Int. J. Mech. Sci. Vol. 27, No. 11/12, pp. 725–740, 1985
Printed in Great Britain.

0020–7403/85 $3.00+.00
Pergamon Press Ltd.

NEW STRIP DRAWING EXPERIMENTS USING TRANSPARENT SAPPHIRE DIES

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(*Received* 21 *December* 1984; *in revised form* 20 *July* 1985)

Abstract—Experimental results are presented for carefully controlled plane-strain strip drawing experiments. Transparent aluminum oxide (sapphire) dies have been used to make direct observations of the die–work interface in strip drawing, including the distortion of scribed lines which were used for estimating velocity profiles at the interface. Such profiles can be used as input to theoretical models (Appleby *et al.*, 1984), thus permitting the calculation of interface friction rather than requiring its assumption. Experiments were conducted with tungsten carbide, as well as sapphire, dies in which process parameters such as reduction, speed, die angle, lubricant, and back tension were varied, and die separating forces and drawing loads were measured. In general the friction was lower for the sapphire dies, but the variation with process parameters was similar. For one experiment, residual stresses in the product strip were measured. The results are believed to be documented in sufficient detail to be of general use in evaluating theoretical models.

INTRODUCTION

Theoretical methods have found increasing application in metal forming analyses [2]. Computer programs have been developed to address problems involving large plastic strains; the goals are to predict working forces, local stress distributions in the deformation zone, and residual stress and strain distributions in the formed product. Experimental data for the quantitative evaluation of these programs have, however, been so far lacking. The strip drawing experiments recorded here provide the opportunity to evaluate many of the forming parameters, under carefully controlled plane-strain conditions. An important aim of the work has been to gather a reference collection of experimental data covering parameters such as die angle, reduction, speed, back tension, and interface friction variations. Two die materials and two lubricants have been used. Then, elsewhere [1], these experimental data have been compared with the results from FIPDEF, a finite element elasto-plastic code.

Quantitative predictions with process models depend on a knowledge of the properties of the material being worked and on the exact specification of boundary conditions. This paper emphasizes the boundary conditions in particular. A novel aspect of the experiments has been the use of transparent aluminum oxide (sapphire) dies in order that interface displacements be observed directly and relative velocities determined. The opportunity to directly observe and photograph the interface has also provided additional information on tribological features between strip and die. The principal intent of the velocity measurements, however, was to provide boundary condition information at the tool interface which could be used directly in models in place of assumed coefficients of friction. Residual stress measurements have also been carried out in some detail for one experiment, and a large number of experiments have been carried out to show the comparative behavior of sapphire dies with tungsten carbide dies under various process conditions.

EXPERIMENTAL APPARATUS AND MATERIALS

The experimental apparatus consisted of a pair of identical dies, either tungsten carbide or transparent sapphire, with a linear bearing between the bottom die and a load cell. In this way it was possible to monitor the die-separating force. The support for the upper die contained a viewing aperture for observing and recording the interfacial behavior when the transparent sapphire dies were used. The gap between the dies was set by means of blocks between the upper die support and the frame of the fixture. The whole apparatus was attached to a horizontal tension testing machine which had a provision to record drawing force. Figure 1 shows an overall view of the experimental set-up including a microscope with a camera.

Synthetic sapphire is aluminum oxide, grown artificially as a single crystal. It was ground and polished to die angles of 4° and 8°. In the present work the term 'die angle' refers to the angle between one die face and the strip center line. The design of the tungsten carbide was the same as the sapphire dies, except that the carbide dies had a larger base area. The work material was tin plated mild steel, 51 mm wide and 0.3 mm thick. The electrolytically applied tin coating on each surface of the strip was about 0.38 μm thick. Light mineral oil and emulsified mineral oil (5% mineral oil by volume in water) were chosen as lubricants.

The tin plated mild steel was tested in tension at a nominal strain rate of about 0.1 s^{-1} to find its plastic tensile behavior. The experimental stress–strain data, obtained by uniform straining up to about 15% was fitted by the following equations:

$$\sigma = m\varepsilon + b \text{ for } 0 \leqslant \varepsilon \leqslant 0.028\ (m = 1900 \text{ MPa},\ b = 269 \text{ MPa})$$

and

$$\sigma = K\varepsilon^n \text{ for } \varepsilon > 0.028\ (K = 570 \text{ MPa},\ n = 0.16). \tag{1}$$

In these equations, σ and ε are uniaxial true stress and true plastic strain, respectively.

EXPERIMENTAL PROCEDURES AND RESULTS

Velocity measurements

For the purpose of quantifying velocities along the interface, lines were scribed on the strip surface by means of a Rockwell scratch micro-hardness tester with a 50 g load. In order to magnify the image of the interface, photographs were taken through a Wild microscope with adapter tube on a 35 mm still camera with motor drive. Fiber optic light pipes were used for illumination. The microscope magnification setting was 25 ×. Drawing experiments were carried out at the slow speed of 0.085 mm s^{-1}. Filming was carried out using 35 mm black-and-white film at a speed of 3.2 frames s^{-1}. The overall magnification of the interface photographic prints was about 80 ×.

Two different patterns of scribed lines were used in obtaining the velocities along the interface. In the first case, lines were scribed perpendicular to the direction of motion and parallel to each other with 0.25 mm spacing. The necessity for an accurately measured time interval was eliminated by measuring the displacement of a grid line which had exited the die as well as those within the die contact. The detailed procedure for determining the velocities from such a pattern is given in reference [3]. In the present paper a new technique using inclined lines is presented. This technique can provide more continuous information than the above mentioned technique.

A photograph of the inclined lines taken through a sapphire die is shown in Fig. 2. As the strip enters the die region the lines become curved and as the strip exits from the die region the lines appear straight again. The slope of the lines at any position can be related directly to the corresponding velocity ratio through the equation below:

$$\frac{V_i}{V_n} = \frac{m_n}{m_i} \tag{2}$$

where V_i and m_i are the velocity and slope at any position within the die zone and V_n and m_n are velocity and slope at the exit. Thus in addition to the reference values, m_n and V_n, m_i must be measured at each place within the die zone where an interfacial velocity is required. However, the changes in the angle are very small and not easy to measure accurately.

