

tional work-hardening, i.e. lower ductility, greater notch-sensitivity, and poorer corrosion-resistance, appear to result from explosive-hardening. However, there is some evidence that the effects of shock waves in metals can be annealed out more readily than is normally the case.<sup>37,70,88</sup> It is useful to note that, provided that excessive melting and thus heating are avoided at the interface, explosive welding is able to weld metals in the heat-treated or work-hardened conditions without loss of mechanical strength.<sup>23,57</sup>

## References

1. V. Philipchuk, 'Creative Manufacturing Seminar, 1965', Paper SP65-100. New York (Amer. Soc. Tool Manuf. Eng.)
2. W. A. Allen, J. M. Mapes, and W. G. Wilson, *J. Appl. Physics*, 1954, 25, 675.
3. G. R. Abrahamson, *J. Appl. Mechanics (Trans. Amer. Soc. Mech. Eng., 1961, 83, (E), 519)*.
4. B. Crossland and A. S. Bahrani, 'Proceedings of the First International Conference of the Center for High-Energy Forming', 1967, p. 1.1.1.
5. F. P. Bowden and D. Tabor, 'The Friction and Lubrication of Solids. 1954: Oxford (Clarendon Press.)
6. D. V. Keller, *Wear*, 1963, 6, 353.
7. V. Philipchuk, *A.S.D. Tech. Rep. (61-124)*, 1961.
8. V. Philipchuk, *Mech. Eng.*, 1960, 82, 48.
9. L. Zernow, I. Lieberman, and W. L. Kincheloe, 'Creative Manufacturing Seminar, 1961', Paper SP60-141. New York (Amer. Soc. Tool Manuf. Eng.)
10. D. E. Davenport and G. E. Duvall, *ibid*, Paper SP60-161.
11. D. E. Davenport, 'Creative Manufacturing Seminar 1962', Paper SP62-77. New York (Amer. Soc. Tool Manuf. Eng.)
12. E. Schmidtmann, W. Koch, and H. Schenk, *Arch. Eisenhüttenwesen*, 1965, 36, 667.
13. P. J. M. Boes, *Tech. Centre for Metalworking, (T.N.O.), Delft, Rep. (103)*, 1962.
14. H. G. Otto, 'Proceedings of N.A.T.O. Advanced Study Institute Conference, on High-Energy-Rate Working of Metals' p. 473. 1964: Oslo (Central Institute for Industrial Research).
15. R. J. Zabelka, M.Sc. Thesis, Univ. California, Los Angeles, 1960.
16. J. Pearson, *J. Metals*, 1960, 12, 673.
17. G. A. Hayes and J. Pearson, *NAVWEPS Rep. (7925)*, 1962.
18. A. H. Holtzman and C. G. Rudeshausen, *Sheet Metal Ind.*, 1962, 39, 399.
19. G. R. Cowan and A. H. Holtzman, *J. Appl. Physics*, 1963, 34, 928.
20. E. S. Wright and A. E. Bayce, Ref. 14, p. 448.
21. A. H. Holtzman and G. R. Cowan, *Welding Research Council Bull.*, (104), 1965.
22. O. R. Bergmann, G. R. Cowan, and A. H. Holtzman, *Trans. Met. Soc. A.I.M.E.*, 1966, 236, 646.
23. R. J. Carlson, 'Western Metal Congress, 1965', *Amer. Soc. Metals Tech. Rep. (W6-3-65)*.
24. A. S. Bahrani and B. Crossland, *Proc. Inst. Mech. Eng.*, 1964, 179, 264.
25. A. S. Bahrani, T. J. Black, and B. Crossland, *Proc. Roy. Soc.*, 1967, [A], 296, 123.
26. G. Birkhoff, D. P. MacDougall, E. M. Pugh, and G. I. Taylor, *J. Appl. Physics*, 1948, 19, 563.
