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BETTER VACUUM FOR BETTER PARTS

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U. S. ATOMIC ENERGY COMMISSION
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BETTER VACUUM FOR BETTER PARTS

Richard S. Culver and George Herbst

Abstract. This report describes the results obtained during explosive forming into a die when both inadequate and adequate vacuums are used. A mathematical analysis of phenomena observed using inadequate vacuums is presented. Details of vacuum system design and operation as well as practical aspects of vacuum measurement as applied to explosive forming are given.

INTRODUCTION

One important factor in successful high velocity forming of sheet metal is the design and operation of the vacuum system used to evacuate the die cavity. Insufficient vacuum can lead to dimpled and burned parts as well as pitting of the die surface. A poorly placed vacuum port can mark the surface of the part. Poor sealing procedures will lead to slower pump-down and reduce the production rate.

In spite of the serious consequences resulting from an insufficient vacuum system, relatively little has been written about the level of vacuum required or the techniques for obtaining the best performance from a given vacuum system. This is perhaps not surprising since the vacuum requirements vary widely depending upon the shape of the part being formed and the forming sequence. Vacuum system problems are most severe when forming thin materials to relatively deep-draw depths. In this case it is not normally possible to place the vacuum port in a trim area, so its diameter must be kept small. This report describes some of the problems in obtaining a good vacuum in a die with a small vacuum port and various solutions to these problems.

A typical vacuum system is illustrated in Figure 1. It consists of a vacuum pump capable of obtaining a vacuum in the range of 10 microns, a surge tank which traps any

FIGURE 1. Schematic Diagram of Typical Vacuum System.

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water that gets into the vacuum line, a heavy-walled rubber hose which leads to the die, a vacuum hole drilled through the die with a small port opening into the die cavity, and finally the die cavity and metal blank. Frequently, a vacuum gage is mounted in the system between the surge tank and the pump to monitor the vacuum in the system.

Obtaining a good vacuum in the die cavity is difficult because of the restriction through the small port leading into the die cavity. Any leaks in the vacuum system downstream of the port effectively prevent obtaining a good vacuum, regardless of the pump capacity. The port also makes it difficult to monitor the pressure in the die cavity. Since it is normally impractical to measure the pressure in the die cavity, it is measured upstream of the port. Obviously, the largest possible port should be used and it should be kept clean during operation to ensure a reproducible vacuum.

Since the port design is normally dictated by the die configuration (as will be discussed later), its size is frequently not negotiable. Obtaining a good vacuum then depends upon an effective means of sealing the multitude of potential leak paths and some method of determining the vacuum in the die cavity.

SUMMARY

The design of the vacuum ports and associated equipment will frequently determine the success or failure of a die. It should, therefore, be given careful consideration and not be added as an afterthought. The location of the vacuum port should be selected so that the port is neither subjected to large impulsive loads from the deforming blank, nor covered during the early stages of forming so that evacuation for subsequent shots is not possible. Consideration should be given to the method of sealing the blank to ensure that it is reliable, rapid, and not tedious. The production rate will be seriously affected by a procedure which does not give a consistently good seal.

Since the evacuation rate is a function of the conductance of the vacuum port rather than the capacity of the pump, a small, reliable pump capable of pulling a vacuum of about 10 microns would be preferable to a large pump which can reach only 100 microns.

A vacuum gauge capable of reading down to about 10 microns would be very useful in determining whether a good seal has been obtained. The typical small gauge

which reads in inches of mercury does little more than indicate that the vacuum pump is turned on. It was once thought that an experienced operator could tell if the system was leak-tight by listening to the sound of the vacuum pump. It was found, however, that most vacuum pumps become quiet at about 3 to 5 millimeters, which is well above the desired operating level. The time invested in calibrating and monitoring the vacuum system should be quickly returned as a result of having a reproducible operation.

Finally, it should be noted that a more careful consideration of the level of vacuum obtained may result in saving time in the forming sequence. Many operations use a forming and a sizing shot to make a part, to minimize the danger of dimpling. With better control of the vacuum, it might be possible to eliminate the sizing shot or other intermediate shots with a resulting increase in production rate.

It is this type of refinement which will eventually be necessary if the high-energy-rate-forming (HERF) processes are to establish themselves in industry.

