Production Technology: Theory and Practice
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Lecture - 11
Measurement of Cutting Forces

Hello and welcome to the discussion sessions of the production technology course theory and practice. I would like to remind you that what we have discussed last time are the friction in metal cutting and then practical machining operations like drilling, turning, milling and so on. There we have seen how the power can be estimated, how the material removal rate can be estimated and how the forces are involved in each of these cases like turning, shaping, planing, drilling and milling.

Then we said that these forces are to be measured and the device in the lab used for measuring the cutting forces is the dynamometer. The dynamometer can be used for measuring forces in all the processes alright. However, since the forces are different or differently located, differently directed in the turning shaping, planing, drilling, milling, and grinding, in that case probably for each of these processes, we have to figure out what kind of dynamometer to be used or we have to design kind of a dynamometer that has to be used for a particular process.

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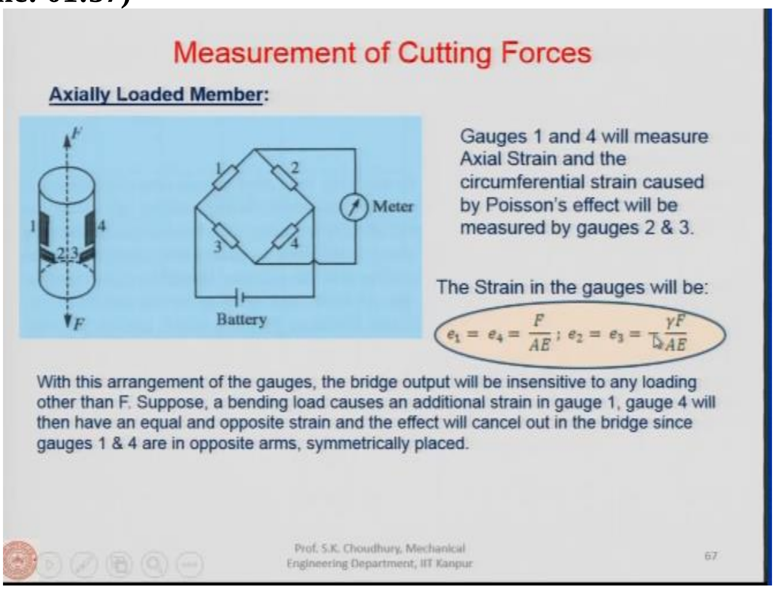

Then we started discussing if you look at this slide, we have discussed the axially loaded member and here is that axially loaded member; here is the load acting on the member. What was said is that there are strain gauges or as I said that this can be the piezoelectric elements.

These strain gauges are mounted diametrically opposite directions 1 and 4 and then perpendicular to that direction will be 2 and 3.

When the axial load will be applied then the axial strain will be measured by 1 and 4 and 2 and 3 gauges will measure the circumferential strain which is the result of the Poisson's effect. Then, it was discussed that if these strain gauges are arranged in the form of a Wheatstone bridge, in that case the strain that is given by 1 and 4 which will be the axial strain, that will be equal to the force, F divided by area, A and modulus of elasticity, E of the material of the member.

It was said that suppose there is a bending load which will try to bend in the member, in that case what will happen is that 1 and 4 since they are in the opposite arms then the strain that is occurring here the additional strain gauge 4 being located diametrically opposite to 1 this will then have an equal and opposite strain and the effect will cancel out in the bridge.

Therefore, what was said is that 1 and 4 strain gauges will exclusively sense the axial force and no other force will be sensed by 1 and 4. Similarly, since gauges 2 and 3 are located in a diametrically opposite positions from each other, the circumferential strain will be measured by 2 and 3 and no other force will influence on that 2 and 3.

Because there will be an opposite effect here, they are also located diametrically opposite from each other and it will be only the circumferential strain caused by the Poisson's ratio that will be measured by 2 and 3 strain gauges. 2 and 3 will give you the same amount of strain as for gauges 1 and 4 multiplied by the Poison's ratio which will be the poisons constant. This is with a negative sign e 2, e 3.

