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Milling Before 1540

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It is a rather arbitrary thing to rank machine tools in order of importance, but many people would put the milling machine second only to the lathe.[1] Circles and straight lines are without a doubt the two most important geometrical elements in machine building, and between them the lathe and the miller cover these. Even with a profile cutter the milled surface will be made up of linear elements. For Americans in particular the milling machine is a historic favorite, for they can associate it with the work of Eli Whitney, or in the light of more recent scholarship, with Simeon North or John Hall. Milling appears to have been a key innovation in the achievement of the "American System" of mass production using machine-made, interchangeable parts.[2]

But milling has a long European prehistory. Going back through clock-gear making in particular, it has been traced as far back as Juanelo Torriano, who in 1540 used a *torno* to make a complex astronomical clock for the Holy Roman Emperor Charles V.[3] Exactly what a *torno* was cannot now be determined, but since the clock had over 1800 gears and Torriano finished its manufacture in only three and a half years, it is assumed that it incorporated a rotary file. The text which describes his achievement states that the torno was "able to carve out with a file iron wheels to the required dimension and degree of uniformity of the teeth."[4] Hence it must have been a profile cutter. But the crucial point about this report is that the rate of production achieved clearly implies that the rotary metal cutter, the chief element in the milling machine, had been invented.

The purpose of the present discussion is to argue that we can push the invention of the rotary metal cutter farther back by about a half century. It will appear that gunmaking, not clockmaking, was its point of origin, and there are good reasons for believing that the inventor was none other than Leonardo da Vinci. The whole story is too long and complex for the present format[5] but at least an outline can be given, and in particular some of the points which are likely to be of the greatest interest to students of machine tool history can be cleared up.

Among Leonardo's many drawings are several of a revolutionary firearms ignition system called the wheellock.[6] Not everyone agrees that he invented it, but that is a matter which can be touched on further below. In its day the wheellock was a technological marvel, with considerable social effects. Previous ignition systems had required keeping a lighted match, red hot iron, or smoldering coal in the vicinity of the weapon. With the wheellock, the gun now became mechanically self-contained, transportable in a fully safe condition, and fireable at an instant's notice without the necessity of going for a light or using flint and steel.

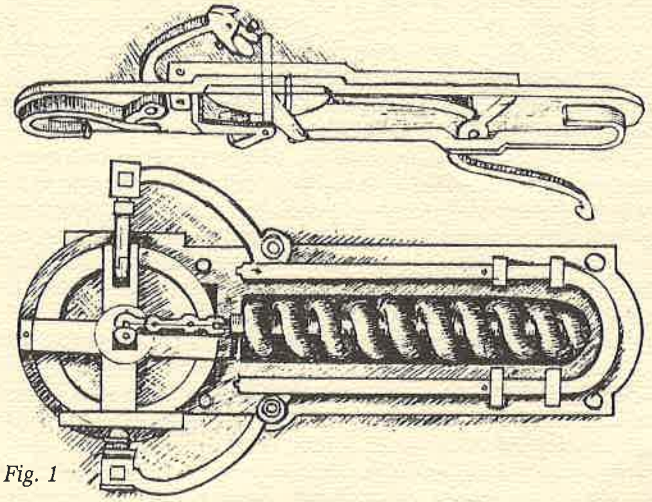

Fig. 1

Two drawings of wheellocks from Leonardo's **Codex Atlanticus.** *The spiral spring lock shows the chain connection between spring and wheel more clearly than the other, which shows the lockplate sectioned through the wheel and its axle, so that the powder pan is missing.*

The lock was operated by using a key or wrench to wind a shaft through a nearly full turn, compressing in this process a powerful mainspring connected to the shaft by a short length of flat-link chain. On the shaft was mounted the wheel which gave the lock its name. The rim of the wheel protruded through a slot cut in the bottom of the pan containing the priming powder. Once