ANALYSIS OF THE REQUIRED VACUUM

Before the design requirements for a vacuum system can be determined, it is necessary to know what magnitude of vacuum is required in the die cavity. It is apparent that this will depend upon the die and blank material, the forming sequence, the required tolerances on the part and, from a practical standpoint, how long the vacuum system can be allowed to pump down. Thin blanks (high D/t ratios) or blanks of soft material will be more likely to dimple and therefore require a better vacuum. For a deep draw, the volume reduction to form to the final die contour is severe, and so a good vacuum is required.

It is apparent, therefore, that there is no single answer to the vacuum level required for all forming operations. By using a severe example, however, it is possible to set an upper limit to the level of vacuum needed for most practical cases of high velocity forming, as well as to determine the effect of changes in the forming procedure. The following analysis will assume that a 15-inch-diameter hemispherical shell is to be formed out of 0.100-inch-thick 6061-0 aluminum. It will be formed into a steel die in one shot. The initial vacuum in the die is 1 mm Hg.

With a D/t ratio of 150, and this vacuum, elastic deflection of the blank into the die cavity will occur; however, the

decrease in the volume of the die cavity is small compared to the unevacuated die volume and will be neglected in the following analysis.

Let us first consider the sequence of operations which might cause a dimple to form. First, the die cavity is evacuated. Next, the blank is driven down by the energy source, compressing the residual air left in the cavity. As the blank bottoms on the die, the air is compressed to a high pressure and temperature. The combination of rebound of the blank from the die and pressure forces the pole of the formed piece up to make the dimple. This sequence is illustrated graphically in Figure 2, and Figure 3 illustrates a typical dimple formed in a thin aluminum cup.

To calculate the peak pressure and temperature achieved in the region of the dimple, let us assume that the compression of the air is adiabatic. This assumption is justified by the fact that the temperature is not high enough, and the time at temperature is not long enough to allow significant heat transfer to occur. For adiabatic compression

$$\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{1/k} = \left(\frac{T_1}{T_2}\right)^{1/(k-1)}$$

where k is the ratio of specific heat at constant pressure to that at constant volume. Both the pressure ratio and temperature ratio are independent of the initial pressure, but are a function of the change in volume from the original die cavity to the final volume of the dimple. An even high pressure and temperature exist at the instant that the dimple begins to form which corresponds to the minimum volume.

Experience has shown that for a dimple whose shape is approximately that of a segment of a hemisphere, the diameter is about 10% of the diameter of the cup. Usually the change in final volume of the cup results by a variation in its depth rather than in this diameter ratio. We will assume that the depth-to-diameter ratio of the dimple is 0.25, which would correspond to a volume reduction ratio, V_1/V_2 of approximately 2000, if the dimple is 10% of the cup diameter. Using $k = 1.4$ for air, $P_2/P_1 = 43,000$, and $T_2/T_1 = 21$. The corresponding final pressure and temperature for an initial pressure of 1 mm and temperature of 80 °F (540 °R) are 830 psi and 11,000 °F, respectively. The pressure and temperature

FIGURE 2. Successive Stages in Dimple Formation.

would be even higher at the instant when the dimple is of a minimum volume.

Obviously, this extremely high temperature could not exist without damaging the die and blank. At some point, late in the stages of forming, heat transfer to the die and blank will become significant.* Nevertheless, there is a trade-off between energy transfer to the blank in the form of heat and mechanical energy (pressure), so for the sake of analysis it is reasonable to ignore the heat transfer and assume adiabatic compression, and expansion accounts entirely for the dimple formation. Even so, it would appear that the temperature would be high enough to cause more serious damage than is usually found in the dimpled area. It does not, however, because the amount of energy available is small owing to the small mass of the air. The increase in internal energy of the air resulting from adiabatic compression from V_1 to V_2 is

$$U_2 - U_1 = \frac{mR(T_2 - T_1)}{1 - k}$$

where m is the mass of air, and R is the gas constant for air. $R = 53.3$ Btu/lb/°R. For this example, the net change

*The value of k for air will not remain constant because of increasing deviation from ideal gas behavior as the temperature and pressure increase.

in internal energy from the initial conditions to the final dimple formation is 0.043 Btu or 34 ft-lb. For adiabatic compression, the work done is equal to the change in internal energy. Thirty-four foot-pounds is about one-half the energy required to mechanically form the assumed dimple. The additional energy required would be available if the minimum volume of the dimple, and hence the compressed air, were 1/30,000 of the original volume or 1/15th of the final dimple volume. Conversely, if the initial air pressure in the die were 3 mm of Hg, it would cause the dimple to form with the volume never decreasing below the final volume, V_2 . The most likely situation would be somewhere between these two extremes.