In the present work the following procedure was used. One convenient line was chosen from each of 31 photographs, similar to Fig. 2. The coordinates of several points on each curve were obtained using a digitizer. The points on each curve were then fitted to a cubic equation. The slope at any position within the die region was obtained by differentiating the fitted cubic equation and substituting the corresponding value of the die position. Then the relative velocity was calculated using equation (1). An average velocity profile was then obtained for the 31 lines with the result shown in Fig. 3. The shaded area represents the bounds of the variations in the 31 individuals lines. The experimental scatter is most obvious at the entry and exit areas.

Interfacial observations

Photographs, taken through transparent dies, are shown in Figs 4–6 for 10, 20 and 30% thickness reductions, and a 4° die angle. Light mineral oil lubricant was used in these experiments.

Measurement of die forces and global friction

An effective coefficient of friction can be calculated for strip drawing by assuming that the interface is a plane, that there is no land (bearing area at the exit) and by balancing the forces on the die [4]. That is,

$$\mu = \frac{((F - B)/2S) - \tan\theta}{[1 + ((F - B)/2S)\tan\theta]} \tag{3}$$

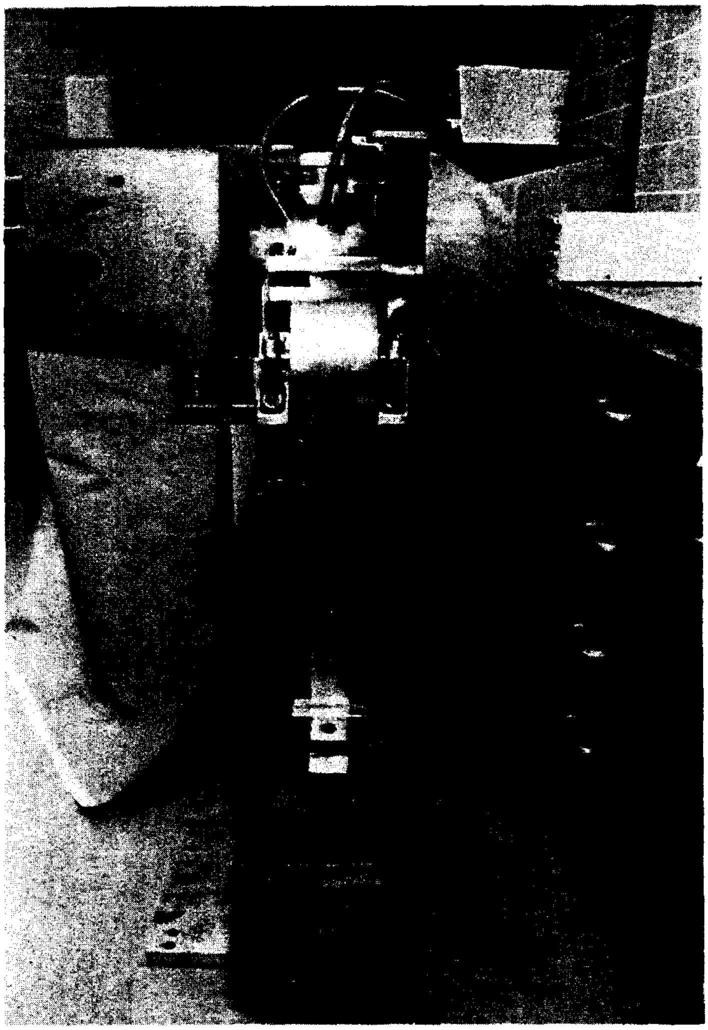

FIG. 1. Overall experimental set-up.

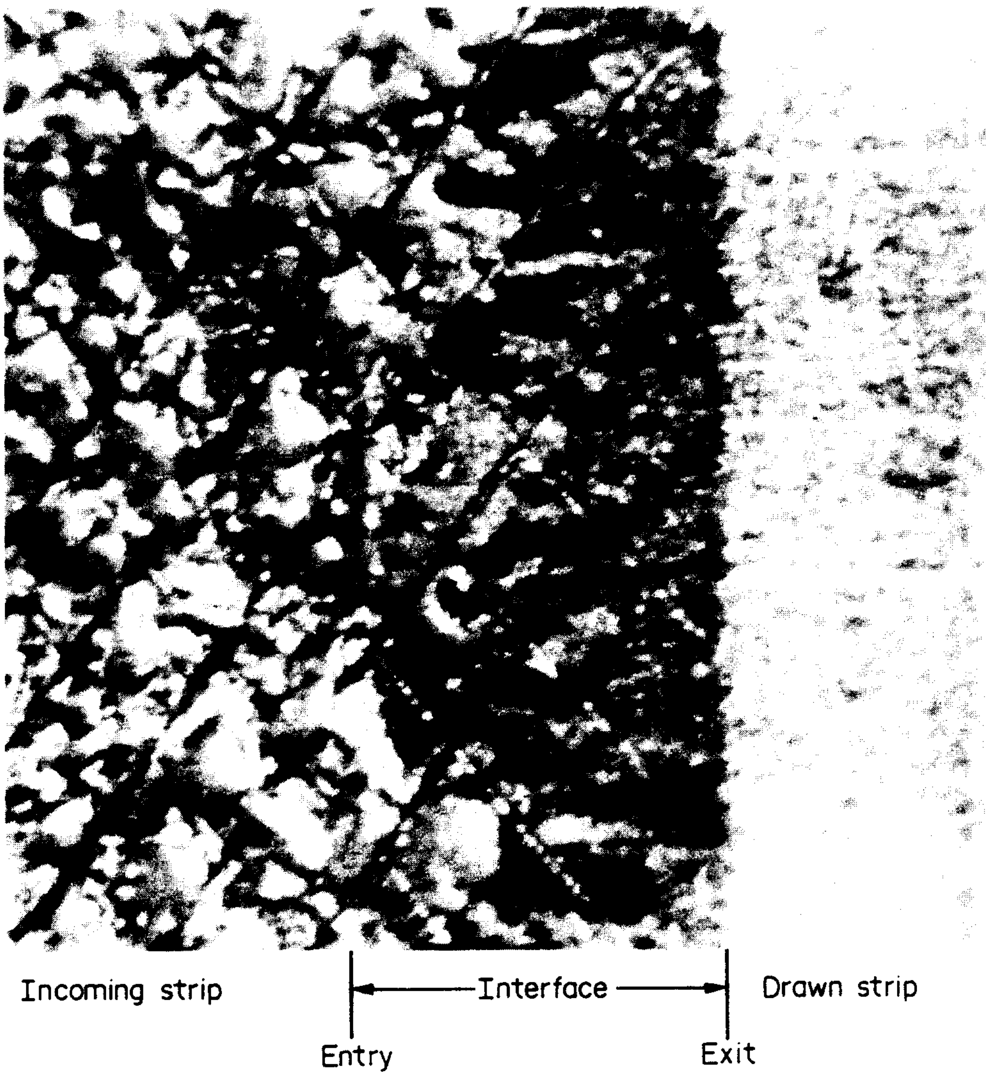

FIG. 2. A photograph of the inclined line technique.

