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Friction welding of plastics

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Using a specially constructed and instrumented machine, the friction welding characteristics of four thermoplastics: nylon 66, acetal, polymethylmethacrylate and polyvinyl chloride (PVC) were investigated. It was found that during the frictioning stage the interfacial torque and burn-off rate are both constant, but dependent on the axial pressure and rubbing velocity. The rate of heat generation was found to be greatest in nylon 66 and least in PVC and this is discussed in terms of the thermal properties and coefficients of friction of each material. It was found that the conditions required to produce good welds in each of the four thermoplastics are quite critical.

1. Introduction

Although the major advantage of plastics is the ease with which they can be moulded into intricate shapes, nevertheless there is an increasing trend towards the fabrication of plastic articles from standard stocks of rod, sheet, tubing, etc. In addition, a large proportion of plastics processors [1] use finishing operations which involve some sort of binding technique to fix plastics to themselves or to other materials. There are many bonding methods which can be used (for example, adhesives or solvent cements) but the methods which are most successful are those which make use of the inherent properties of the materials. Friction or spin welding is unique in this respect. Since plastics are poor conductors of heat, frictional heat generated at the surface is only slowly transmitted to the interior. Therefore, if the heat build-up is rapid, as happens when one part is held stationary and in contact with another part which is rotated very fast, the surfaces can be melted and a bond formed without any softening of the interior.

Friction welding is reported to have been used in Germany as a jointing technique for plastics during the Second World War [2]. However, for about a decade after the war the interest declined because exciting discoveries were being made in relation to the processability of plastics. Then, in the 1950s, as friction welding became established as a jointing method for metals, there was a renewed interest in the technique for plastics. It is perhaps unfortunate that although there is now a wealth of information available on the friction welding of metals there has been very little research interest in the friction welding of plastics. At present most of the information available has been provided by the materials suppliers [3, 4]. In a recent paper, Nicholas [5] reviewed the literature available and concluded that the technique is a viable bonding method for many plastics. A number of applications were described where sound, high strength bonds were obtained and it was felt that there could be exciting development potential in areas such as the automative industry. Cheney and Ebeling [6] have described the successful application of friction welding in the manufacture of pressurized bottles. In particular they gave details of the types of joint design which should be used for optimum bond strength. In general, however, most of the published work on friction welding of plastics is of a very general, descriptive nature [7–11] and there are only a few papers which give technical details of the interrelation of the process variables [12, 13]. Therefore, in an effort to supply some of this information, a specially instrumented friction welding rig was constructed and the welding characteristics of several thermoplastics were investigated. This paper presents the results of the initial trials which established the variations of axial pressure, interfacial torque and burn-off rate for a range of welding conditions.

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2. Equipment and materials

In order to investigate the friction welding behaviour of plastics an instrumented welding machine was built, as illustrated in Fig. 1. This is capable of welding circular sections up to 13 mm diameter at rotational speeds up to $4600\,\text{rev}\,\text{min}^{-1}$ (mean rubbing velocity of $2.3\,\text{m}\,\text{sec}^{-1}$). During welding, the speed of rotation was continuously monitored by means of a pre-calibrated tacho-generator, the output of which was supplied to a four-pen chart recorder. The other three pens were used to monitor the applied axial pressure, the interfacial torque and the burn-off. The axial pressure was measured by means of a strain gauge load cell as shown in Fig. 1. The torque was measured by causing the stationary chuck to react on a strain gauged cantilever arm. The burn-off was determined by means of a long stroke variable capacitor type transducer. The rotational speed of the driving motor was infinitely variable up to the maximum speed. The axial pressure to the weld zone was applied by means of a pneumatic actuator, the circuitry of which is illustrated in Fig. 2. This system had the facility of being able to apply a boost, or forging, pressure when the relative rotation between the two samples of plastic had been brought back to zero. This latter effect could be achieved by either switching off the motor, in which case the interfacial friction caused the rotating part to stop quickly, or alternatively, the amount of burn-off could be pre-set so that the stationary chuck would eventually slip off the end of the torque arm and so the relative velocity reached zero almost instantly.