27. J. M. Walsh, R. G. Shreffler, and F. J. Willig, *ibid.*, 1953, 24, 349.
28. W. Lucas, J. D. Williams, and B. Crossland, 'Proceedings of the Second International Conference of the Center for High-Energy Forming', 1969, p. 8.1.1.
29. S. Fordham, 'High Explosives and Propellants'. 1966: Oxford, &c. (Pergamon Press).
30. V. Shribman and B. Crossland, Ref. 28, p. 7.3.1.
31. R. W. Gurney, *Aberdeen Proving Ground, Maryland, Ballistic Research Lab. Rep. (405)*, 1947.
32. J. D. Williams, W. Lucas, and B. Crossland, *Queen's Univ. Belfast Internal Rep.*
33. A. L. Foley, 'International Critical Tables', 1967.
34. S. Carpenter, R. H. Wittman, and R. J. Carlson, Ref. 4, p. 1.2.1.
35. V. Shribman, Ph.D. Thesis, Queen's Univ. Belfast, 1968.
36. M. D. Chadwick, 'Select Conference on Explosive Welding', p. 21. 1968: London (Inst. Welding).
37. W. Lucas and J. D. Williams, *Proc. High-Pressure Tech. Assoc., Queen's Univ. Belfast*, 1968.
38. J. N. Hunt, *Phil. Mag.*, 1968, 17, 669.
39. V. Shribman, A. S. Bahrani, and B. Crossland, *Production Engineer*, 1968, 48, 69.
40. G. R. Cowan, J. J. Douglas, and A. H. Holtzman, U.S. Patent 3 137 937, 1960.
41. B. Crossland, J. D. Williams, and V. Shribman, see Ref. 36, p. 15.
42. B. Crossland, A. S. Bahrani, and V. Shribman, Provisional Patent Spec. 55 241/67, 1967.
43. J. M. Stone, see Ref. 36, p. 55.
44. H. Addison, Jr., W. E. Fogg, I. G. Betz, and F. W. Hussey, *Welding Research Suppl.*, 1963, 42, 359.
45. A. S. Bahrani and B. Crossland, *Proc. Inst. Mech. Eng.*, 1966, 180, 31.
46. J. O. De Maris, *Amer. Soc. Tool Manuf. Eng. Tech. Paper (AD 66-113)*, 1966.
47. A. S. Gelman, G. Z. Zaitsev, W. Ya. Ponornarev, and B. D. Tsemakpovich, *Svar. Proizv.*, 1966, 10, 4.
48. G. Rowden, see Ref. 36, p. 31.
49. S. K. Banerjee, M.Sc. Thesis, Queen's Univ. Belfast, 1969.
50. J. A. Dewy, *English Elect. J.*, 1968, 23, (4), 28.
51. D. G. Dalrymple and W. Johnson, *Internat. J. Machine Tool Design Research*, 1967, 7, 257.
52. B. Crossland, A. S. Bahrani, J. D. Williams, and V. Shribman, *Welding*, 1967, 35, 88.
53. M. D. Chadwick, D. Howd, G. Wildsmith, and J. H. Cairns, *Brit. Weld. J.*, 1968, 15, 480.
54. J. H. Cairns and R. Hardwick, see Ref. 36, p. 67.
55. V. Shribman, J. D. Williams, and B. Crossland, *ibid.*, p. 47.
56. M. W. Hardie, *ibid*, p. 73.
57. J. D. Williams and B. Crossland, *Welding*, 1969, 37, 20.
58. A. S. Bahrani and B. Crossland, *Metals and Materials*, 1968, 16, 41, 68.
59. P. Robinson, C. J. Abrahams, and R. Gibson, see Ref. 36, p. 39.
60. H. J. Addison, Jr., *Amer. Soc. Mech. Eng. Paper (64-MD-47)*, 1964.
61. A. K. Kogya and K. Kaisha, U.K. Patent 1 046 655, 1966.
62. F. C. Polhemus, Ref. 4, p. 1.3.1.
63. C. V. Jarvis and P. M. B. Slate, *Nature*, 1968, 220, 782.
64. G. Buck and E. Hornbogen, *Metall*, 1968, 20, 9.