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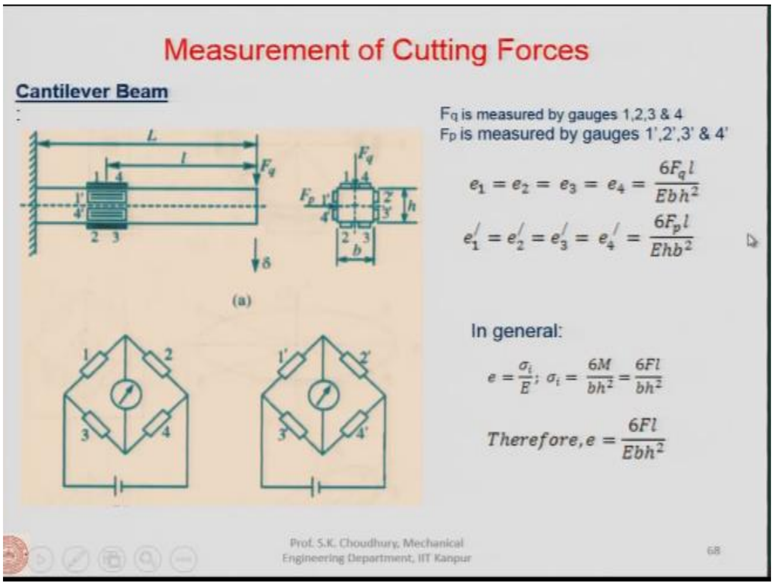

Next, let us discuss the measurement of cutting forces with the help of a cantilever beam. This is the cantilever beam shown; let us say on this cantilever beam, there are 2 opposite forces. If this is the cantilever beam which is fixed on one side then there are 2 loads, one vertically located another one is the vertical to that at a 90^0 angle to that that is located like this.

One which will try to bend in this plane, bend the cantilever in this plane and another force which will try to bend the cantilever beam along another plane and those 2 planes are mutually perpendicular planes. In that case, let us say these 2 forces that is F_p and F_q are to be measured. Here of course, that F_q is shown and F_p will be not visible because it is perpendicular to this axis in another plane, in a plane perpendicular to the plane where F_q is located.

Let us take a cross section here, it will be shown like this and F_q force is located here and another force which is perpendicular to this will be seen in this cross section as the F_p which is shown here. In this cross section what is shown is that this bar or the cantilever beam, this height is the h and the dimension at the 90^0 to that is the b. This is the b and this is the h which is the cross section of this beam.

Now to measure these forces, F_p and F_q we can have 2 sets of 4 strain gauges each, so that both F_p and F_q can be measured. If you see here, these are the 2 strain gauges which are showing 2 sets of 4 strain gauges 1, 2, 3, 4 will be glued on this surface. On this face will be $1', 2'$ on the other side, $3'$ and $4'$.

So, 1, 2, 3, 4 strain gauges will sense the force which will try to bend the cantilever beam because of the F_q. Similarly, $1', 2', 3'$ and $4'$ sensors are these gauges which will sense the force which will try to bend the cantilever beam because of the F_p. F_q will be sensed by 1, 2, 3, 4 and F_p will be sensed by $1', 2', 3'$ and $4'$.

Now if we make 2 Wheatstone bridges one consisting of 1, 2, 3 and 4 and another comprising of $1', 2', 3'$ and $4'$ then the strain that you can measure in that Wheatstone bridge comprising of 1, 2, 3, 4 is due to the F_q So, *e 1, e 2, e 3* and *e 4* in this Wheatstone bridge this with the 1, 2, 3 and 4 gauges will be equal to, general formula is sigma $e = \frac{\sigma_i}{E}$, i.e. the stress by modulus of elasticity.

Stress overall is equal to $\sigma_i = \frac{6M}{bh^2} = \frac{6Fl}{bh^2}$. Here, M is the moment. If the point of application of the force is known, so in this case F_q is located or applied at a distance of l as shown in the slide. Let us say this is the l from the sensor where the force has to be sensed.

So, if it is known, then whatever moment is here, it can be written as $\frac{6Fl}{bh^2}$. Therefore, the strain can be written as $e = \frac{6Fl}{Ebh^2}$. This formula we are using to find out the e_1, e_2, e_3 and e_4 strain shown by the Wheatstone bridge which is here. Here the F has to be replaced by *Fq* since gauges 1, 2, 3, 4 will measure F_q.