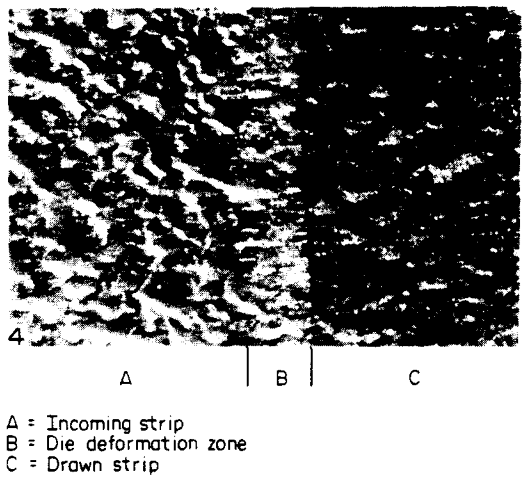

FIG. 4. 10% Reduction with light mineral oil, 4° die (25 ×).

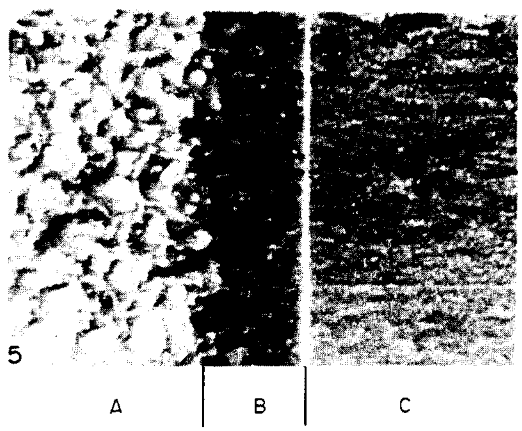

FIG. 5. 20% Reduction with light mineral oil, 4° die (25 ×).

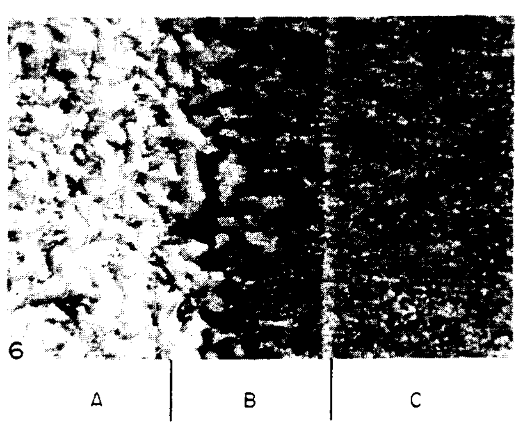

FIG. 6. 30% Reduction with light mineral oil, 4° die (25 ×).

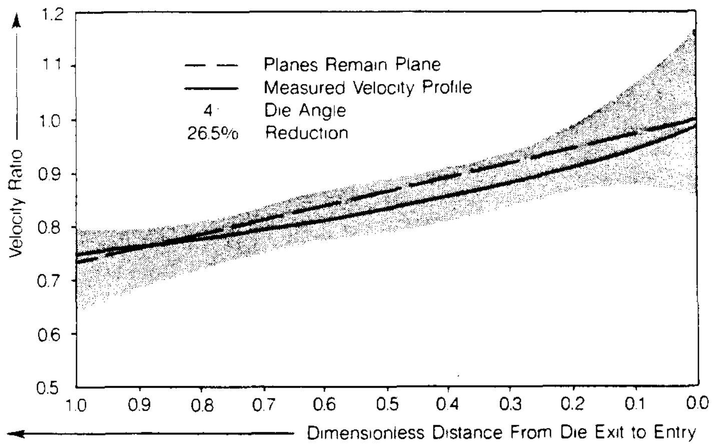

FIG. 3. The average measured velocity profile along the interface with the shaded area representing the experimental scatter.

where:
μ is effective coefficient of friction
F is forward tension
B is backward tension
S is die-separating force
θ is die angle.

Experiments were conducted by systematically varying the following six process parameters, and the effective coefficient of friction in each case was calculated by using the appropriate experimental values in equation (3).

1. Die material: tungsten carbide and sapphire.
2. Die angle in degrees: 4 and 8.
3. Drawing speed in mm s^{-1}: 0.085, 0.85 and 8.5.
4. Percentage reduction in thickness: 10, 20 and 30.
5. Lubricant: light mineral oil and emulsified mineral oil.
6. Back tension in N: 0, 445, 890 and 1335.

The results are presented in Tables 1–12 and the effects of these process parameters on friction are shown in Figures 7 and 8. It should be pointed out that the percentage reduction values shown in Tables 1–12 are based on initial thickness (0.3 mm) and final thickness (depends on the reduction) measured using a micrometer. The tolerance on the percentage reduction is about $\pm 0.5\%$.

Residual stress measurements

The residual stresses in a strip can be measured by appropriate removal of material. Removal of layers by chemical thinning or by a mechanical method causes imbalance of stresses and consequent changes in strain. These changes in strain due to partial relief of stress are measured and used to determine the stresses in the material removed.

TABLE 1. FRICTION DATA ON TIN-PLATED MILD STEEL REDUCED BY 10% USING 4° DIE AND LIGHT MINERAL OIL. NOTE THAT IN ALL THE TABLES THE REDUCTIONS ARE $\pm 0.5\%$ TO ACCOUNT FOR MINOR STRIP VARIATIONS AND THE ACCURACY OF THE MICROMETER

Exp. No.	Drawing Speed in mm/sec	Black Tension in N (B)	Forward Tension in N (F)		Die Separating Force in N (S)		Effective Coefficient of Friction (μ_{eff})	
			Carbide	Sapphire	Carbide	Sapphire	Carbide	Sapphire
1	0.085	0	1135	797	3649	3649	0.085	0.040
2	0.850	"	1157	1068	3716	3961	0.085	0.064
3	8.500	"	1259	1184	4005	4139	0.085	0.072
4	0.085	445	1660	1237	3916	3560	0.084	0.041
5	0.850	"	1704	1442	4050	3805	0.085	0.061
6	8.500	"	1758	1513	4183	3694	0.086	0.074
7	0.085	890	2092	1633	3783	2915	0.088	0.057
8	0.850	"	2092	1780	3791	3026	0.088	0.076
9	8.500	"	2136	1825	3894	3026	0.089	0.083
10	0.085	1335	2336	2047	3293	2893	0.081	0.052
11	0.850	"	2359	2114	3320	2893	0.083	0.064
12	8.500	"	2434	2225	3560	2982	0.084	0.078