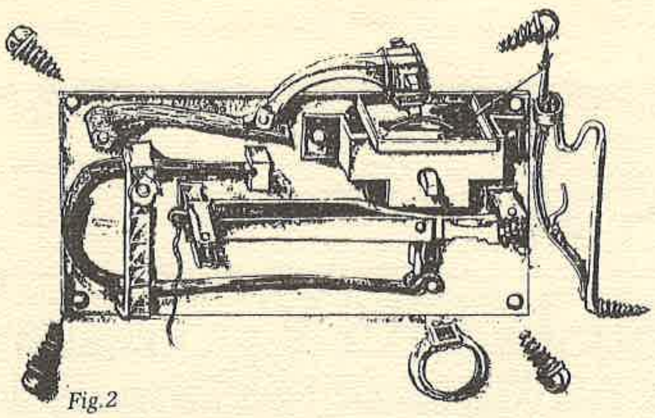

Fig.2

A version of the wheellock from the 1504 Nuremberg manuscript of Martin Loffelholz. this design was probably intended as a fire striker, to be screwed to the wall near a fireplace, and used for lighting the miniature candle shown separately at the right. The ring at the bottom forms a wrench for winding up the wheel via its squared shaft.

wound up, this wheel was held in place by a system of catches, the sear assembly, which could be released by the trigger when desired. Before firing one had to lower a pivoting arm with a miniature vise on its free end down onto the pan so that the vise was near the wheel rim. Gripped in the vise jaws would be a piece of very hard stone, such as flint, agate, or, especially, iron pyrites. As the wheel was released and began to spin, this stone would strike sparks from the wheel rim, igniting the powder in the pan, and this in turn would set off the main charge inside the barrel, firing the gun.

The lock thus mechanized the flint and steel fire starting process. It is also common to compare its action to that of a modern cigarette lighter, but that is not quite accurate. The wheels of both devices have rims whose profiles are not smooth, and this is crucial to the milling machine story, as we will see. But in the cigarette lighter, the serrated wheel is made of hardened steel, and it machines away the so-called flint, which is not flint at all. Its main constituent is Cerium, a rare earth metal which oxidizes so fast that when it is machined rapidly it gives off sparks.[7] Hence, in the cigarette lighter, the wheel acts as a tiny milling cutter.

In firing the wheellock, the reverse is true. Here too the wheel is made dead hard, but the stone is even harder—up to about 6.5 on the Mohs hardness scale.[8] In firing the lock the pyrites or other stones machine away small bits of the wheel rim at such high speeds that they are heated to incandescence, and it is these tiny hot steel cuttings that fire the powder. In a good lock of this kind the metal bits will be heated to the fusion point, and one can find microscopic steel balls in the pan after a powderless test. Thus the wheellock acts as a miniature, spring-powered, high speed metal lathe, using stone-age tooling, while operating during its firing cycle. Hence it is even thus far not a bad place to look for the origin of a new production process.

The wheellock had extensive social consequences. It made the one-hand weapon, the pistol, practical for the first time, and was soon taken up by assassins, highwaymen, and others who had need of concealable weapons. It also gave the feudal cavalry new life, for they had been losing military ground in the face of infantry musket fire. Thus one may say that it helped to prolong the social system of the Middle Ages, and to stave off for a while the rise of the middle classes. It was not a trivial invention.[9]

Frequently one reads that the rim of the wheellock wheel is "serrated," or otherwise textured, and that the function of this is to strike better sparks. This does not appear to be the case. On a lock in good condition the wheel rim will appear to be threaded, with vee grooves immediately next to each other, forming vee crests in between. The threads have no helix angle, however; they all run parallel to the plane of the wheel. Running at more or less right angles to the threads will be further grooves which we may call cross grooves. They will be approximately as deep as the threads, but may be much narrower.