So, this force will be F_q and this distance is l from the point of application of the force up to the sensors or up to the gauges and divided by E and the bh^2. The value of the strains is as given in the slide. Similarly, on the other plane, you understand that the *bh* will be interchanged, because it is the other plane. They are the e_1', e_2', e_3' and e_4' which will sense the force F_p.

So, in place of F we will put F_p; again, the l will be the distance. These values will be $e_1' = e_2' = e_3' = e_4' = \frac{6F_p l}{Ehb^2}$ .We will be knowing the strain, and the modulus of elasticity, E is the material property of the material that we are using for the cantilever beam, b and h are the physical parameters that will be given by us and will be known to us.

Strain, e we are measuring from the Wheatstone bridge; F_q and F_p are unknown. So, from those two equations of e and e' we can find out the values of F_q and F_p .

Therefore, if the point of application of the force is known then the moment can be found out and from the moment indirectly, we are finding out what is the amount of force which is acting. This is one of the easiest ways to find out or to measure the forces. And this is the principle which is used in the dynamometer which are the devices which are used in the laboratories.

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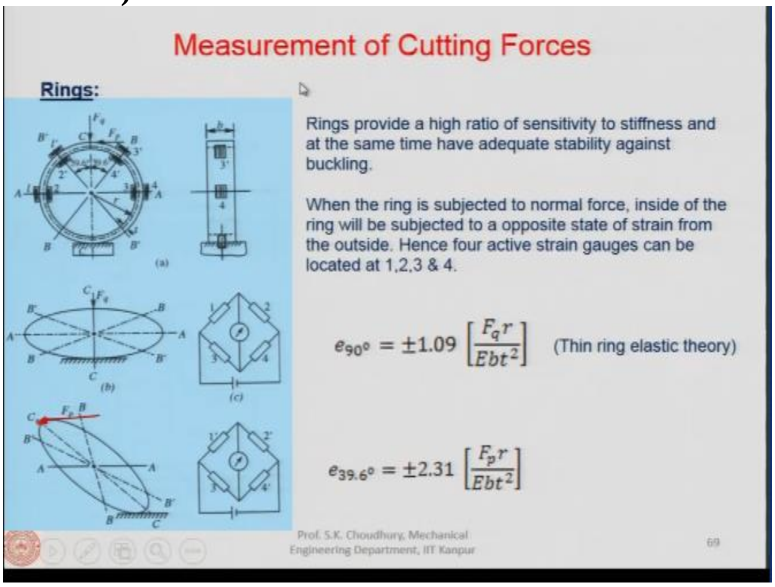

Now let us discuss the measurement of cutting forces when there is a ring type structure used. Here you can see that there is a ring type structure and this ring type structure is rigidly mounted on the base somewhere and this structure has the pitch circle diameter, this is $2r$ and it has the thickness t and the width of this is the b which has been shown in the side view

Now, it has been seen from the photo elastic studies of the thin ring elastic theory and photo elastic studies that the maximum strains will occur at the nodes located at a 90^0 angle and at an angle of 39.6^0. This is not for all the structures, this is particularly for the ring type structure and these ring type structures go through the photo elastic studies to find out what are the nodes where the maximum strain can occur.

This is for the purpose of fixing or putting the sensors particularly in those positions. So, in the ring type structure, we will have the gauges 1, 2, 3 and 4 at a 90^0 angle and at an angle of 39.6^0 because these are the nodes where the maximum strain will occur. B' and the B are the nodes where there will be maximum strain. Therefore, A-A section in the ring and $B'-B'$ section and the B - B section will have the 2 sets of 4 strain gauges that is 1 2, 3 and 4.

Here you can see in the other cross section other view, these are the all the 4 gauges. We will have the $1', 2', 3'$ and $4'$ this will be attached here at an angle of 39.6^0 in these nodes and along 90^0 we will have 1, 2, 3, 4.