Four materials were chosen from the standard stock of tube which were available. These were two semi-crystalline plastics (acetal[*] and nylon 66[†]) and two amorphous plastics (Polymethylmethacrylate (PMMA)[‡] and polyvinyl chloride[¶]). In all cases the samples to be welded had an outside diameter of 12.75 mm and an inside diameter of 7.45 mm. The length of each of the samples was 65 mm and in all the welding trials, the pipe ends were flat.

3. Results

Typical variations of rotational speed, axial pressure, interfacial torque and burn-off are shown in Fig. 3. The experimental procedure adopted was to start the motor, with the plastic samples not touching, and when it had reached its set speed, the axial pressure was applied. When the samples

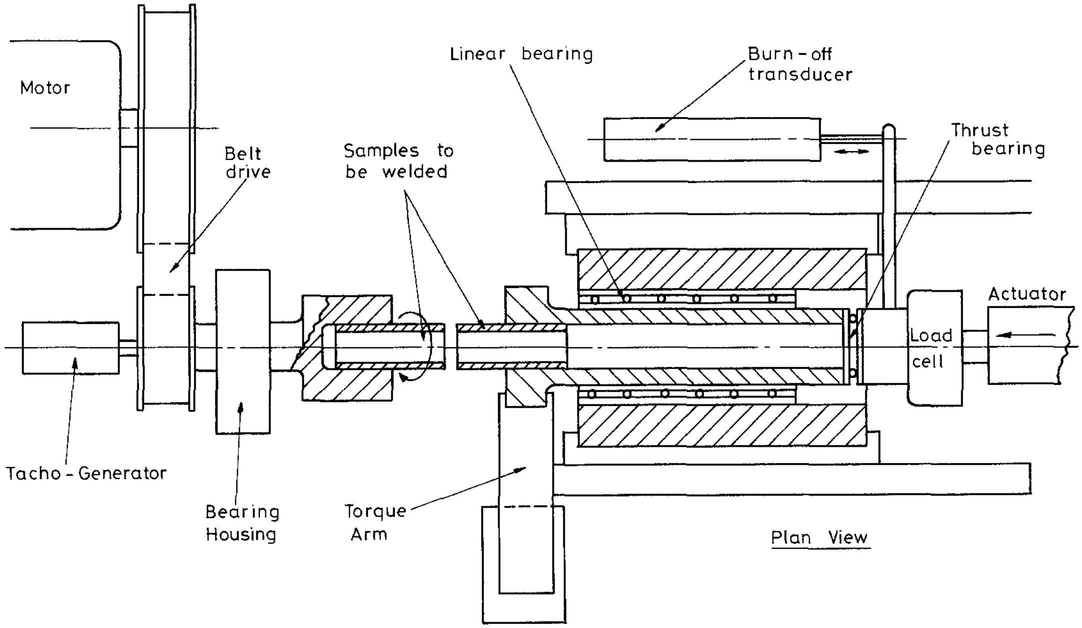

Figure 1 General layout of friction welding rig.

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[*] Acetal homopolymer was supplied by Polypenco Ltd, Gate House, Welwyn Garden City, Hertfordshire, UK.
[†] Nylon 66 was supplied by Polypenco Ltd, Gate House, Welwyn Garden City, Hertfordshire, UK.
[‡] Extruded PMMA was supplied by Richard Daleman Ltd, 325 Latimer Road, London, UK.
[¶] Grey PVC was supplied by Plastics Constructions Ltd, Seeleys Road, Birmingham, UK.