65. G. Buck and E. Hornbogen, Ref. 14, p. 51.
66. L. Trueb, *Trans. Met. Soc. A.I.M.E.*, 1968, 242, 1057.
67. D. C. Murdie and G. Blankenburgs, *Inst. Metals*, 1966, 94, 119.
68. P. Spinedi, G. P. Cammaroto, and L. Morettini, *Met. Ital.*, 1964, 56, 249.
69. J. Pearson, Ref. 9, Paper SP60-159.
70. A. Pocalyko and C. P. Williams, *Weld. J.*, 1964, 43, 854.
71. J. Pearson and G. A. Hayes, *Machin. Design*, 1963, 35, (April), 170.
72. A. H. Holtzman, Ref. 14, p. 488.
73. J. Pietteur, paper presented at '21st Annual Assembly of the I.I.W.', (Warsaw, 1967).
74. R. F. Tylecote, 'The Solid-Phase Welding of Metals'. 1968: London (Edward Arnold).
75. S. W. Hollingum, *J. Australian Inst. Metals*, 1967, 12, (3), 199.
76. A. P. von Rosenstiel, E. G. Chirer, and P. J. M. Boes, *Z. Metallkunde*, 1964, 55, 732.
77. A. A. Deribas, F. Matveenko, T. Sobolenko, and T. Selenko, paper presented at 'Symposium on High Dynamic Pressures' (Paris, 1967).
78. G. E. Duvall and J. O. Erkman, *Tech. Rep. (1)*, 1958, S.R.I. Project GU-2426.
79. P. G. Shewmon and V. F. Zackay, 'Response of Metals to High-Velocity Deformation'. 1961: New York and London (Interscience Publishers).
80. C. S. Smith, *Trans. Met. Soc. A.I.M.E.*, 1958, 212, 574.
81. D. C. Brillhart, R. J. de Angelis, A. C. Preben, J. B. Cohen, and P. Gordon, *ibid.*, 1967, 239, 836.
82. H. E. Otto and R. Mikesell, Ref. 4.
83. A. S. Appleton, G. E. Dieter, and M. J. Bever, *Trans. Met. Soc. A.I.M.E.*, 1967, 221, 90.
84. F. E. van Wely, see Ref. 77.
85. S. S. Batsanov, S. S. Derbenjova, G. S. Dovonin, and E. V. Dulepov, *ibid.*
86. D. R. Curran, S. Katz, J. J. Kelly, and B. Nicholson, *Trans. Met. Soc. A.I.M.E.*, 1959, 215, 151.
87. J. B. Cohen, A. Nelson, and R. J. de Angelis, *ibid.*, 1966, 236, 133.
88. G. Rowden, *Metallurgia*, 1967, 75, 199.
89. H. G. Bowden and P. M. Kelly, *Metal Sci. J.*, 1967, 1, 75.
90. A. A. Deribas, M. Mogilevsky, and T. Sobolenko, see Ref. 77.
91. W. C. Leslie, E. Hornbogen, and G. E. Dieter, *J. Iron Steel Inst.*, 1962, 200, 62.
92. G. E. Dieter, 'Strengthening Mechanisms in Solids', p. 279. 1962: Metals Park, Ohio (Amer. Soc. Metals).
93. G. E. Duvall, *Internat. Sci. Technol.*, 1967, (16), 45.
94. R. L. Nolder and G. Thomas, *Acta Met.*, 1963, 11, 994.
95. J. C. Jamieson and A. W. Lawson, *J. Appl. Physics*, 1962, 33, 776.

## Acknowledgements

This review would have been impossible without the assistance of many people. In particular, the authors would like to thank their collaborators Dr. A. S. Bahrani, Dr. V. Shribman, Mr. W. Lucas, Mr. S. K. Banerjee, and Mr. K. Wylie, whose data they have used extensively. They would also like to take this opportunity to acknowledge that the work from Queen's University reported here has been made possible only through generous grants from the Science Research Council.