TABLE 2. FRICTION DATA ON TIN-PLATED MILD STEEL REDUCED BY 10% USING 4° DIE AND EMUSLSIFIED MINERAL OIL

Exp. No.	Drawing Speed in mm/sec	Back Tension in N (B)	Forward Tension in N (F)		Die Separating Force in N (S)		Effective Coefficient of Friction (μ_{eff})	
			Carbide	Sapphire	Carbide	Sapphire	Carbide	Sapphire
1	0.085	0	1202	930	3827	3872	0.080	0.050
2	0.850	"	1335	1108	4094	3961	0.092	0.069
3	8.500	"	1424	1153	4183	3961	0.099	0.075
4	0.085	445	1633	1380	3738	3827	0.088	0.065
5	0.850	"	1691	1482	3738	3827	0.095	0.065
6	8.500	"	1807	1629	4005	3961	0.099	0.078
7	0.085	890	2123	1825	3560	3671	0.084	0.057
8	0.850	"	2180	1985	3827	3827	0.098	0.072
9	8.500	"	2283	2092	4094	3872	0.099	0.084
10	0.085	1335	2345	2225	3204	3560	0.087	0.055
11	0.850	"	2492	2314	3382	3605	0.098	0.065
12	8.500	"	2590	2474	3649	3805	0.100	0.079

TABLE 3. FRICTION DATA ON TIN-PLATED MILD STEEL REDUCED BY 10% USING 8° DIE AND LIGHT MINERAL OIL

Exp. No.	Drawing Speed in mm/sec	Back Tension in N (B)	Forward Tension in N (F)		Die Separating Force in N (S)		Effective Coefficient of Friction (μ_{eff})	
			Carbide	Sapphire	Carbide	Sapphire	Carbide	Sapphire
1	0.085	0	1246	1010	2893	2893	0.073	0.033
2	0.850	"	1304	1157	3026	3026	0.073	0.049
3	8.500	"	1424	1277	3293	3115	0.073	0.063
4	0.085	445	1571	1424	2626	2581	0.072	0.048
5	0.850	"	1780	1558	3071	2670	0.075	0.066
6	8.500	"	1900	1660	3293	2804	0.078	0.074
7	0.085	890	1945	1749	2448	2225	0.073	0.051
8	0.850	"	2047	1896	2581	2314	0.081	0.074
9	8.500	"	2176	1989	2804	2403	0.086	0.085
10	0.085	1335	2345	2225	2314	2270	0.075	0.054
11	0.850	"	2492	2434	2537	2448	0.085	0.081
12	8.500	"	2600	2523	2715	2608	0.090	0.084

TABLE 4. FRICTION DATA ON TIN-PLATED MILD STEEL REDUCED BY 10% USING 8° DIE AND EMULSIFIED MINERAL OIL

Exp. No.	Drawing Speed in mm/sec	Back Tension in N (B)	Forward Tension in N (F)		Die Separating Force in N (S)		Effective Coefficient of Friction (μ_{eff})	
			Carbide	Sapphire	Carbide	Sapphire	Carbide	Sapphire
1	0.085	0	1215	1215	2759	2982	0.077	0.061
2	0.850	"	1304	1406	2848	3204	0.086	0.076
3	8.500	"	1380	1451	2982	3293	0.088	0.077
4	0.085	445	1722	1513	2848	2448	0.081	0.075
5	0.850	"	1825	1633	2937	2626	0.091	0.083
6	8.500	"	1958	1722	3204	2759	0.093	0.088
7	0.085	890	1989	1900	2492	2359	0.078	0.071
8	0.850	"	2167	2000	2759	2425	0.088	0.086
9	8.500	"	2252	2136	2848	2626	0.095	0.094
10	0.085	1335	2416	2345	2359	2359	0.086	0.071
11	0.850	"	2550	2492	2538	2492	0.096	0.089
12	8.500	"	2715	2600	2848	2626	0.098	0.097

TABLE 5. FRICTION DATA ON TIN-PLATED MILD STEEL REDUCED BY 20% USING 4° DIE AND LIGHT MINERAL OIL

Exp. No.	Drawing Speed in mm/sec	Back Tension in N (B)	Forward Tension in N (F) Carbide	Forward Tension in N (F) Sapphire	Die Separating Force in N (S) Carbide	Die Separating Force in N (S) Sapphire	Effective Coefficient of Friction (μ_{eff}) Carbide	Effective Coefficient of Friction (μ_{eff}) Sapphire
1	0.085	0	2532	1869	9657	8188	0.060	0.044
2	0.850	"	2608	2016	9879	8233	0.060	0.052
3	8.500	"	2670	2163	10324	8277	0.059	0.060
4	0.085	445	3427	2296	9345	8166	0.062	0.043
5	0.850	"	2982	2492	9612	8233	0.062	0.054
6	8.500	"	3071	2639	10235	8322	0.058	0.061
7	0.085	890	3249	2639	8900	8144	0.061	0.037
8	0.850	"	3320	2759	9167	8188	0.062	0.044
9	8.500	"	3373	2937	9523	8277	0.060	0.053
10	0.085	1335	3471	2968	8188	8010	0.062	0.032
11	0.850	"	3493	3115	8166	8077	0.062	0.040
12	8.500	"	3560	3262	8455	8144	0.061	0.048

TABLE 6. FRICTION DATA ON TIN-PLATED MILD STEEL REDUCED BY 20% USING 4° DIE AND EMULSIFIED MINERAL OIL

Exp. No.	Drawing Speed in mm/sec	Back Tension in N (B)	Forward Tension in N (F) Carbide	Forward Tension in N (F) Sapphire	Die Separating Force in N (S) Carbide	Die Separating Force in N (S) Sapphire	Efficient Coefficient of Friction (μ_{eff}) Carbide	Efficient Coefficient of Friction (μ_{eff}) Sapphire
1	0.085	0	2434	1780	8900	8099	0.066	0.040
2	0.850	"	2581	2034	9078	8144	0.071	0.054
3	8.500	"	2670	2194	9345	8166	0.072	0.064
4	0.085	445	2746	2256	8544	8144	0.064	0.041
5	0.850	"	2848	2488	8633	8188	0.068	0.054
6	8.500	"	2995	2670	9078	8233	0.070	0.064
7	0.085	890	3231	2550	8589	7943	0.065	0.034
8	0.850	"	3373	2759	8989	8032	0.067	0.046
9	8.500	"	3516	2901	9345	8077	0.070	0.054
10	0.085	1335	3605	3071	8384	8010	0.065	0.038
11	0.850	"	3738	3262	8722	8055	0.067	0.049
12	8.500	"	3859	3440	9123	8099	0.068	0.059