With the blank of aluminum and the die of steel, it is safe to assume that all of the energy of the compressed air is used in deforming the aluminum. On the other hand, if the blank material has a strength level comparable to the die material, a significant portion of the energy of the air may be transmitted to the die. This may result in serious damage to the die surface as well as the parts. (See Figure 4.) For a high strength material, the dimple will usually be smaller than was previously assumed.

Frequently, there is evidence of burning of the part surface. It can be shown that this is a localized surface effect, unless there is additional energy release as a result

FIGURE 3. Dimple in Thin Aluminum Cup.

FIGURE 4. Damaged Polar Region of Steel Die.

of decomposition of die lubricant. Burning is more common in parts made from high-strength materials or on thick parts where it is impossible to dissipate the energy of the compressed air by dimpling.

Figure 5 shows the burned surface of a one-half-inch-thick stainless steel cup. A soft material, such as 1100-0, shows evidence of both surface burning and melting when formed in a section too thick to permit typical dimpling (Figure 6).

FIGURE 5. Burned Surface on Thick Stainless Steel Cup.

FIGURE 6. Burned Surface on Thick Aluminum Cup.

Returning to the previous energy balance on the compressed air, if it is assumed that the energy of compression is used to heat the blank rather than deform it, which is a more reasonable assumption in the case of high strength materials, the temperature rise would be

$$T_2 - T_1 = (U_2 - U_1) / mC_p$$

Approximately one half of the available energy would be transferred to the die, so about 0.02 Btu is available to heat the blank. If this were used to uniformly heat the mass of blank material in the dimple region it would account for a temperature rise of only 6 °F. If on the other hand it were assumed that the surface of the aluminum blank just reaches its melting temperature, the temperature gradient will extend about 0.002 inches into the blank.* Thus, it can be seen that the burning effect will always be associated with a thin surface layer, so long as the initial pressure is in the range of 1 mm of Hg.

Whereas this example is useful in illustrating the source of the dimple problem, it represents far more extreme conditions than exist in most forming operations. There are many techniques in use to circumvent the dimple problem. In most cases it is impossible to form a material to a full hemisphere in one operation because of the formability limits of the material. Even when it is possible, the blank is usually formed part way on the first shot and final sizing is done in a subsequent shot where the initial volume has been significantly reduced. In the preceding example, if the part had been formed to within 0.1 inch of the die surface, the volume reduction would be about 1/50, and the corresponding pressure and temperature ratios would be 240 and 4.8, respectively. Even though the volume reduction on the sizing shot would still theoretically be infinite if there is to be no dimple formed, the mass of air will have been reduced to 2% of its original value, so the internal energy of the gas will be low.

It is also possible to eliminate the dimple problem by using a lower initial vacuum. At 100 microns, the pressure and internal energy terms would be reduced by an order of magnitude, which is probably low enough to eliminate dimpling in all but the most extreme cases.

It should also be noted that there are other sources of dimpling besides entrapped air. Obviously, water trapped in the die cavity will cause a dimple. A more common source of trouble is lubricants used on the die or blank surface to assist in the drawing mode of deformation and to prevent the blank from welding to the die. Not only can the lubricant cause a dimple because of its volume, but some lubricants will decompose as a result of the high temperatures achieved by the compressed air and burn to give additional heat and gas volume. This process is commonly referred to as "dieseling". Our experience has shown that standard silicone vacuum grease and molybdenum sulfide, if used sparingly, do not cause "dieseling" but will assist in reducing surface friction.