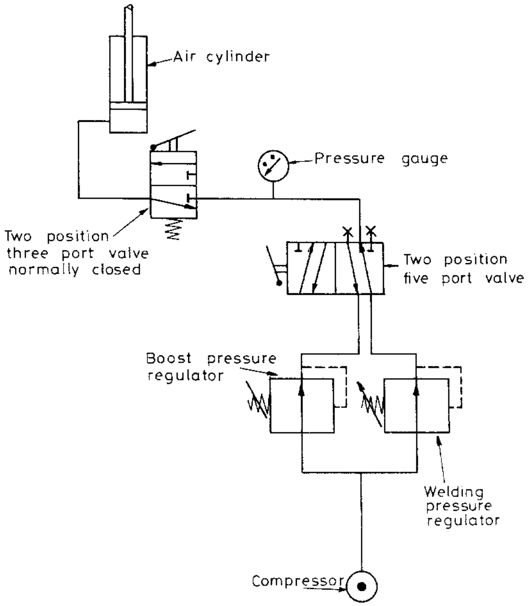

Figure 2 Pneumatic circuit for friction welding rig.

came into contact there was a slight drop in motor speed which had to be allowed for in the initial speed setting. During the welding process the speed was perfectly constant. As the axial pressure quickly increased to its pre-set value, there was a proportionate increase in the resisting torque at the interface. During welding the torque remained constant although there was generally a slight fall off of axial pressure, as shown in Fig. 3. The burn-off transducer showed that when the samples first came into contact, and during the period that the axial pressure was building up, there was very little shortening of the samples. However, once the axial pressure reached its maximum value there was a steady decrease in the length of the test samples (Section AB on Fig. 3). In the subsequent analysis the slope of AB, i.e. the burn-off rate, was studied as a function of the process variables.

After a pre-set time the welding process was stopped by either switching off the motor or allowing the stationary chuck to slip off the torque arm. This latter effect was studied because it was felt that simply switching off the motor would result in weld shearing which could have deleterious effects on weld strength particularly in cases where the material solidifies rapidly (e.g. semicrystalline plastics). When the stationary chuck slipped off the torque arm, the shear stresses at weld interface immediately dropped to zero and a boost, or forging, pressure could be applied. This caused a further axial shortening of the samples as the softened material at the interface was forced out as flash.

In order to analyse the results, the mean rubbing velocity, V_m, was calculated from

$$V_m = \omega r_m, \qquad (1)$$

where ω is the angular velocity and r_m is the mean radius. This velocity is approximately equal to the average point velocity [2] and was used because of the simple form of the expression in Equation 1.

Fig. 4 shows how the torque at the weld interface between PMMA samples, varied when the average rubbing velocity was changed. The axial pressure in each case was constant at 6.2 MPa and, as would be expected, the torque is less at the higher rubbing velocities. However, the effect is not as large as one might expect. A six-fold increase in rubbing velocity, with the proportional increase

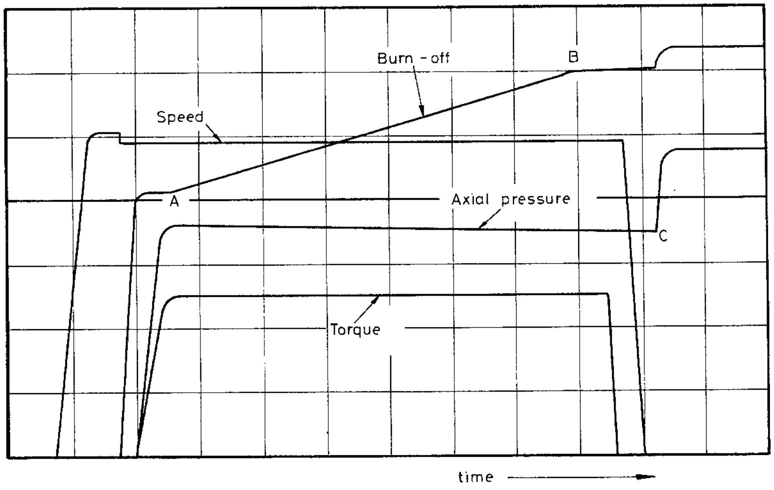

Figure 3 Typical variations of welding parameters.