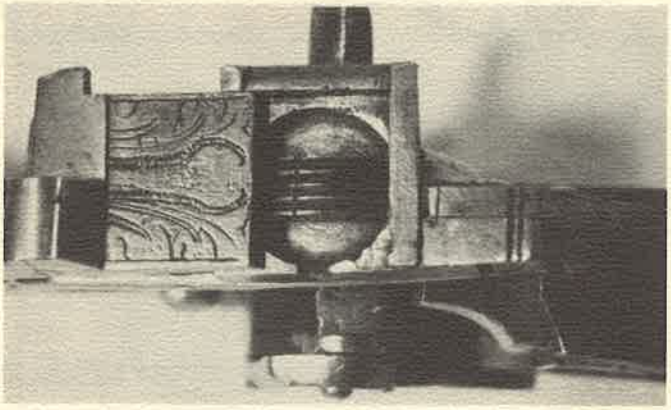

Fig.3

Pan & Wheel of an original, late 16th century wheellock.
The pan was obviously cut using an end mill, or rotary cutter fed axially - the concentric circular striations are quite visible. This setup would make the pan bottom flat, and would make it quite thin. Perhaps this reduction in the metal to be removed, in comparison to the ordinary pan milling set up, accounts for the decision of the gunsmith to use an unusually wide wheel.

Since the wheellock was a portable arm, it is not surprising to find that the slot in the bottom of the powder pan, in which the wheel turned, was fitted closely to the wheel. It had a surface which was the mirror image of the wheel rim, vee grooves and all. The top of the pan was similarly tightly closed by a lid or cover. On many locks this lid or cover was automatically opened as the wheel began to turn. This permitted the arm carrying the stone to drop against the wheel, firing the gun. Since priming powder was very fine grained, about like fine meal, the fit between wheel and pan had to be very good or the powder would dribble away in walking or riding, and the gun would not fire when needed.

This meant that the fit between wheel and pan had to approach modern standards. On locks from the sixteenth and seventeenth centuries the author has found clearances as low as 0.015 inches between the sides of

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the wheel and the wheel slot sidewalls.[10] The rim clearances can be as low as half this. And when one recalls that each side of each vee had to be fitted to the pan, it immediately becomes doubtful that the job was done by hand. In fact, to visualize the action of the wheel during the manufacture of the lock, one should think of it as a kind of screwcutting tap, with zero thread angle, cutting away at the pan as the latter is fed sideways against it. Leonardo was apparently the first to draw such taps,[11] and his sketches show very narrow, vee shaped flutes which closely match the cross grooves. The idea was probably not a new one, however, for suits of armor from the 1400s are sometimes held together with metal screws.[12] Hence the screw tap is probably the ancestor of the wheellock wheel.

To anyone with any metalworking or machining experience it will be immediately obvious that using the wheel rim as a cutter is the way to go, providing of course that its profile will do the job. The wheels are as thin as 0.070 inches, and they sometimes protrude into the pan for a quarter inch or more. When one remembers that vee grooving has to be cut at the bottom of this woodruff key shaped slot, the job begins to be a trifle tedious for handwork.

Fig.4

A close-up view of the wheel slot sidewall of an original 17th century wheellock pan. Note the circular and parallel form of the striations left by the wheel when used as a cutter, and compare the shot of the modern pan, made as described in the text. Compare also the small drawing at the corner of the **Codex Atlanticus** *folio, shown in Fig. 8.*

A close examination of the surfaces of the wheels and their slots reveals that in fact the process had been mechanized, in an overlooked but important early stage in machine tool history. Under magnification the vee grooves on the wheels reveal tool marks, parallel striations which run fairly continuously around the circumference of the wheel, which could only have been produced by turning them. In the wheel slots, the mirror images of these vees show similarly parallel and continuous striations. The sidewalls of the slots show striations taking the form of nearly parallel arcs, approximately concentric with each other and with the wheel axis, when the pan is fastened in operating position. That the arcs are not fully concentric is caused by feeding the pan toward the wheel while cutting the slot.

