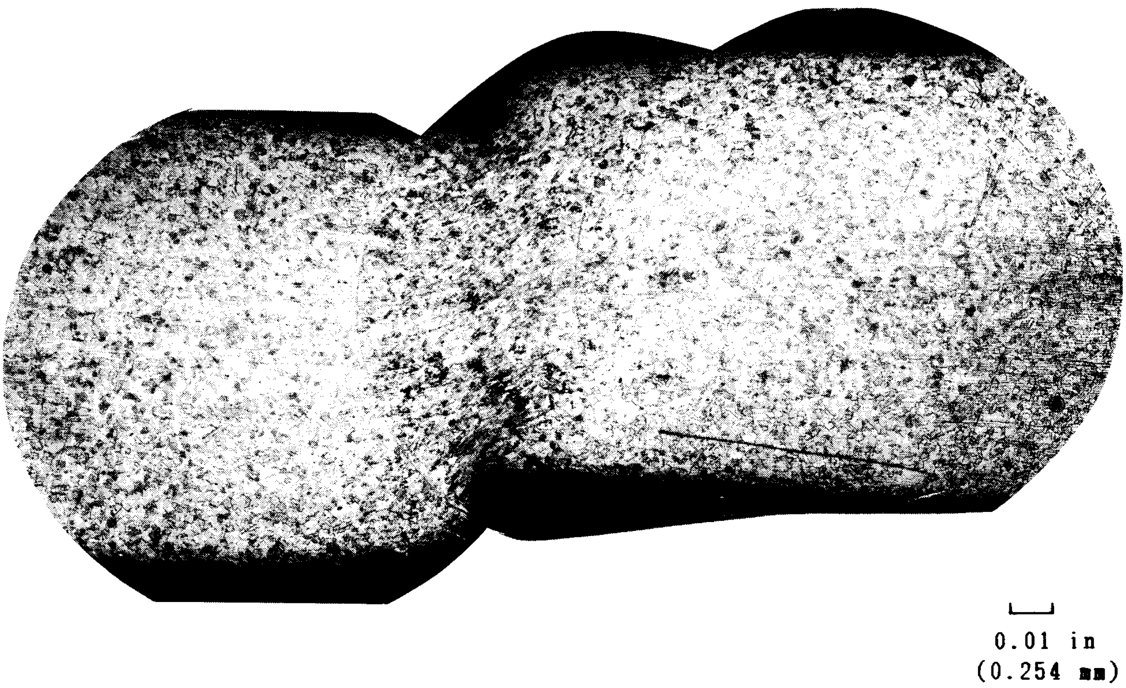


Fig. 5.14 Stainless Steel Half-Way Specimen Section
P.D. 1 in (25.4 mm) P.S. 18%

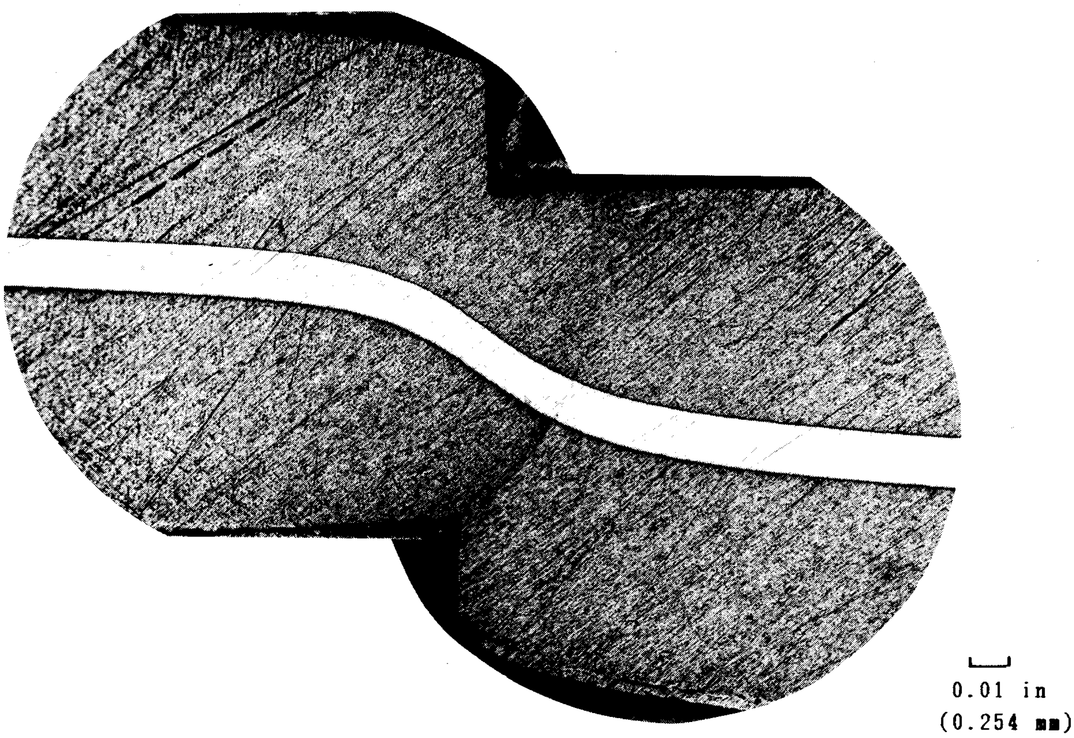


Fig. 5.15 Al-clad SS Half-Way Specimen Section
P. D. 5/8 in (15.9 mm) P. S. 34%

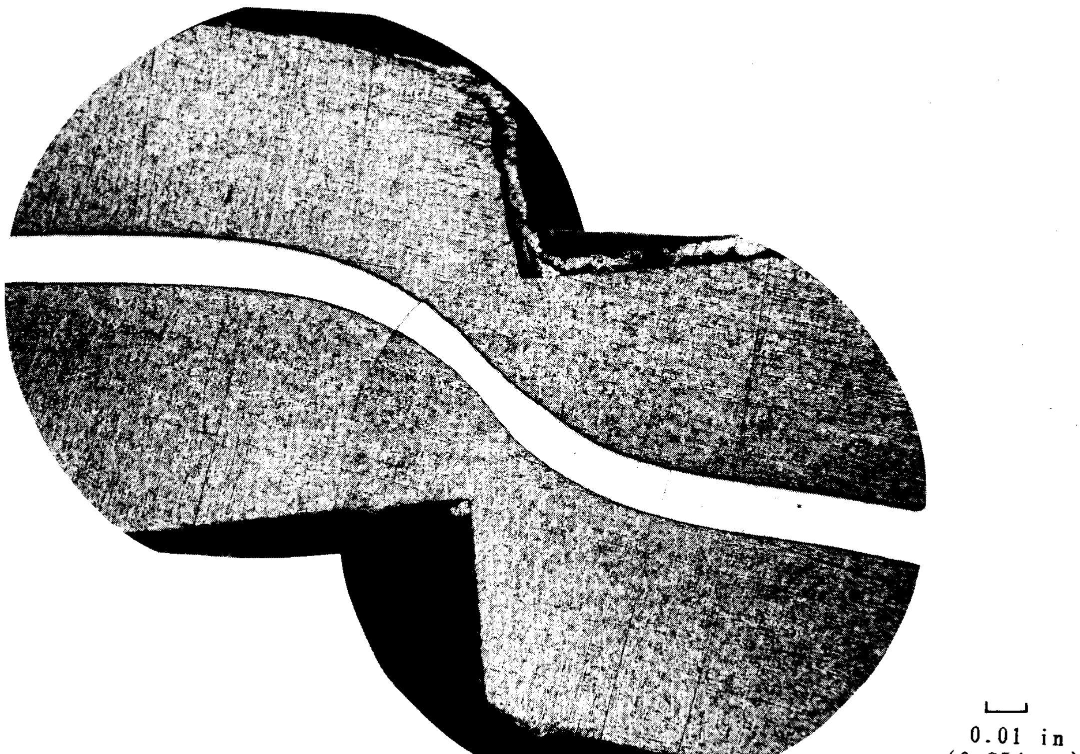


Fig. 5.16 Al-clad SS Half-Way Specimen Section
P. D. 3/8 in (9.5 mm) P. S. 56%

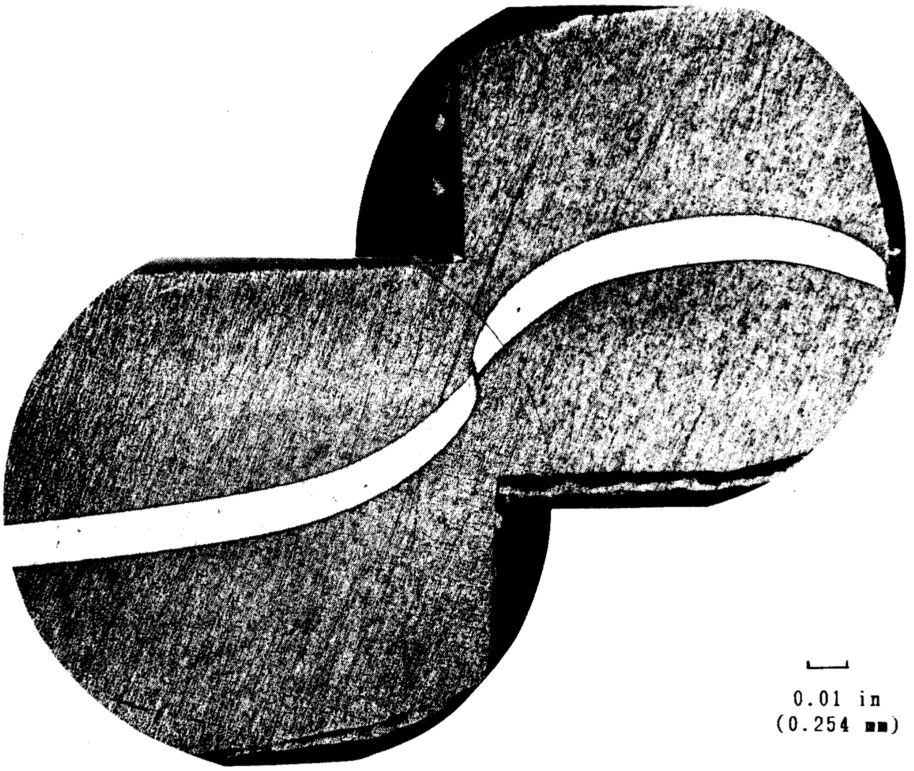


Fig. 5.17 Al-clad SS Half-Way Specimen Section
P. D. 3/8 in (9.5 mm) P. S. 54%

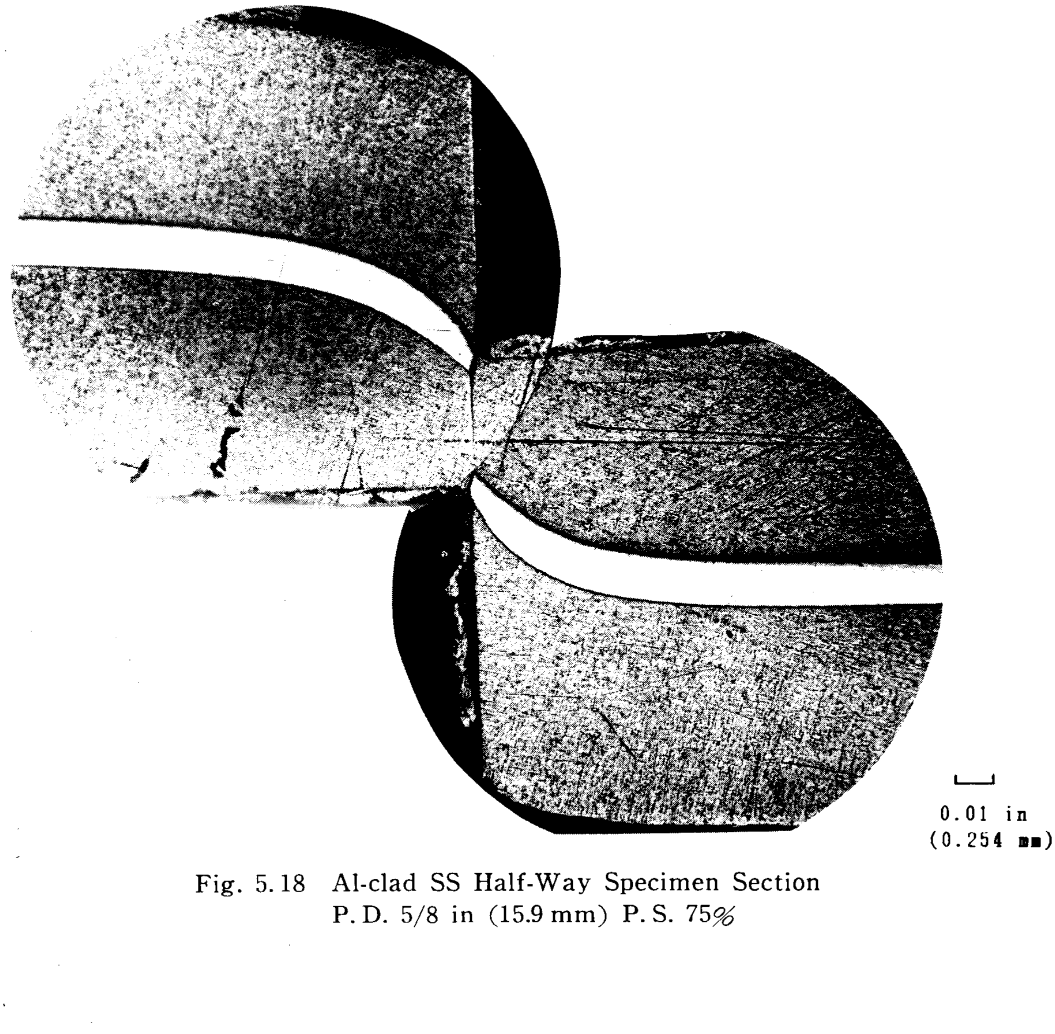


Fig. 5.18 Al-clad SS Half-Way Specimen Section
P. D. 5/8 in (15.9 mm) P. S. 75%

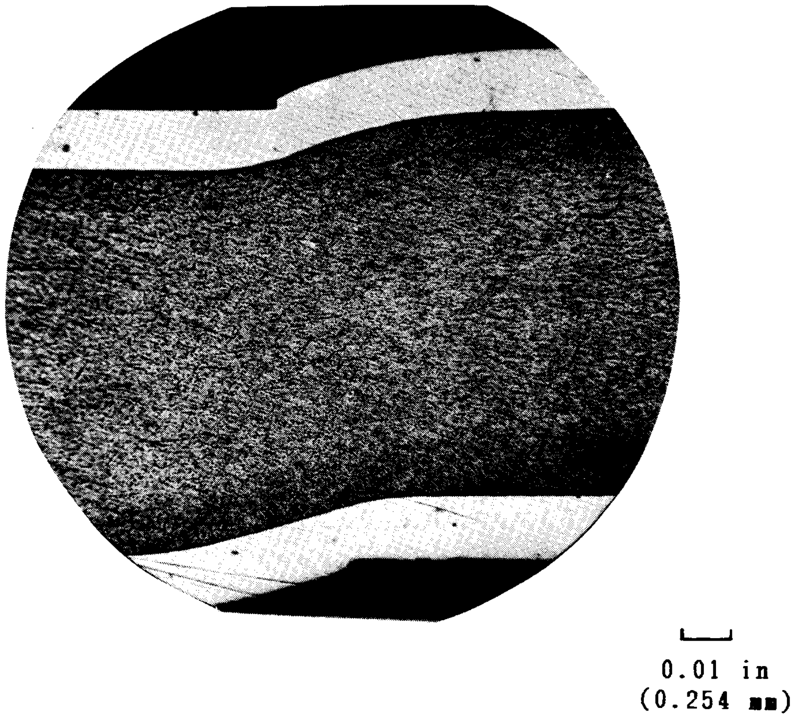


Fig. 5.19 SS-clad Al Half-Way Specimen Section
