about 5,000-90,000 psi. A number of abrasive materials can be used, such as garnet, aluminum oxide, silicon carbide, and glass beads. The process can be used in various embodiments of this invention, e.g., for the formation of passage holes through a metal substrate, or through the substrate and a protective coating over the substrate, as described previously. Unlike some of the other cutting processes used on metals, the water jet process does not involve heating of the substrate to any significant degree. Therefore, there is no “heat-affected zone” formed on the substrate surface, which could otherwise adversely affect the desired exit geometry for the passage hole.

[0061] Moreover, the water jet system can include a multi-axis computer numerically controlled (CNC) unit. The CNC systems themselves are known in the art, and described, for example, in U.S. Patent Publication 2005/0013926 (S. Rutkowski et al), which is incorporated herein by reference. They CNC systems allow movement of the cutting tool along a number of X, Y, and Z axes, as well as rotational axes.

[0062] FIG. **9** is a schematic perspective of one water jet cutting machine **150**, suitable for the present invention. FIG. **10** is a schematic perspective view of the nozzle assembly of the machine of FIG. **9**, depicting the function of the machine with respect to a substrate, described below. The water jet machine of FIG. **10** is usually equipped with a high capacity pump (not shown,) capable of delivering a liquid supply **178** (typically water), at a high rate of pressure to a jet orifice **152** (FIG. **10**). The jet orifice is supported within a distribution head **154**, which defines, internally, a mixing chamber **156**. The pressurized liquid is delivered from the mixing chamber, into and through a delivery nozzle **158**, to be emitted at a correspondingly high force, as mentioned above, in a linear jet stream **160** (see FIG. **10**). (Various details regarding this type of equipment are also set forth in the above referenced patent to Miller et al).

[0063] With continuing reference to FIGS. **9** and **10**, the distribution head **154** and the nozzle **158** can be supported on a cantilevered arm **162** from an upright movable stanchion **164**. This arrangement allows for controlled reciprocatory movement of the distribution head **154** and the nozzle **158** about multiple axes of movement, e.g., horizontally in perpendicularly oriented directions of movement, as signified by axes X and Y, and vertically, as signified by axis Z (as mentioned above). In addition, appropriate motors (not shown) may also be provided on the cantilevered arm **162**. These motors can provide associated rotary motion of the distribution head and nozzle e.g., about perpendicularly oriented rotational axes represented by axes B and C.

[0064] With reference to FIG. **10**, a portion of a typical substrate **166** is depicted. In a non-limiting illustration, metallic coating **168** has been applied directly over the outer surface of the substrate, and a ceramic coating **170** (e.g., a TBC as discussed above) has been applied over the metallic coating. According to the mechanism depicted in the figure, a supply of a flowable abrasive material **172** is delivered through a metering device **174**, via the tube **176**. The abrasive material can be drawn by the venturi effect into the mixing chamber **156**, for mixing with a primary pressurized stream of water **178**, in the formation of the jetted fluid stream **160**. (The abrasive materials can be of the type described above).

[0065] As described in the patent to Miller et al, the control of the movement of the jet stream **160** is critical to the effective performance of the water jet apparatus. By the controlled motion of the jet nozzle **158** (e.g., by the CNC device mentioned previously) selectively about the multiple axes B, C, X, Y, Z (FIG. **9**), it is possible to reciprocate the jet nozzle in a three-dimensional path of movement. These motion paths conform precisely to the three-dimensional configuration and shape of substantially any substrate, coated or uncoated, while maintaining the nozzle **158** at a precisely consistent spacing and angular orientation with respect to the substrate. Moreover, those skilled in the art understand that many features and parameters can be selectively set, varied and controlled, to optimize the use of the water jet cutting tool. Non-limiting examples of adjustments include: the pressure of the abrasive water jet stream as emitted from the nozzle; the mixing ratio of the abrasive with respect to the water, the shape and relative diffusion of the fluid stream; the particular type of abrasive material, and its size; and the nozzle diameter.

[0066] In most of the preferred embodiments of the invention, the water jet technique is carried out by directing the linear jet stream to a pre-selected region of the substrate, according to one or more selected patterns. The delivery nozzle is programmed to direct the jet stream in a single or repeated plunging motion, sweeping motion, or combination of plunging motions and sweeping motions. The selected pattern is one which provides the passage hole geometry described previously, which includes formation of the inlet bore and formation of the chevron outlet.

[0067] FIG. **11** is a simple illustration of the plunging motion for making the particular passage holes, according to some embodiments of the invention. The plunging motion is usually carried out by a cylindrical tool, which can be associated with various types of equipment, e.g., a water jet, a laser, an electro-discharge machining (EDM), or a mechanical bit. While the plunging technique will be described in detail here for a water jet apparatus, those skilled in the art will be able to adapt the technique to the other equipment described herein, without undue effort.

[0068] With continuing reference to FIG. **11**, a water jet machine such as that described above can be used. A series of pre-programmed plunges (“multi-plunges”) is used to form circular hole shapes **190** through the outer surface **192** of substrate **194**. (The delivery nozzle and water-jet stream are not pictured here, but would be positioned above the substrate, as described previously. Moreover, while a large number of holes can be formed in the substrate by this technique, a single hole is illustrated here) As one non-limiting illustration, the direction of successive hole shapes can proceed across surface **192**, from the pre-selected region for one trough **196** to a trough **198** (somewhat obstructed from this view) on an opposite side of the substrate. The controlled movement of the water-jet stream could also follow a generally horizontal path **200**, after formation of the troughs. This movement could be considered a controlled “sweeping” across the surface of the substrate. Thus, formation of the hole shapes could be carried out with a combination of plunging and sweeping motions. A CNC-type device like that described previously is especially suited for the plunging (e.g., the “Z” direction in FIG. **9**) and sweeping (e.g., the X and Y directions) motions used to form each passage hole.

[0069] FIG. **12** is a representation of a portion of a passage hole **210**, formed by way of the multi-plunge technique. Troughs **196** and **198**, and inlet bore **211**, are depicted in the figure. Plateau **212** is also shown, having a triangular shape in which one vertex **214** “points” in the direction of inlet bore **211**. The shaded features **216** depict differences in features, as