We will have 2 sets of strain gauges consisting of 1, 2, 3, 4 and $1', 2', 3' 4'$ these gauges of course will sense this force which is the F perpendicular to this axis and this is the normal force. Now the F_p is the tangential force which will be sensed by the sensors $1', 2', 3'$ *and* $4'$.

When the normal force acts on the ring, the maximum deformation or the maximum strain can be obtained along this axis or along this section this A -A. Similarly, when the tangential force acts the ring will be deformed like this as shown in the slide.

As shown here in the slide, because of the tangential force F_p which is acting here at this point, the shape of the ring will be like this because it is mounted here rigidly at the base, it is fixed here. Therefore, the maximum strain has been found out to be occurring along these points, at an angle of 39.6^0 as I said that this is revealed by the photo elastic experiments.

Overall, the ring structures provide a high ratio of sensitivity to stiffness and at the same time have adequate stability against buckling means that it will not break under the thrust force. It is very sensitive in the sense that a small force will also be sensed and when very large magnitude of force is measured, it will not lose its stiffness.

When the ring is subjected to normal force let us say this is the F_q ,inside of the ring will be subjected to opposite state of strain from the outside then whatever strain will be coming on the outside inside will be opposite strain. Hence 4 active strain gauges can be located at 1, 2, 3, 4 so that F_q can be sensed and at 90^0 the strain that can be measured from the formula as given in the slide. This formula is taken from the thin ring elastic theory. This is the thin ring structure.

Therefore, the thin ring elastic theory says that the strain produced at 90^0 node can be calculated by this formula. The coefficient is 1.09 and the force is F_q. F in this case will be F q, this is the normal force or the thrust force and E is the modulus of elasticity of the ring material; *b* is this width and *t* is the thickness of the ring and *r* is the pitch circle radius.

This is how the thin ring elastic theory suggests for 39.6^0 nodes. In this formula the coefficient is different although the formula is the same, but the coefficient is 2.31 and using this formula, the strain will be measured. From here using this formula, we can find out the force.

Here in this case we are measuring strain as output and from that strain we are finding out what will be the value of the forces, either the normal force or the axial force, whichever is acting.

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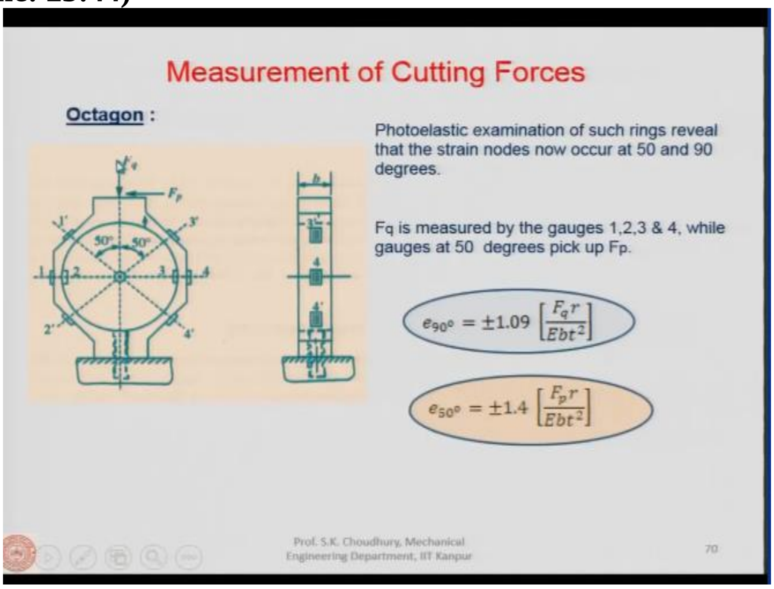

In this slide we have the measurement of cutting forces using an octagon type ring. If we come back and see the ring type structure, it has a tendency of rolling, you can see this from the diagram. When the F_p is acting, it has a tendency to roll along the horizontal direction.

Although we said that it does not have any problem with the buckling and it has a high ratio of sensitivity to stiffness.

But still, it has a tendency to roll and that is why rather you can say that they are not very reliable in case of forces when they are high in magnitude, because high magnitude force will try to roll it and then it will give you the error in the measurement, the measurement of the strain. To strengthen the structure, we have the octagon type you can see in the slide, this is the modification of ring type structure.