MEASUREMENT OF DIE VACUUM

From the above analysis it can be concluded that for most operations a vacuum of less than 1 mm of Hg (1000 microns) would be desirable. While this is a relatively easy vacuum to obtain in most cases, the problem of pulling a vacuum through a small orifice makes it difficult both to obtain a good vacuum in the die and to determine its magnitude. To visualize this problem, it is helpful to consider the general equation, as follows, for steady-state flow into and out of a cavity through two small leaks. (See Figure 7.)

$$C_1 (P_a - P_d)^{m_1} = C_2 (P_d - P_p)^{m_2}$$

where C_1, C_2 = conductance of leak paths

P_a = atmospheric pressure

P_d = pressure in die cavity

P_p = pressure at vacuum pump

m_1, m_2 = exponents depending on character of flow:

$m = 1$ for molecular flow, where $aP < 5$, a being a characteristic dimension such as orifice diameter in cm, and P being the pressure in microns.

$m = 2$ for viscous flow, where $aP > 500$, and between 1 and 2 for $5 < aP < 500$ (Dushman, 1962). For a typical

*For an estimate of this type, the Schmidt plot technique is useful for describing transient temperature profiles. See Kreith, p. 153.

vacuum system, $P = 100$ microns and the orifice diameter less than 1 mm, so the product aP is close to 5. The exponents m_1 and m_2 will therefore be assumed equal to 1. The equation can then be rewritten

$$P_d - P_p = \frac{C_1}{C_2} (P_a - P_d) \frac{C_1}{C_2} P_a$$

It can be shown that a leak with a conductance, C , in the order of one-thousandth of the vacuum part conductance, C_2 , would result in P_d being about 1 mm greater than P_p . In this case, it would be impossible to determine the magnitude of P_d by measuring P_p without having accurate values for the conductances, C_1 and C_2 . As there is no practical way to determine C_1 and C_2 , it is necessary to use a more direct method to determine P_d .

P_p has been related to P_d through a special calibration procedure which uses an additional vacuum gauge and a needle valve mounted in a dummy blank. With the needle valve closed, it is possible to obtain pressure-time curves for the leak-free die (assuming all unintentional leaks have

been plugged). The valve is then opened very slightly, and the system is allowed to stabilize with the new leak rate. When this is done with several settings of the valve, a curve is obtained which serves as a reference. Because a steady state condition is never fully achieved in this test, it is wise to run the test two or three times to evaluate the scatter to be expected during forming operations.

A plot of P_d versus P_p for a typical cup-shaped die is shown in Figure 8. In this instance, the zero flow pressure of the vacuum pump varied from 25 to 65 microns. Depending on the magnitude of the leak, C_1 , the die pressure, P_d , stabilized at from 5 to 10 times the pump pressure, P_p .

The typical pump-down time for this die was about 30 minutes, owing to a small vacuum port. However, with a good seal a die vacuum of 1000 microns (1 mm) could be obtained in about 5 minutes, so for many operations it would not be necessary to wait 30 minutes before shooting.

FIGURE 7. Schematic Diagram of Leaks in Die Cavity.

FIGURE 8. Plot of Die Pressure Versus Pump Pressure.

with vacuum systems. It is assumed that the reader is aware of the proper use of a vacuum pump or has access to someone who is. The following discussion is concerned primarily with the problems unique to high velocity forming.

Vacuum Ports

Circular Hole – The most common type of vacuum port is a small circular hole placed in the bottom of the die cavity. The diameter of the hole is typically about one-half the thickness of the blank. The hole should be placed in a region where the formed part does not strike the die at a high velocity. The pole of a dished part is one of the most highly stressed parts of the die, but by tradition that is where the vacuum port is placed. About 10 to 20 degrees away from the pole would be a better place to put the vacuum port.

Vacuum Plug – In forming very thin parts or parts with a high D/t ratio, it is difficult to make the vacuum port small enough to avoid marking the part and still be able to pull a good vacuum. This problem has been solved by placing a plug (Figure 9) in the bottom of the die, upon which shallow flats have been ground. The width of the flats at the die surface is about one-half the part thickness of the blank, but the effective cross sectional area of the slit-shaped ports is about 400 times that of a single hole with a diameter comparable to the width of the slits. For large dies it may be sufficient to drill many small holes rather than going to the trouble of making such a plug, but for small dies with thin parts it is impossible to drill a hole small enough to prevent severely marking the part. In this case the plug concept is very useful. Even with the plug, minor marking may occur on soft materials as indicated in Figure 3.