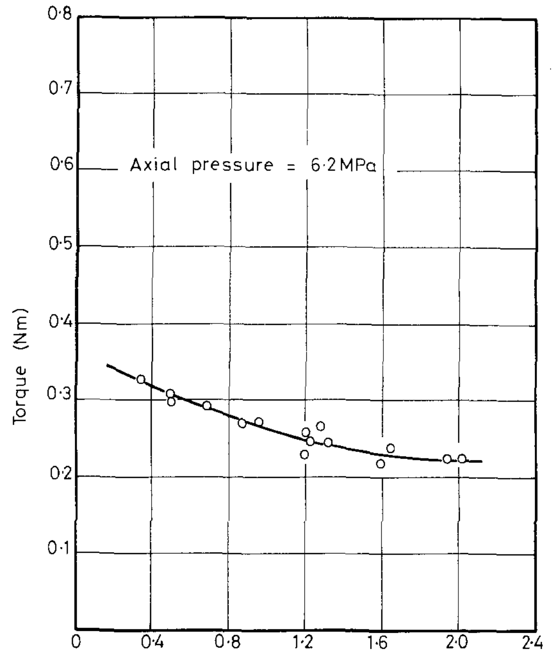

Figure 4 Variation of torque with rubbing velocity for PMMA.

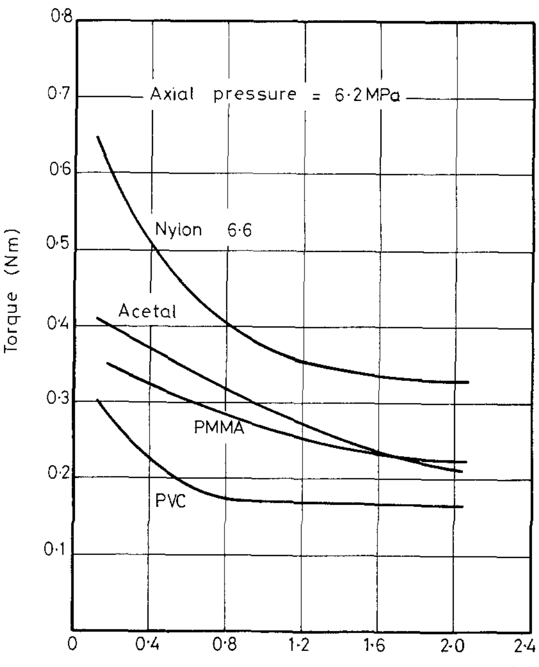

Figure 5 Variation of torque with rubbing velocity for a range of thermoplastics.

in frictional heating, only caused a decrease in resisting torque from 0.32 to 0.22 Nm. Although the rate of heat generation in the material is related to the product of angular velocity and torque [14], it may be seen that for a fixed value of axial pressure, the heat build up is almost directly proportional to the rubbing velocity.

Fig. 5 compares, for a range of rubbing velocities, the torque variations in the four thermoplastics investigated. To avoid unnecessary complexity on the diagram, the experimental points have been omitted. For nylon 66, acetal and PVC the reductions in torque are greater then those observed in PMMA. The effect is most pronounced for nylon 66 although it is interesting to note that for PVC the torque is essentially independent of rubbing velocity for speeds greater than 0.8 m sec^{-1}. Fig. 5 also illustrates that, of the four materials, nylon 66 has the greatest rate of heat generation whereas PVC is the worst in this respect. In a series of tests to determine the temperature rise at the weld interface this trend was confirmed. A non-contacting infra-red radiation thermometer was directed at the weld zone during the frictioning period and although there may have been some error in the measurement of the absolute value of temperature, in relative terms the PVC samples exhibited the lowest weld temperature whereas the nylon 66 samples attained the highest weld temperature (over twice the value for PVC under the same welding conditions). The temperature rise in each of the materials will depend on their thermal properties and also on the coefficient of friction, which will be considered later. Of the four materials, nylon 66 has the highest coefficient of thermal conductivity and specific heat capacity, (0.43 W m^{-1} K^{-1} and 1.68 kJ kg^{-1} K^{-1}, respectively) and PVC has the lowest values of these properties (0.16 W m^{-1} K^{-1} and 0.93 kJ kg^{-1} K^{-1}, respectively).