P.D. 3/8 in (9.5 mm) P.S. 12%

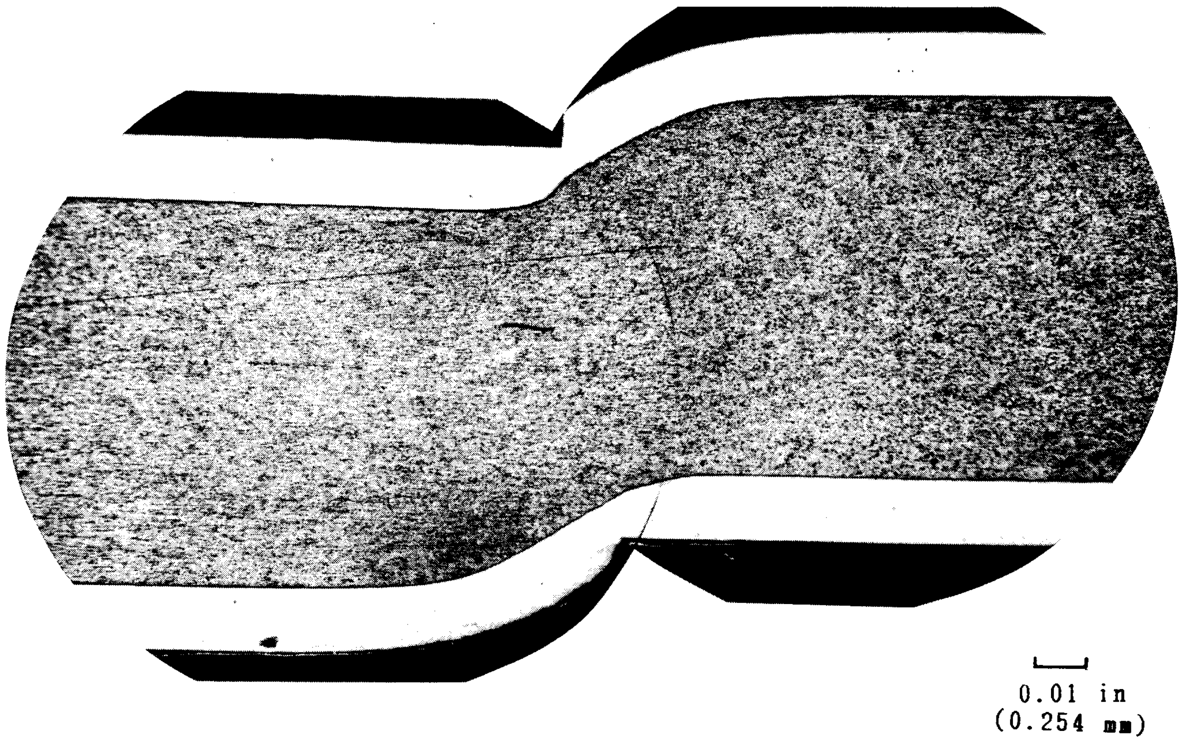


Fig. 5.20 SS-clad Al Half-Way Specimen Section
P.D. 5/8 in (15.9 mm) P.S. 27%

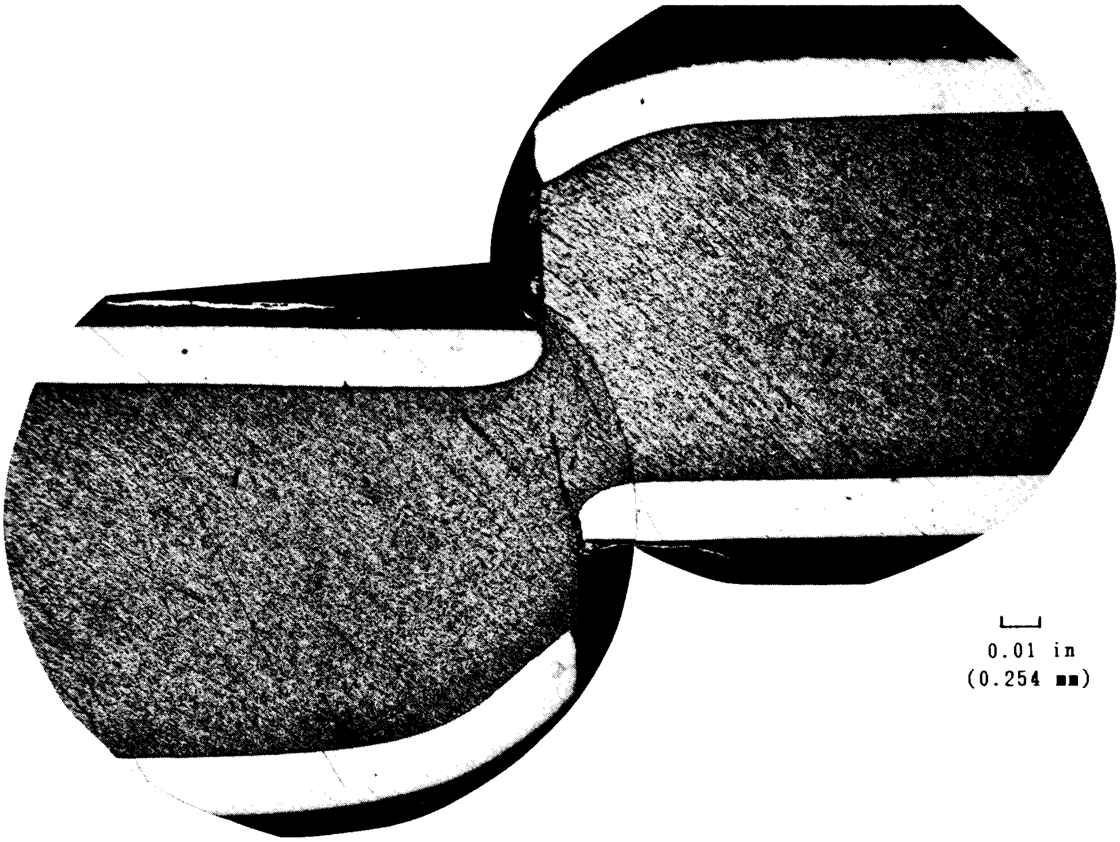


Fig. 5.21 SS-clad Al Half-Way Specimen Section
P.D. 3/8 in (9.5 mm) P.S. 55%

Stainless Steel in the clad material to be sheared is sufficiently elongated, a crack through the whole specimen can be generated. As mentioned above, it depends upon the difference in yield point, ultimate tensile strength, and work hardenability.

Figs. 5.19 thru 5.21 show that the sheet has less curvature than the blank. Those figures show that after the punch penetrates the Aluminum layer, the shearing process can immediately advance.