DESIGN AND OPERATING DETAILS OF A VACUUM SYSTEM

The discussion on measurement of die vacuum gives an indication of the level of vacuum required and a means of measuring it, but the vital difference in achieving a successful vacuum is the correct design of the system and effective means of sealing the numerous potential leak paths. These problems have not been solved conclusively, as can be seen in the preceding photographs, but several practical lessons have been learned which have helped us obtain a better vacuum.

There is much to obtaining full efficiency of a vacuum pump and it is thoroughly discussed in textbooks dealing

FIGURE 9. Vacuum Plug.

For successful operations, there are certain design considerations which must be observed in the fabrication of a vacuum plug. The plug must be a "slip" fit into the cylindrical cavity in the bottom of the die. If a press fit is used, the plug will invariably move back from its seating surface a slight amount when the press is removed. As soon as it is struck by a rapidly moving part, the plug will move down, leaving a circular mark on the part. For the same reason, the mating surfaces on the bottom of the plug and cylindrical cavity in the die must be carefully machined, or preferably lapped together, to avoid further seating of the plug under use. The plug should be tightened in place before the final die contour is machined. The plug should be made of the same material as the die to obtain as uniform response to the impulsive action of the striking blank as is possible.

The minimum practical size of the plug appears to be about 1-1/2 inches in diameter and 3/4-inch deep, with a 3/8-inch-diameter bolt machined to the bottom. Plugs smaller than this become deformed or broken after use.

Peripheral Slots — In dies which are used for both sizing and forming, the draw-ring is made separately and an additional series of slots are placed in the bottom of the

ring which are connected by an internal passage in the die to the main vacuum port in the bottom of the die. (See Figure 10.) These slots greatly increased the effective vacuum port area during the first shot when a large volume has to be evacuated. After the first shot they are blocked by the part, but the volume to be evacuated has been significantly reduced, so a single port in the bottom of the die is sufficient to evacuate the die. Because the slots are in a region in the die where the blank does not strike the cavity surface with much force, the slots do not affect the final surface of the part.

Vacuum Seals

O-Rings — One of the major problems in explosive forming, both from the standpoint of obtaining a successful vacuum and reducing the forming cycle time, is sealing the blank against the die face. In general, O-ring seals have not proven satisfactory for this purpose. The O-ring is usually torn up by the moving blank after a few shots. The O-ring groove which is machined in the die tends to grab the blank and make control of the pull-in difficult. Paynter (1968) has used square, rubber strip, set in a shallow, square recess, with beveled corners. (See Figure 11.) This eliminates the edges which catch the moving blank and, apparently permits good sealing.

FIGURE 10. Schematic Diagram of Slotted Vacuum Ports.

Sealants — In most instances, additional sealing is required whether an O-ring is used or not. For close fitting surfaces this can be done with a silicone vacuum grease. For small gaps and rough edges, a putty-like substance is usually used. Traditionally, zinc chromate has been used for this purpose, but it has certain disadvantages. If the gap is too large the zinc chromate will pull through, causing a leak and covering the bottom of the blank where it may deform the part. It sticks to a cleaned metal surface so well that it may be scraped off and then dissolved with an organic solvent. Recently, we have been using Duxseal* with much better results. It appears to bridge across a larger opening than the zinc chromate, so that pull-in is less of a problem. It is more cohesive and

less adhesive than the zinc chromate so that normally it can be stripped from the part without being scrapped or dissolved.

Rubber Diaphragm — Another approach to sealing the blanks has been used on gather forming dies, which have no hold-down ring. A thin rubber sheet is stretched across the entire blank surface and held down around the sides of the die with a rubber O-ring (Figure 12). This proved to be a particularly good system for sealing large dies where it became a lengthy procedure to seal the blank edge with Duxseal. This procedure was originally used on a hot forming die fixture by Hageland (1963).

*Tradename, Johns-Manville

FIGURE 11. Square Rubber-Sealing Ring.

FIGURE 12. Rubber Sheet Die Seal.