In this structure, the strength has become more by giving it an octagon shape of the ring. Now the photo elastic examination of such rings, reveal that here the strain nodes are 1, 2, 3, 4 at an angle of 90^0 and $1', 2', 3'$ *and* $4'$ are at an angle of 50^0 degree. We can see from the diagram that here it is $1', 2', 3'$ *and* $4'$ they are at an angle of 39.6^0.

Here we are putting the gauges on the opposite sides to compensate for the other forces rather than the force that we are measuring. We have already talked about this earlier. Here it will be at 90^0 and at an angle of 50^0. So, in this case, as you can see, the sensors are attached as $1', 2', 3'$ *and* $4'$ at an angle of 50^0.

F_q which is the thrust force or normal force will be sensed by sensors 1, 2, 3 and 4which are attached at an angle of 90^0. And the axial force or the tangential force F_p will be sensed by the sensors $1', 2', 3'$ *and* $4'$ ..

If you take two Wheatstone bridges similar to this that is one which comprises of 1, 2, 3 and 4 and another which has $1', 2', 3'$ *and* $4'$ then that Wheatstone bridge which is of 1, 2, 3, 4 gauges will measure the force which will be F_q thrust force. And this formula from the thin ring elastic theory has been used. You can see that the coefficient of 1.09 is the same because this is the angle at 90^0 degrees.

For nodes at 50^0 that is, $1', 2', 3'$ *and* $4'$ the strain that will be measured by the Wheatstone bridge comprising of $1', 2', 3'$ *and* $4'$ will have the formula as shown in the slide and from this formula, you can find out the value of the F_p.

Because $1', 2', 3'$ *and* $4'$ will sense the force F_p which is the axial force or the tangential force. you can see that only thing that has been changed is that we have strengthened the structure and because of that the photo elastic experiments have shown that the nodes have changed instead of 39.6 in the case of the ring structure here it is at 50^0 angle.

So, we are placing the sensors at 50^0 angle. With this formula, we can find out the appropriate value of the F_p or F_q by measuring the strain which is coming from the Wheatstone bridge comprising of 1, 2, 3, 4 or comprising of $1', 2', 3'$ *and* $4'$. Here we can see that this octagon is also not very rigid when large forces are acting. We will discuss later how to increase the rigidity of this structure.

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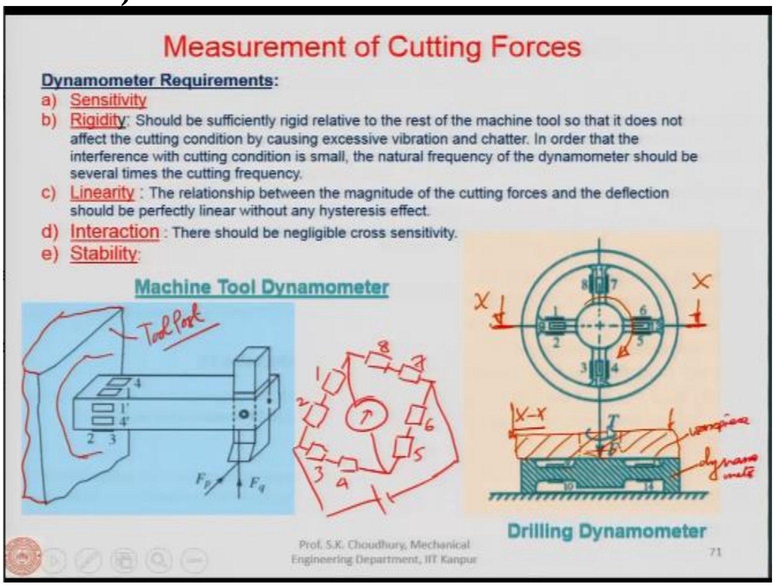

Now for the measurement of cutting forces, the dynamometers that are used have certain requirements. And whatever is the dynamometer it is either a ring type dynamometer or it is a cantilever beam dynamometer or it is an octagonal dynamometer all these requirements remained valid for all of them. First is the sensitivity

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Sensitivity means that they should be highly sensitive, that is, even a small force which is acting on the dynamometer, it should be able to sense and it should be able to sense properly, correctly; it should not have the error in the reading. Second is their rigidity, rigidity should be sufficiently high. Dynamometers should be sufficiently rigid relative to the rest of the machine tool so that it does not affect the cutting condition by causing excessive vibration and chatter.