Fig. 6 illustrates how the torque at the weld interface in PMMA varies with axial pressure. There are two distinct sections to the characteristic. For axial pressures up to about 3 MPa the torque increases rapidly, in a linear fashion, as the axial pressure is increased. For axial pressures in the region of 3 to 4 MPa there is a transition and beyond 4 MPa, although the torque increases linearly with pressure, the rate of increase is only about one-tenth of that experienced at low pressures. This same type of behaviour was observed at two rubbing speeds in PMMA and, as shown in Fig. 7, the other three thermoplastics also displayed similar characterisitcs. Once again nylon 66 exhibited the greatest rate of heat generation and PVC exhibited the lowest rate.

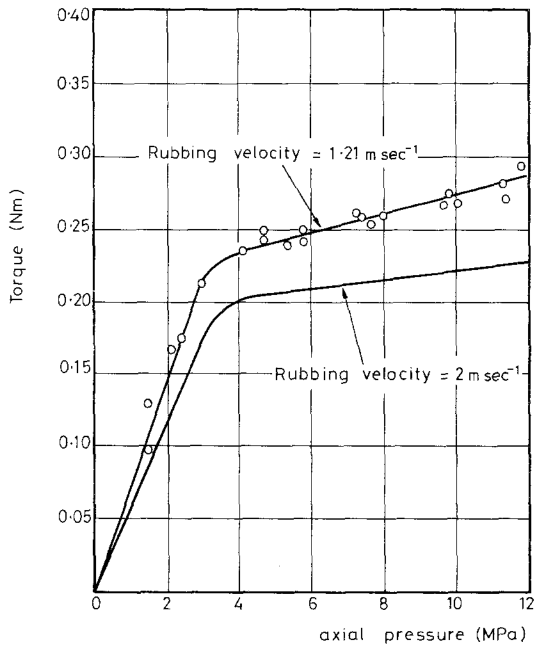

Figure 6 Variation of torque with axial pressure for PMMA.

As mentioned earlier, the coefficient of friction, μ, of each of the materials has a considerable effect on the rate of heat generation during friction welding. As the values of μ were not readily available for the materials being investigated, it was necessary to determine the values in each case. This was done using a simple inclined plane apparatus. The value of μ was calculated by noting the angle of tilt necessary to cause each material to slide on a surface of the same material. A range of normal loads was used for each material and the following results were obtained.

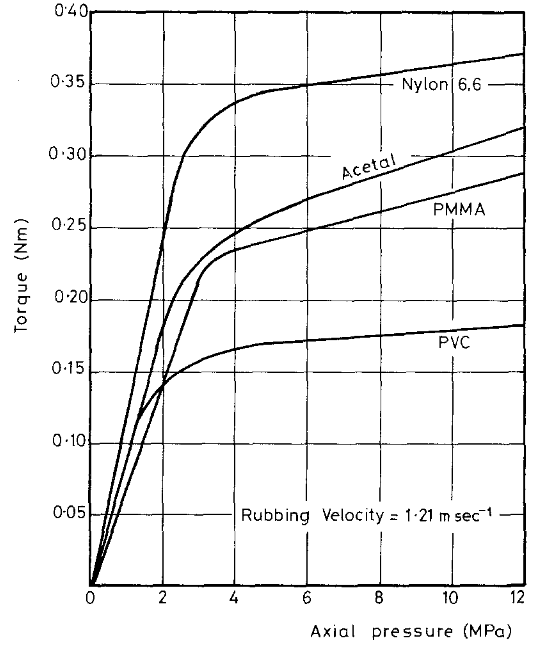

Figure 7 Variation of torque with axial pressure for several thermoplastics.