TABLE 7. FRICTION DATA ON TIN-PLATED MILD STEEL REDUCED BY 20% USING 8° DIE AND LIGHT MINERAL OIL

Exp. No.	Drawing Speed in mm/sec	Back Tension in N (B)	Forward Tension in N (F) Carbide	Forward Tension in N (F) Sapphire	Die Separating Force in N (S) Carbide	Die Separating Force in N (S) Sapphire	Effective Coefficient of Friction (μ_{eff}) Carbide	Effective Coefficient of Friction (μ_{eff}) Sapphire
1	0.085	0	2194	1691	5385	4739	0.061	0.037
2	0.850	"	2207	1869	5429	4806	0.061	0.052
3	8.500	"	2359	2047	5785	4984	0.062	0.063
4	0.085	445	2581	2078	5207	4628	0.063	0.035
5	0.850	"	2594	2341	5251	4984	0.062	0.048
6	8.500	"	2700	2492	5607	5340	0.059	0.050
7	0.085	890	3026	2434	5207	4397	0.063	0.034
8	0.850	"	3057	2697	5300	4539	0.062	0.057
9	8.500	"	3084	2848	5474	4762	0.058	0.063
10	0.085	1335	3320	2879	4717	4272	0.068	0.039
11	0.850	"	3320	3084	4806	4450	0.064	0.054
12	8.500	"	3382	3262	4962	4717	0.064	0.062

TABLE 8. FRICTION DATA ON TIN-PLATED MILD STEEL REDUCED BY 20% USING 8° DIE AND EMULSIFIED MINERAL OIL

Exp. No.	Drawing Speed in mm/sec	Back Tension in N (B)	Forward Tension in N (F)		Die Separating Force in N (S)		Effective Coefficient of Friction (μ_{eff})	
			Carbide	Sapphire	Carbide	Sapphire	Carbide	Sapphire
1	0.085	0	2314	1869	5629	5006	0.063	0.045
2	0.850	"	2448	1989	5741	5073	0.071	0.054
3	8.500	"	2581	2181	5874	5251	0.077	0.065
4	0.085	445	2612	2181	5251	4717	0.064	0.042
5	0.850	"	2790	2403	5429	5073	0.073	0.051
6	8.500	"	2968	2612	5608	5340	0.082	0.061
7	0.085	890	2861	2461	4762	4139	0.065	0.048
8	0.850	"	2995	2701	4940	4406	0.073	0.063
9	8.500	"	3191	2861	5162	4628	0.080	0.070
10	0.085	1335	3293	2835	4717	3961	0.065	0.048
11	0.850	"	3502	3071	5029	4288	0.073	0.063
12	8.500	"	3680	3204	5340	4406	0.077	0.070

TABLE 9. FRICTION DATA ON TIN-PLATED MILD STEEL REDUCED BY 30% USING 4° DIE AND LIGHT MINERAL OIL

Exp. No.	Drawing Speed in mm/sec	Back Tension in N (B)	Forward Tension in N (F)		Die Separating Force in N (S)		Effective Coefficient of Friction (μ_{eff})	
			Carbide	Sapphire	Carbide	Sapphire	Carbide	Sapphire
1	0.085	0	2982	2194	10947	9145	0.065	0.050
2	0.850	"	3026	2577	11125	9212	0.065	0.069
3	8.500	"	3115	2670	11748	9278	0.062	0.073
4	0.085	445	3249	2690	10680	8945	0.060	0.054
5	0.850	"	3315	2817	10947	9011	0.061	0.061
6	8.500	"	3338	2937	11125	9078	0.060	0.067
7	0.085	890	3502	3146	9723	8856	0.064	0.057
8	0.850	"	3516	3235	9770	8922	0.064	0.060
9	8.500	"	3671	3382	10324	8989	0.064	0.068
10	0.085	1335	3898	3404	9612	8900	0.063	0.046
11	0.850	"	3916	3636	9790	8945	0.062	0.058
12	8.500	"	3916	3769	10235	9034	0.056	0.064

TABLE 10. FRICTION DATA ON TIN-PLATED MILD STEEL REDUCED BY 30% USING 4° DIE AND EMULSIFIED MINERAL OIL

Exp. No.	Drawing Speed in mm/sec	Back Tension in N (B)	Forward Tension in N (F)		Die Separating Force in N (S)		Effective Coefficient of Friction (μ_{eff})	
			Carbide	Sapphire	Carbide	Sapphire	Carbide	Sapphire
1	0.085	0	2786	2372	10769	8989	0.059	0.061
2	0.850	"	2968	2550	11259	9034	0.061	0.070
3	8.500	"	3182	2640	11659	9078	0.066	0.075
4	0.085	445	3427	2879	11036	9078	0.064	0.063
5	0.850	"	3631	3026	11570	9123	0.067	0.070
6	8.500	"	3765	3293	12015	9189	0.067	0.084
7	0.085	890	3649	3262	10502	8989	0.060	0.061
8	0.850	"	3738	3413	10680	9078	0.062	0.068
9	8.500	"	3938	3560	11303	9167	0.064	0.075
10	0.085	1335	3827	3471	9568	8811	0.060	0.051
11	0.850	"	3916	3680	9790	8900	0.063	0.060
12	8.500	"	4072	3800	10235	8945	0.063	0.067