Dynamometer is attached to the tool post, let say we are talking about turning. In case of turning the dynamometer will be placed on the tool post and the tool will be attached to the dynamometer. The tool will be hanging. In that case the dynamometer should be of the cantilever beam type.

In case of drilling, the thrust force is applied by the drill to the workpiece. So, the dynamometer has to be attached to the workpiece. Therefore, the dynamometer is fixed on the table on which the workpiece is mounted and then on top of the dynamometer the workpiece will be fixed.

So that the forces which are applied to the workpiece can be transmitted to the dynamometer and the dynamometer could sense the forces. It is told here that the rigidity of the dynamometer should be sufficient; and when it is attached to the tool post, it should not cause excessive vibration or self-excited vibration which is chatter.

In order that the interference with cutting condition is small, the natural frequency of the dynamometer should be several times the cutting frequency. What it means is that when you are fixing the dynamometer on the tool post, in that case it is an additional mass attached and that additional mass should not have a natural frequency which is equal to the natural frequency of some parts of the machine tool.

In that case if it is so, then there will be resonance. And therefore, the natural frequency of the dynamometer is selected much away from any of the natural frequencies of the components of the machine tool. By machine component we mean the headstock or the tailstock or the bed in case of turning. Similarly, in case of milling these are column or arbor, spindle and so on.

Third requirement is the linearity which is the relationship between the magnitude of the cutting forces and the deflection that should be perfectly linear without any hysteresis effect. That means the curve of the cutting force and the deflection should be exactly linear.

That means as the cutting forces increase, the deflection also increases linearly. It should not have any hysteresis in the sense that if is removed, it should come back along the same line. It should be exactly linear that is what the linearity means.

Next is the interaction. There should be negligible cross sensitivity. We have already said about the cross sensitivity in case when the cylindrical job is used as an axially loaded member; the cross sensitivity is that 1 and 4 should not have any other values or any other influence of any other force, bending force or the 2 and 3 should not have the influence on the 1 and 4.

Here for example, when you are measuring F_q ,1, 4 2 and 3 only will sense the F_q. $1', 2', 3' \textit{ and } 4'$ will not sense anything and vice versa, that is, when you are measuring the F_p, the1, 2, 3 and 4 will not show anything. This is the cross sensitivity that when you are measuring one force that will be sensed only by a particular set of transducers or the gauges and other gauges will not be affected.

Next is the stability. It should be sufficiently stable so that it does not disturb the machining process because instability in the process will give rise to the vibration, to the chatter or self-excited vibration. So, we are saying that the dynamometers should be very stable. Now we will discuss the machine tool dynamometer.

If you see here, the machine tool dynamometer designs are shown here. This is the dynamometer that is used in a turning process. This is a cantilever beam type dynamometer. Here this is the tool post and on this we have the dynamometer along with the tool.

Inside this dynamometer we will have the strain gauges or the piezo crystals in the modern dynamometers like the dynamometers made by the Chrysler in Switzerland Best dynamometers available so far in the world are the Chrysler make dynamometers and those dynamometers use piezoelectric elements, they do not use the strain gauges.

Because strain gauges have their disadvantages that I already told you that they can be torn somewhere or they do not work in the high temperature environment. Therefore, the piezoelectric elements are used in the dynamometers. Now; when it is subjected to forces like F_q and F_p which we have shown in the cantilever beam type of the dynamometer, then the sensors or the piezoelectric elements which are mounted on this surface of the tool post would be able to sense them.

On this surface of the of the cantilever beam 1, 2, 3 and 4 sensors will sense the force F_q and the F_p which is perpendicular to this will be sensed by $1', 2', 3'$ *and* $4'$ $2'$ and $3'$ are at this face opposite to this.