TABLE I Derived coefficients of friction during welding using a rubbing velocity of 1.21 m sec^{-1}

Material	PVC	PMMA	Acetal	Nylon 66
Pressure = 1 MPa	0.21	0.16	0.21	0.28
Pressure = 10 MPa	0.04	0.065	0.072	0.086

Material	PVC	PMMA	Acetal	Nylon 66
Coefficient of friction, μ	0.35	0.41	0.52	0.76

It will be noted that these values increase in the same order as the observed rate of heat generation during friction welding. However, the coefficients of friction will be dependent on temperature and will change, therefore, during the welding process. No information could be found on the temperature dependence of μ, so, in order to get some idea of the variation involved, the ratio of the torque to the applied pressure was studied for a range of welding conditions. By including a factor to allow for the cross-sectional area of the test-pieces and the average radius it was possible to estimate a value for the coefficient of friction during welding. From Figs 5 and 7 the values in Tables I and II may be derived.

For all materials, therefore, the derived values for the coefficient of friction show a significant decrease with temperature. However, it should be remembered that the values in Tables I and II are not true coefficients of friction because as the materials heat up a viscous film is formed at the interface. The values in the tables are, therefore, probably more akin to a coefficient of shear viscosity.

During welding the viscous film which forms is generally squeezed out from the weld interface due to the application of the axial pressure. The material squeezed out forms a weld bead, the extent of which depends on the welding para-

TABLE II Derived coefficients of friction during welding using an axial pressure of 6.2 MPa

Material	PVC	PMMA	Acetal	Nylon 66
Velocity = 0.2 m sec^{-1}	0.085	0.12	0.14	0.22
Velocity = 2 m sec^{-1}	0.063	0.084	0.08	0.12

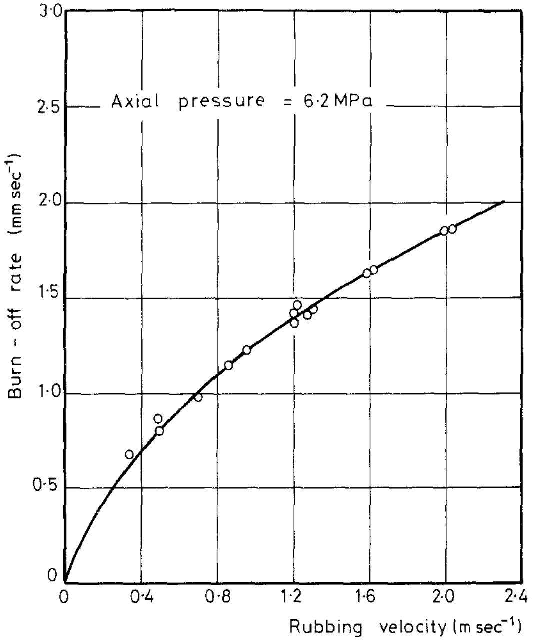

Figure 8 Variation of burn-off rate with rubbing velocity for PMMA.

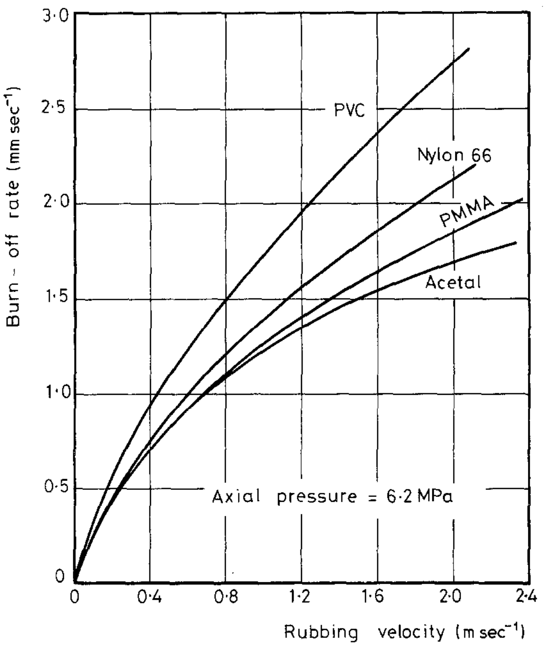

Figure 9 Variation of burn-off rate with rubbing velocity for several thermoplastics.