TABLE 11. FRICTION DATA ON TIN-PLATED MILD STEEL REDUCED BY 30% USING 8° DIE AND LIGHT MINERAL OIL

Exp. No.	Drawing Speed in mm/sec	Back Tension in N (B)	Forward Tension in N (F)		Die Separating Force in N (S)		Effective Coefficient of Friction (μ_{eff})	
			Carbide	Sapphire	Carbide	Sapphire	Carbide	Sapphire
1	0.085	0	2964	2390	7209	6586	0.063	0.040
2	0.850	"	2995	2639	7343	6809	0.062	0.052
3	8.500	"	3026	2817	7498	7031	0.060	0.058
4	0.085	445	3249	2830	6800	6453	0.064	0.043
5	0.850	"	3280	3084	6942	6702	0.062	0.055
6	8.500	"	3369	3262	7262	6900	0.059	0.062
7	0.085	890	3649	3217	6497	6186	0.070	0.046
8	0.850	"	3707	3418	6764	6319	0.066	0.058
9	8.500	"	3783	3560	7120	6453	0.061	0.065
10	0.085	1335	3872	3529	6141	5741	0.064	0.049
11	0.850	"	3916	3725	6372	5896	0.060	0.060
12	8.500	"	3996	3860	6519	6186	0.062	0.061

TABLE 12. FRICTION DATA ON TIN-PLATED MILD STEEL REDUCED BY 30% USING 8° DIE AND EMULSIFIED MINERAL OIL

Exp. No.	Drawing Speed in mm/sec	Back Tension in N (B)	Forward Tension in N (F)		Die Separating Force in N (S)		Effective Coefficient of Friction (μ_{eff})	
			Carbide	Sapphire	Carbide	Sapphire	Carbide	Sapphire
1	0.085	0	2848	2505	6853	6631	0.065	0.047
2	0.850	"	3084	2670	7031	6853	0.076	0.053
3	8.500	"	3204	2786	7209	6898	0.079	0.060
4	0.085	445	3262	3186	6675	6853	0.068	0.058
5	0.850	"	3471	3382	6942	7209	0.075	0.061
6	8.500	"	3591	3560	7120	7476	0.078	0.066
7	0.085	890	3484	3306	6141	6319	0.069	0.049
8	0.850	"	3694	3591	6453	6542	0.074	0.064
9	8.500	"	3885	3769	6675	6764	0.081	0.070
10	0.085	1335	3809	3604	5741	5518	0.073	0.063
11	0.850	"	3974	3769	5963	5785	0.078	0.068
12	8.500	"	4183	3885	6364	5920	0.081	0.073

A strip that had been reduced by 30% in thickness using a 4° sapphire die, was chosen for residual stress measurements. A specimen approximately 76 mm long was cut from the drawn strip. It was dipped in a microstop coating, then removed to allow the coating to dry. This was repeated a few times to ensure thorough coating on both sides of the specimen. The coating was then allowed to congeal for about $1\frac{1}{2}$ h, after which it was peeled away at each end of the specimen in a 12 mm × 51 mm area on both sides. The tin coating on the exposed specimen was removed using a chemical solution of 10 parts hydrochloric acid, 2 parts nitric acid and 15 parts distilled water. Then the steel was removed by dipping the specimen in a chemical solution of 200 ml distilled water, 16 g oxalic acid, 10 ml sulfuric acid, 106 ml hydrogen peroxide, and 2 ml hydrofluric acid. Once the exposed steel was dissolved in the chemical solution, the remaining square specimen of 51 mm × 51 mm was taken from the bath and the microstop coating was peeled off. A careful specimen preparation of this type was needed to avoid any possibility of influencing the existing residual stresses in the drawn strip which might have occurred if the specimen had been cut from the drawn strip by some mechanical means such as guillotining.

A strain gauge was mounted at the center of the 51 mm × 51 mm specimen according to the procedure prescribed by the gauge manufacturer. In order to complete the half-bridge, a dummy gauge was used in conjunction with the active gauge on the specimen in the drawing direction and they were connected to the strain indicator. The specimen was placed on a horizontal table, gauge side facing up. Then sufficient microstop coating was applied to the gauge side of the specimen to prevent chemical removal of material on that side. Thickness was measured at four different places and an average was taken. The strain indicator reading was set to zero. First the tin coating was stripped using a chemical solution similar to the one used in specimen preparation. Then the strain reading and the corresponding thickness were recorded. It was found that about 50 ml of steel stripper, similar to the one used in specimen preparation, was needed to remove uniform layers of steel about 0.013 mm in thickness. In this way it was possible to control the process to some extent. A layer of about 0.013 mm thickness was removed each time, and the corresponding strain was recorded. This procedure was repeated until half the thickness of the specimen was removed. The strain and corresponding specimen thickness are given in Table 3. The analysis of the experimental

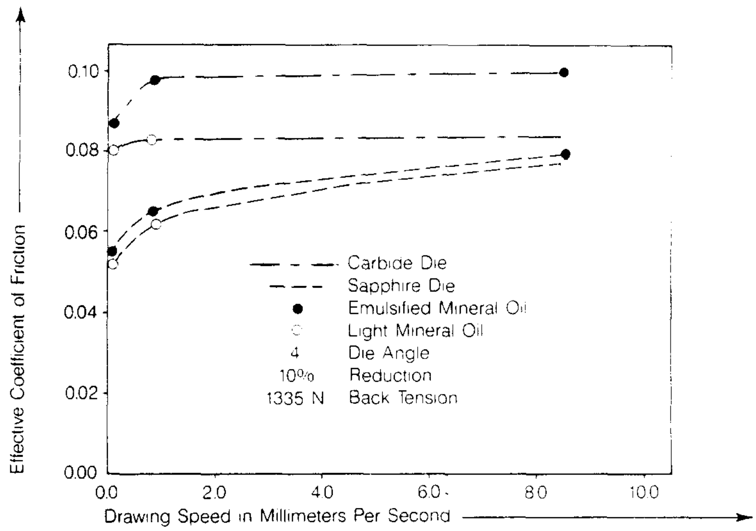

FIG. 7. A plot of drawing speed vs effective coefficient of friction.

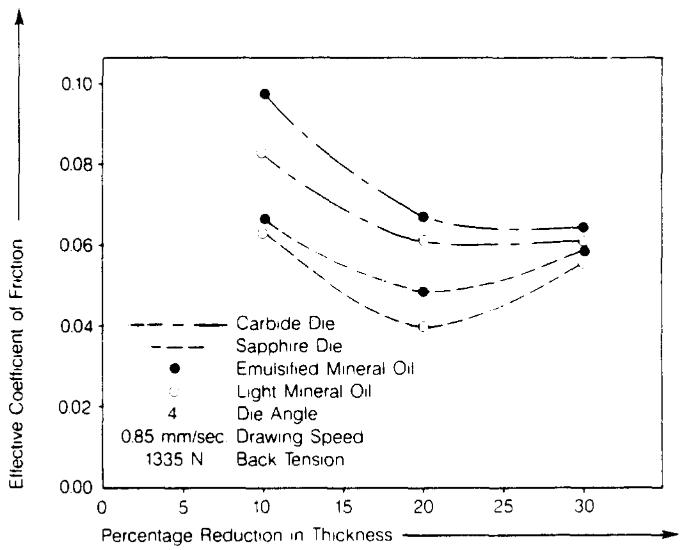

FIG. 8. A plot of percentage reduction in thickness vs effective coefficient of friction.