Otherwise, if it is piezoelectric elements, so, with the help of the preamplifier and the amplifier you can find out what is the strain which is occurring here. So, either using strain gauges or with the help of piezoelectric elements, you can find out the magnitude of the F_q and the F_p indirectly from the moment and from the strain that you are measuring either from the Wheatstone bridge in case of the strain gauges or in terms of the curves which the output of the dynamometer will give.

Here is the kind of the ring type structure that we have seen and this is the view of the dynamometer or inside view of the dynamometer which is used for measuring the forces in drilling. Now, the cutting force and the thrust force are the forces which are typical for the turning.

These forces are different than the drilling forces as we have already discussed that the thrust and the torque both are applied to the drill. Therefore, if you have a dynamometer like that, it is very obvious that this cannot be used for the drilling, for measuring the forces in drilling. But if we have a dynamometer like this here, if you can see this is the dynamometer and this other view is the ring type, this will be able to measure the forces in drilling.

This has a ring and this ring will have the spikes so these are the kind of arms or the spikes and inside this is the solid body. This is solid body these are the spikes which are solid arms. Now on these 4 arms we will have 16 strain gauges let say 1, 2, 3, 4,5, 6, 7, 8, and similarly, we will have on the other side 9,10 ,11, 12, 13, 14, 15, 16, as shown in the slide.

There are 16 elements of gauges or piezoelectric elements which will sense 2 types of forces one is the torque and another is the thrust force which helps the penetration of the drill to the workpiece. If you see the thrust force which is applied like this it will be sensed by the sensors which are located after 8 that is 9, 10, 11, 12, 13, 14, 15, and 16 because, when the thrust force will be acting it will be vertical to this. You cannot see it here because it will be vertical.

And then in this plane where we have the 9 to 16 these are the elements which will be affected. In the cross section you can see 9, 10 and here you can see that these are the 13, 14 11, 12 and 15, 16 are here. So, if you take the cross section here along this you will find that here you can see the 9 and 10, 9 here and on the opposite side it is 10.

Here, let us say this is X-X and here we can see the 9 and the opposite side is 10 and here suppose we have 13 and opposite side we have the 14. So, that is about the gauges 9 to 16 when the thrust is acting. When the torque is acting as you understand that suppose if there is a torque acting here, then these arms will be affected by the bending, these arms will be bending and 1, 2, 3, 4, 5, 6, and 7, 8 these are the sensors which will then sense this torque which is applied.

This is the T which will be sensed by the sensors1 to 8. Let us say you have to drill a hole here this is the workpiece which is clamped and it will be drilled. When the drill has penetrated or the drill is penetrating, the force which is acting on this will be imparted on this. These are rigidly fixed; this is the workpiece and this is the dynamometer.

The forces which are acting, let say this T, this will be acting through the workpiece on the dynamometer and then this force will help to deform the arms in this direction. The arms will be deformed in the horizontal direction and similarly when the torque is applied it will be deformed in the vertical direction.

Therefore, 2 opposite direction sensors will sense, like 1, 2, 3, 4, 5, 6, 7, 8 will sense the torque and 9, 10, 11, 12, up to 16, these other sensors will sense the thrust. Again, we have two Wheatstone bridges - one comprising of 1 to 8 and in that case, you understand that we will have on each arm we will have gauges like this because earlier we had one gauge on each arm and here there are 8 of them.

So, gauges 1 to 8 will measure the torque and the Wheatstone bridge comprising of 9 to 16 will sense the thrust.

Now when the dynamometer will have the piezoelectric elements, these elements will be connected to the preamplifier initially output of the electric elements and after the preamplifier it will be amplified and that signal is passed into the personal computer, laptop or PC and in the PC, you can see the curve which will show you on each axis F x, F y, F z.

How the forces are varying with cutting time can be observed from the curves and that is a easy way to monitor how the force behaves as the cutting process goes on. You can also find out the magnitude of forces.