meters (i.e. rubbing speed and axial pressure). During the friction welding of the four thermoplastics considered it was found that the rate of axial shortening (burn-off), which is associated with bead formation, was constant for any particular set of welding conditions. However, the rate changed as the welding variables were altered. Fig. 8 shows how the burn-off rate for PMMA varied for rubbing velocities up to 2 m sec^{-1}. In Fig. 9, where the experimental points have been omitted for clarity, the burn-off rates for the four materials may be compared. As would be expected, in all cases the rate of axial shortening increases as the rubbing velocity (and hence the heat generation rate) increases. However, it is apparent that some complex interaction of material properties must influence the amount of burn-off because PVC, which heats up more slowly than the other materials and is generally regarded as having a high melt viscosity, does in fact exhibit a much greater burn-off rate than any of the other materials. One possible explanation for this is that the PVC weld bead forms uniformly whereas with the other materials the low viscosity film is formed quickly at the interface but is then immediately squeezed out so that two relatively cooler surfaces come together and must generate more frictional heat to form a new viscous film. Therefore although the viscous film is formed quickly the continual process of having to reform the film may explain partially why the overall burn-off rate is relatively slow.

When the rubbing velocity was kept constant and the axial pressure was varied it was found that, for PMMA, the burn-off rate increased relatively quickly for pressures up to 2 MPa (Fig. 10). For pressures in excess of 4 MPa the burn-off rate increased linearly once again but the relative increase, for each increment of axial pressure, was much less. Fig. 11 shows that for each of the other thermoplastics the same general shape of characteristic was observed, with PVC once again exhibiting the highest burn-off rate under all welding conditions.

Although the primary objective of the present study was to investigate the inter-relationships between the main welding variables, clearly the long-term aim would be to optimize the weld strength in terms of these variables. This aspect of the work is continuing. Tensile tests on the samples welded in this initial programme showed that the weld strengths obtained in all four thermoplastics were relatively low. For the range of welding variables considered in Figs 4 to 11, the best tensile strength which could be achieved in the welds was about 50% of the strength of the parent materials, even with the weld beads removed.

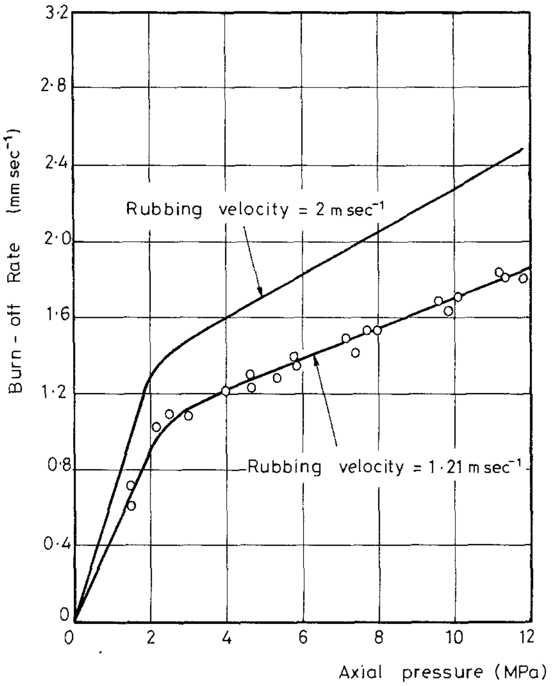

Figure 10 Variation of burn-off rate with axial pressure for PMMA.