TABLE 13. RESIDUAL STRESS MEASUREMENTS

Exp. No.	W (mm)	Eg ($\times 10^{-6}$) (−)	dEg/dw ($\times 10^{-3}$ mm^{-1})	Eg/w^2 ($\times 10^{-3}$ mm^{-1}) (−)	σ (M Pa)
0	0.2127	0	4.6520	0.0000	100
1	0.2108	8	4.5114	0.1800	93
2	0.2013	33	3.8154	0.8144	65
3	0.1981	50	3.5854	1.2738	53
4	0.1848	84	2.6327	2.4600	19
5	0.1695	130	1.5677	4.5224	−17
6	0.1581	151	0.7862	6.0399	−35
7	0.1454	165	−0.0654	7.8030	−47
8	0.1353	140	−0.7335	7.6528	−41
9	0.1257	116	−1.3492	7.3380	−27
10	0.1162	104	−1.9552	7.7017	−33
11	0.1041	92	−2.7079	8.4830	−31
12	0.0953	66	−3.2524	7.2746	−22

results was carried out using the equation derived by Leeser and Daane [5]. That is,

$$\sigma_{iw} = E\left[2\varepsilon_g + \tfrac{1}{2}W\frac{d\varepsilon_g}{dW} - 3W\int_W^{W_i}\frac{\varepsilon_g}{W^2}dW\right] \tag{4}$$

where

σ_{iw} is residual stress when the specimen thickness is W
W_i is initial specimen thickness
ε_g is the change in strain at the gauge surface, and
E is Young's modulus.

The variation of gauge strain with respect to thickness was fitted to a cubic equation and slope $d\varepsilon_g/dW$ was obtained by differentiating the cubic equation. The integration part of equation (4) was carried out by the trapezoidal rule. Figure 9 presents the residual stress distribution up to the central plane of the strip.

DISCUSSION

Interfacial velocities

The measured velocity profile for a 26.5 % reduction as obtained from the photographs using a 4° die is shown in Fig. 3. For comparison, the linear variation in velocity along the interface from entry to exit for the special case of 'planes remain plane' is also shown. The characteristic features of the observed velocity profile are speeding up at the entry and exit and a nearly linear increase in the central region.

These empirical data have been used as the prescribed boundary conditions in a large strain elastic–plastic finite element analysis of the strip drawing process [1]. With such information, it is not necessary to assume a model of friction. Instead, the solution provides information on the local friction as well as on the stress and strain distributions, drawing load, and residual stresses.

Interfacial morphology

As shown in Figures 4–6, there are three distinct regions:
— the undeformed incoming tin plated mild steel strip,
— the die deformation zone, and
— the drawn strip.

The surface of the original tin plated strip has an undulating, or wave-like, appearance which is a result of the method by which the tin plate is produced in the temper rolling of the base

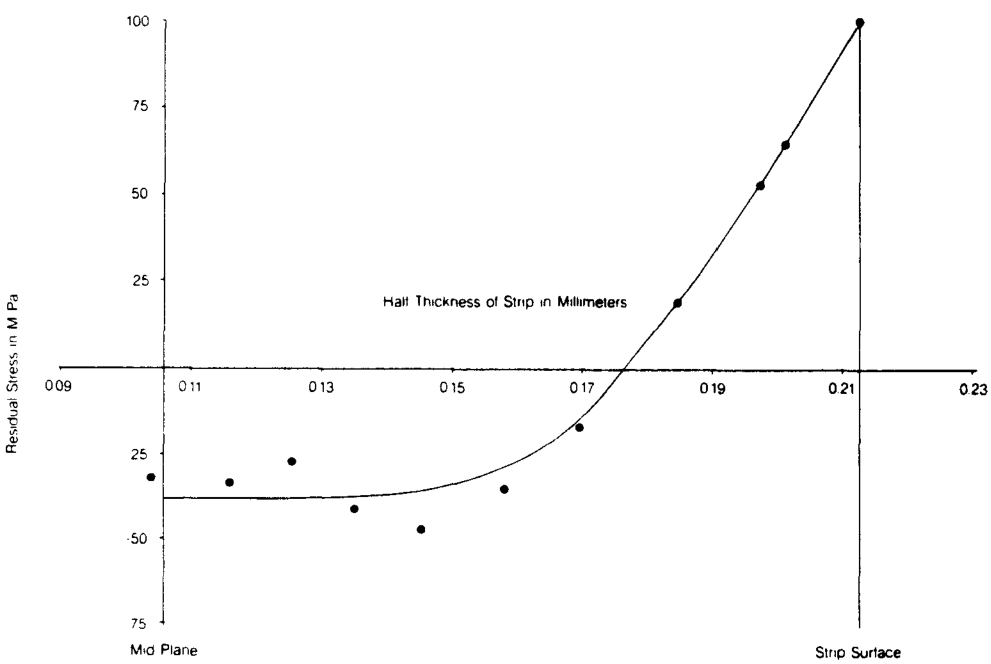

FIG. 9. Residual stress distribution.

steel. The electrolytically applied tin represents about 0.38 μm in thickness compared to the arithmetic average roughness of 1.8 μm. The photographs show the gradual flattening of the asperities and the resulting burnishing of the tin plate as the reduction increases through the die. During the drawing process some depressed pockets remain on the drawn strip and these continue to exhibit the matte tin finish. This is particularly evident for low reductions and low die angle, as shown in Fig. 4. As the reduction increases the pockets become smaller, as shown, for example, in Fig. 6 for 30% reduction where the entire surface is burnished. Similar features were observed for the 8° die.

Process parameters

1. *Die material.* In general the effective coefficient of friction was lower with the sapphire dies than with the carbide dies. The ionic materials such as single crystal sapphire have a very high internal binding energy due to their 'closed structure'. Thus when placed in contact with metals such as tin plated mild steel, it is to be expected that they will not form strong bonds across the interface [6]. Another factor may be the surface roughness of the dies which is slightly less for sapphire than for carbide.