6 Conclusions

1) There is a little difference between the maximum shearing stress predicted by mixture rule and actual experimental maximum shearing stress. It depends upon the bonding strength, work hardanability, and etc.
2) The maximum shearing stress calculated from the experiment for each punch diameter is less then the ultimate tensile strength of them.
3) The hole of the 3/8 in diameter punch of the sheet is distinctly better than those of the other sizes. In all the diameters of blanks, except for SS-clad Al material, a prominent difference in size cannot be found. The difference of the diameter of hole and blank, except for the Aluminum blank, does not depend on

the kind of material.

4) Observation results of the sheets show that as follows:

(1) Al-clad SS sheet inward concavity does not start at the edge but rather at a small distance from the edge. This is because the distortion zone is very pronounced.

(2) SS-clad Al sheet shows much doming in a localized region near the punched surface. Beyond this region there is no distortion.

(3) In the Al-clad SS sheet though, distortion shows over the entire surface instead of in a localized region as with the SS-clad Al. The Stainless Steel section of the Al-clad SS sheet becomes tapered near the punched surface.

(4) The curvature of the Stainless Steel in Al-clad SS material is greater than that of the Aluminum in the punched material because the strain in the Alumium is greater than that in the Stainless Steel.

5) Observation results of the blank show that as follows:

(1) Each specimen shows a different shape and size of deformation zone. Especially remarkable is the difference between Al-clad SS and SS-clad Al materials.

(2) The deformation zone of SS-clad Al material can be found at the perimeter of the hole, while Al-clad SS material has two different kinds of deformation zones which are doming and dishing. Much doming in the latter can be found.

(3) The monolithic Aluminum shows smooth and straighter surface than its sheet sections counterpart.

(4) The other three materials except Aluminum do not have much difference between the sheet and the blank sections in appearence.

(5) The curvature of doming in Stainless Steel, SS-clad Al, and Al-clad SS is greater in the blank than in the sheet. The separations are very small.

6) The difference in seperation between the two clad matexials in Al-clad SS and SS-clad Al materials cannot be found.

7) A difference that exists between the two clad punched sheet sections is that in the Al-clad SS, the Aluminum is cleanly cut whereas in the SS-clad Al the Aluminum has a cut with jogs.

8) The monolithic materials exhibit a smoother surface on both sheet and blank sections than either clad material show.

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