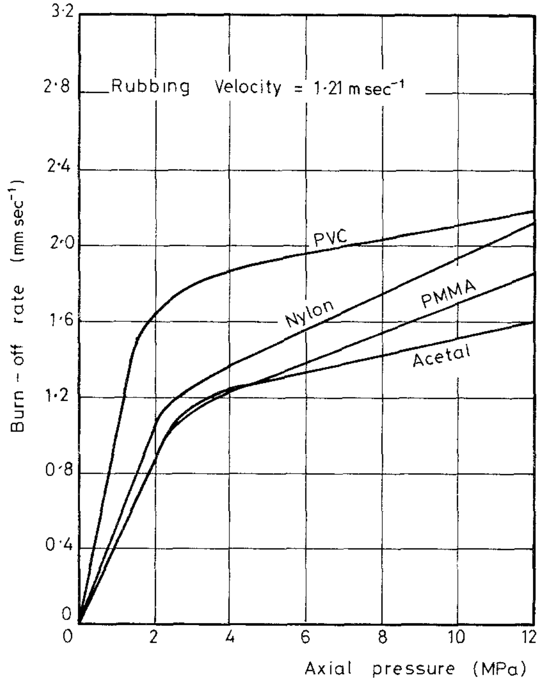

Figure 11 Variation of burn-off rate with axial pressure for several thermoplastics.

In recent years there has been some research interest in butt-fusion welding of plastics. Since the principles of the two processes are similar, it could well be that some of the information which has been accumulated in this field may be of use in optimizing the strength of friction welded joints. The first interesting point is that, in agreement with the results obtained in this investigation, Barber and Atkinson [15] found that the optimum conditions for welding are very critical. In common with other workers [16, 17] they found that long heating times are better than short. De Courcy and Atkinson [16] reported that with a range of different grades of polyethylene it was more harmful to have the weld temperature below the optimum than above it. Their results suggested that weld strength was not very sensitive to axial pressures in the range 0.1 to 0.6 MPa although low pressure ($<$ 0.1 MPa) was detrimental. Bucknall *et al.* [17] have summarized most of the early findings by reporting that during butt-welding, the weld strength depends on the temperature at the interface, the duration of the heating period and the extent of the melt displacement during welding. They also make the point that low pressures produce poor welds but add that high pressures are equally undesirable. This is because the viscous film, which offers the potential of a good weld through molecular chain entanglement, is squeezed out of the weld area and causes high transverse orientation in the weld.

Although there was no mechanism on the friction welding machine for controlling the melt displacement independently of the other processing variables it was decided that it might be possible to reproduce some of the optimum conditions suggested for butt-welding. Therefore, a few explanatory trials were conducted on PMMA. In order to keep the temperature high and the heating period as long as possible, combinations of low axial pressures (0.5 → 2 MPa) and relatively high rubbing velocities (1.8 → 2 m sec^{-1}) were explored. It was found that under these conditions the weld strength was in fact improved.

Using a rubbing velocity of 2 m sec^{-1} and an axial pressure of 0.7 MPa, the weld strength in PMMA was found to be 80% of the strength of the unwelded material. Using a boost (or forging) pressure of 2 MPa after the frictioning stage it was found that the weld strength was improved to 87%. In each case it was found that the weld strength was much better when the stationary chuck was allowed to slip off the torque arm (thereby avoiding any shearing of the bond when the motor was switched off). Also, in order to reduce the notch effect caused by the weld bead

[15], the latter was always removed prior to testing.

It is considered that the weld strength in each of the plastics can be improved in the same way and the next phase of the work will be to determine optimum welding conditions and joint designs for each of the materials.

Conclusions

From this series of friction welding trials on nylon 66, acetal, polymethylmethacrylate (PMMA) and polyvinyl chloride (PVC), the following conclusions may be drawn.

(1) The resisting torque, between the fixed and rotating samples to be welded, remains essentially constant throughout the frictioning stage.

(2) The values of the resisting torque increase as the axial pressure and the rubbing velocity increase.

(3) The rate of heat generation was greatest in nylon 66 followed by acetal, PMMA and PVC in descending order.

(4) The rate at which the plastic samples become shorter during friction welding remains constant during the frictioning stage.

(5) The burn-off rate increases as the axial pressure and rubbing velocity increase.

(6) The burn-off rate was greatest in PVC followed by nylon 66, PMMA and acetal in descending order.

(7) It was found that satisfactory welds in these four thermoplastics are not easy to achieve because the optimum conditions appear to be quite crucial. A set of explanatory tests on PMMA showed that a combination of low axial pressures, high rubbing velocities and a final boost pressure gave a weld factor of 0.87.

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