2. *Die angle.* It is known from the literature that there is an optimum die angle from the point of view of the combined effect of frictional and redundant work in strip drawing. In the present work the chosen die angles of 4° and 8° were close to the reported [7, 8] optimum die angle and thus the results showed only small differences in drawing loads (3% lower for the 4° die than for the 8° die for sapphire, and the reverse for carbide).

3. *Drawing speed.* As shown in Fig. 7, both dies showed an increase in friction with drawing speed, especially in the region below 0.7 mm s^{-1}. Similar and opposite trends have been reported in the literature depending on the speed and lubricants used [7].

4. *Reduction.* It is evident from Fig. 8 that the friction generally decreased as reduction was increased. One possible explanation is that at greater reductions the surface roughness of the strip was smoothed out and the entrapped lubricant thus became a more effective film, separating the strip from the die [9].

5. *Lubricant.* A lubricant may reduce the friction in two ways. It serves as a reservoir for the boundary film and it prevents intermetallic contact. Figures 7 and 8 indicate that the friction was less for the light mineral oil than for the emulsified mineral oil for both types of dies.

6. *Back tension.* As far as the experimental results summarized in Table 1 are concerned, no regular effect of back tension on the friction was observed. The above effects can be summarized as follows:

Parameter	*General influence on friction*
Speed	Increasing with speed (0.08–8.5 mm s^{-1})
Reduction	Decreasing with reduction, especially from 10 to 20%
Lubricant	Less for light mineral oil than for emulsified mineral oil
Die material	Less for sapphire compared to tungsten carbide
Die angle	No significant difference for 4° and 8° observed
Back tension	No regular effect

Residual stress distribution

As shown in Fig. 9, the drawn strip had a residual tensile stress near the surface, of nearly 100 MPa. At 1/3 of the half thickness, stress reversal occurred with a maximum compressive stress about 38 MPa near the center. The general features of the stress distribution are reasonable and compare favorably with model predictions [1]. However they are not balanced; possibly due to some influence of the chemical-thinning technique on the stress distribution.

Friction distribution along die interface

The measured velocity profile (Fig. 3) was used as the prescribed boundary condition in the finite element analysis to provide complete information on the forces and displacements throughout the solution domain [1]. From this complete solution it was then of interest to analyze in detail the friction effects at the die/strip boundary. It was first necessary, for the nodes under the die, to convert the horizontal and vertical nodal forces into the die tangential and normal forces. These nodal quantities were divided into two equal parts and assigned to the two adjacent elements. The summation of the contribution from the two neighboring nodes was then assigned to the midpoint of that element side. The tangential and normal forces were plotted against the normalized die contact length as shown in the Fig. 10. Their ratio, the coefficient of friction is given in Fig. 11. The experimental scatter around the die entry and exit (see the shaded areas in Fig. 3) lead to uncertainty in the values of stress and friction coefficient in these areas. In the experimental work with the inclined lines it was especially difficult to monitor the changes in the slope of the lines at the entry. This was partly due to the very small changes in slope at the beginning of the die zone and partly due to the undulations of the tin plating which meant that the entry was a slightly spread-out zone along the strip rather than a distinct line from which measurements could be made. Examination of Fig. 2 indicates the uncertainty in determing the entry area. In fact the exit is much more distinct, hence the reason for using this as the origin in the experimental analysis. In the presentation of results (Figs 10 and 11) the uncertain areas have been shown as dashed lines. In the main body of the die zone, where the experimental scatter was small, both the friction stress and the friction coefficient rise to a peak. Physically this may be associated with the flattening of the strip and the consequent elimination of lubrication pockets as the draw

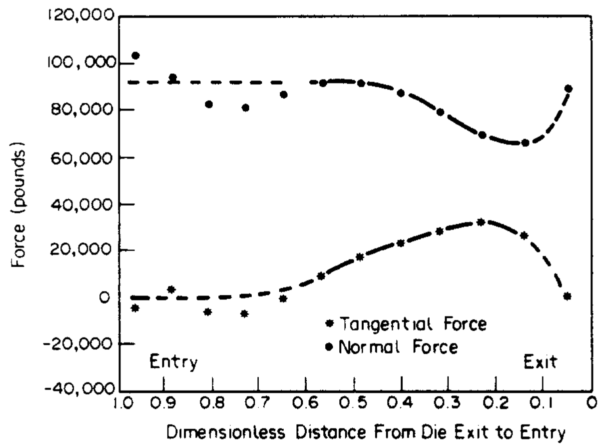

FIG. 10. Variation of normal force and tangential force along die interface using results from Fig. 3 as the boundary conditions.

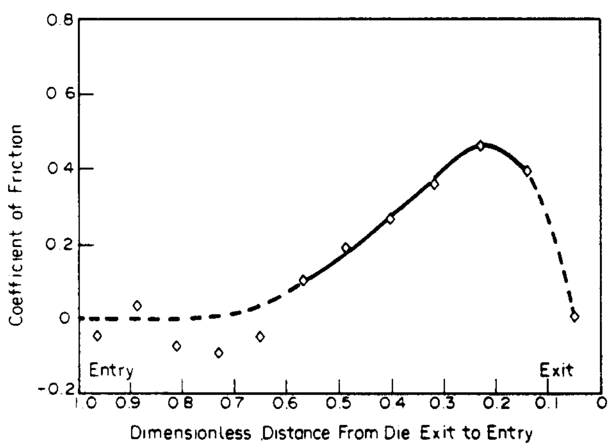

FIG. 11. Variations in the coefficient of friction.

proceeds. The maximum value of coefficient of $\mu = 0.45$ occurs approximately three-quarters of the way through the die and may be compared with a mean value of $\mu = 0.06$ obtained by averaging out all the nodal values along the die (see also the effective coefficient of friction values in Table 9).

CONCLUDING REMARKS

The transparent die technique has proven to be very useful for observing the tribological conditions along the tool interface in deformation processes. By using this technique it is possible to determine the relative velocity profile at the interface which in turn can be used as input to a model of the process. In this way, it is unnecessary to assume a friction model. In fact the distribution of friction on the interface can be calculated from the model. Also, the presently constructed apparatus makes possible the observation of tribological features at the interface using movie films. The experimental results comparing sapphire with tungsten carbide dies showed less friction for sapphire, but the qualitative variations with process parameters were similar for both die materials.

Acknowledgement—This work was supported by the Solid Mechanics Division of the National Science Foundation.

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