Hence these locks must have been constructed in a process that began by fitting the wheel arbor into its bearings in the plate of the lock, and in an attached piece called the bridle. Then a rough turned wheel blank was fitted to the arbor, and turned in place down to trueness, leaving turning marks on its rim. Then the wheel rim was cross-grooved, and the faces of these cross-grooves were able to act as tooth faces to mill out the slot in the pan. Hence, if this were true, the wheellock at one stage in its manufacture served as a miniature metal turning lathe, and at the next as a miniature milling machine, before returning to the lathe configuration described above as its firing mode.

Fig.5

Inside of wheel slot a modern replica pan showing striations made in milling process.

Upon asking mechanical engineers whether this design would in fact cut, doubtful opinions were received. Nothing would do but to try it. After mounting a wheel blank on the arbor, it was trued in less than ten minutes cutting with a jeweler's graver, supported in a collar resting against a convenient screw to absorb back thrust. The cross grooves were then hand filed, the wheel hardened and left so, and a blank powder pan applied to the wheel rim with one of the feeding arrangements described below. The wheel was turned by a hand crank, at about 60 rpm. The wheel began cutting immediately, but worked very slowly. Wheellock wheels have several kinds of cross-groove arrangements, and a wheel with the best of these cross grooves required two and a half hours of steady work to drive the wheel a mere eighth inch or so into the pan bottom. The least useful design took five hours! The results were gratifying otherwise, however. The cut surfaces had almost a mirror finish to the naked eye, and the tolerances achieved were slightly better than most of the originals. Even with such low rates of metal removal, the fits achieved were done faster than the major author, an amateur machinist, could have made them by hand. In the Renaissance, drilling or chipping may well have been used in the initial stages of the cut, so that much of the time spent in milling could have been saved.

Fig.6

A wheel in its ordinary position in the wheellock pan. The portion of the rim exposed in the pan contains a slanted cross-groove, the triangular walls of which, formed by intersections with the threads of the rim, served as the teeth which milled the slot in the pan for the wheel. To the right is the homemade rasp cutter which cut the powder cavity in the pan.

There is nothing exceptional in assuming that tools for cutting the wheel rim would have been available. Gravers are described in Theophilus,[13] who wrote before 1140, and by the time wheellocks were invented, about 1500, the age of engraving had begun.

For those who doubt the geometrical evidence of the striations pictured herein, there are two further considerations. Note first, however, the striation similarity between the original wheels shown, which are mid 16th century, and the modern replicas, made as described above. Next, consider the mechanics of metal cutting. We know that at the boundary between the workpiece and the chip, the metal is displaced in a plastic way rather than being sheared off. This plastic zone gives rise to an exit burr as the cutter leaves the workpiece for here the metal is no longer cut away, but simply bent to one side. If the cut is continued with machine-aided regularity, this small bent burr, subjected to repeated plastic displacement, can grow into a curl which can extend through more than a complete circle. Original locks often show such curled burrs, and they were recreated during the testing process. Let him who thinks he can create these by hand filing or chiseling, try it; the burrs are only 0.015-0.020 inches thick at most.

The remaining consideration is that the more cross grooves a wheel rim has, the worse it fires. The cutting faces chew up the stones steadily and can cause ignition failures. It is obvious that the early gunsmiths knew this, for they devised several ways of avoiding the problem, even making a second wheel, completely free of cross grooves, to fit inside the pan slot made by the first one.

How then does the wheel cut when its teeth have no back relief, and when the cutting gaps are so small in comparison to the wheel circumference? A close examination of the action of wheel and pan provides the answer. When no tooth is at work, the pan bottom is tangentially supported on a vee crest. When a tooth moves into position, the pan can drop down very slightly because the tooth gap interrupts the curve of the circumference, and the pan, resting on the adjacent points, can bridge straight across. Then, as the wheel turns further, the rising tooth face can dig into the metal, taking out an initial chip.

For subsequent cuts the process is repeated, but with a difference. Since the initial concave cut is certainly

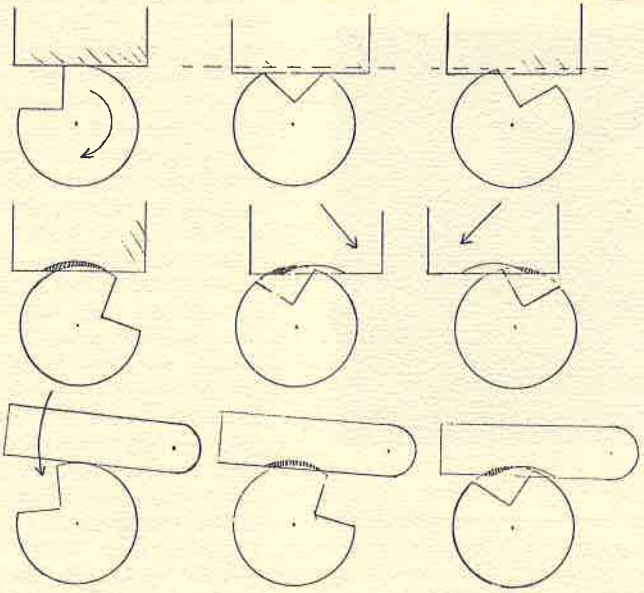

Fig. 7

How a cutter can act though it has zero back relief. Here, for clarity the wheel is given only a single tooth (or cross groove), much enlarged beyond its true scale. Other dimensions and motions are exaggerated also. The wheel rotates clockwise in all cases. The workpiece, or powder pan, is shown as a block. In the top three drawings we see how the cut is begun. At first, left hand picture, the workpiece merely rides on the rim of the wheel, being tangent to it. When the cross groove moves into position, however, the workpiece can drop down slightly (middle picture). Then, as the cutter continues to revolve, (right hand) its cutting face can reach the lowered workpiece and begin to remove metal (shaded portion).

In the middle series of illustrations we follow the progression of the cut with a pan which is fed downward and slantingly into the cutter. Since the workpiece feed was almost certainly via hand pressure, or via hanging a weight upon it, rather than being mechanical, the workpiece could respond to growing pressure as the cut proceeded, and move backward slightly from the wheel. The increased pressure comes from the growing portion of the rim of the wheel riding in the cut on the workpiece. Since pressure is force divided by area, as the area in contact increases, it becomes more difficult to push the pan toward the wheel. This effect has been observed in practice; the cut diminishes toward its end. This is shown by the taper of the curved shaded area in the middle left illustration. Because of this effect the curvature of the cut and of the wheel rim no longer coincide. Hence the wheel on its next revolution will be able to cut at either the beginning or end of its pass. This is shown in the middle and right hand center illustrations, respectively, by shaded areas. The pan feed in this setup is not straight toward the wheel axis, the discrepancy between the wheel-rim curve, and the curvature of the cut, is enhanced, and the wheel cuts more efficiently. Whether this was deliberate is hard to say, but almost all wheellocks which slide the pan toward the wheel seem to display it.

In the bottom three illustrations we consider the sort of pan pivoted at one side around a screw, and fed thus to the cutter. After the first pass and the creation of a diminishing initial cut, the continued rotation of the pan around its screw insures that a slight discrepancy between the wheel curve and the cut curvature is maintained, permitting the wheel to continue to act.

These geometries seem to explain the wheel's effectiveness, in spite of its poor design. In practice the cuts taken at each pass are so small, that any sloppiness of fit between the pan and its feeding groove, or around its pivot screw, can act as effectively as the motions shown here. With some wheel designs the cross grooves remove only an average 0.000014 inches at each revolution! With gravity feed the wheel speed has to be kept quite low, at around 60 rpm or so, to enable the workpiece to fall toward the wheel fast enough to permit the tiny cross grooves, sometimes only about .040 inch or 1 m/m wide, to make their cut.