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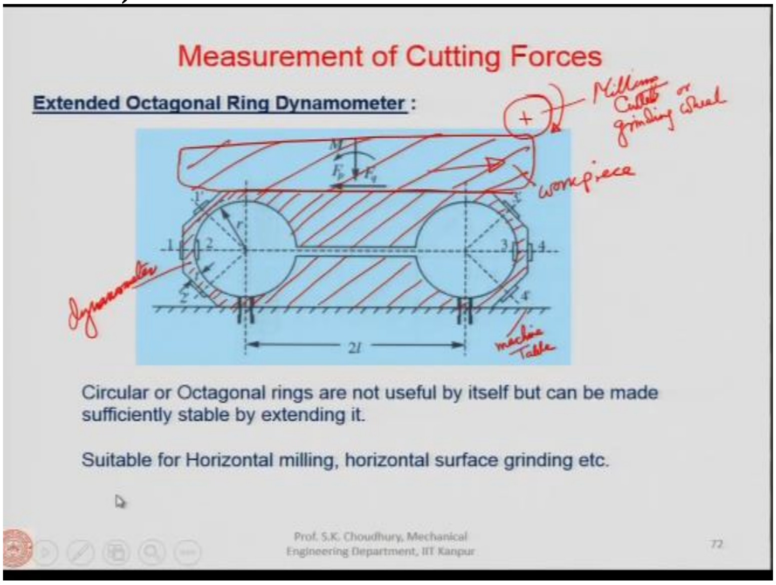

Sown in the slide here is the structure which we are familiar with. We have seen one of the smaller versions of that is the octagonal dynamometers and we said that it is a modification of the ring type dynamometer. Here the, octagonal dynamometer has been further modified you can see this. Now here the rigidity of the octagonal dynamometer has been further increased.

The structure is like this that we have the octagon but this is an extended octagon. Therefore, it is called the extended octagonal ring dynamometer because principle is of the ring dynamometer but this is not simply octagon but this an extended octagon. Therefore, all the principles of the octagon structure that we have discussed is remaining the same means that at a 90^0 angle you will have the 1, 2, 3, 4 sensors and those sensors will sense the thrust force.

Let's say that in this case it is the F_p or F_q and F_p is the tangential force, this will be sensed by the sensors which are located at a 50^0 angle and $1', 2', 3'$ *and* $4'$ sensors will sense the tangential force.

So, F_p is sensed by $1', 2', 3'$ *and* $4'$ and F_q which is the thrust, is sensed by 1, 2, 3 and 4. Here as you can see that the entire structure of the dynamometer is fixed on some base. This is fixed on the table this is the machine table and on this the workpiece will be fixed like in case of the drilling. Let us say that this is a flat workpiece and the milling cutter starts working because this is normally used for milling or for grinding.

So, this is the dynamometer, dynamometer is rigidly fixed the on the table and the workpiece is mounted on the dynamometer. This is the milling cutter. This can also be grinding, I mean that this set up can also be used for measuring the grinding forces.

Because principle remains the same. In case it is used for measuring the grinding forces, in that case the dynamometer is rigidly fixed on the grinding machine table and the workpiece is mounted on the on the dynamometer. Circular or octagonal rings are not useful by itself but can be made sufficiently stable by extending it. I will once again remind you that here we have this circular ring type structure.

We said that although these structures are rigid enough and they can withstand a lot of force against buckling, but in these cases when the ring type structures are used, they have a tendency to roll at the horizontal surface. So, you can see that if the tangential forces applied in that case, it will have a tendency to roll.

Let us say when you are using this kind of octagonal structure in the dynamometer for grinding, the cutting forces may be very high. In case of milling also the forces may be very high and the octagon structure itself may not be able to withstand the magnitude of forces which are applied during the milling process or during the grinding process. In that case it is extended.

By the way here this is these are metallic parts which are connected here. A sectional view is shown here. As you can see that by making this slot and connecting these holes, we are giving more flexibility to the dynamometer.

So it is more flexible as well as very rigid. Now this hole and this slot will provide the flexibility so that a small amount of force acting, either it is a thrust or it is an axial force, tangential force, can be easily sensed by the dynamometer.

So, here if you see the ring type dynamometer which is not very useful for the milling or the drilling milling or the grinding or the octagonal ring type dynamometer these principles are used here, but in in a better way so that the rigidity becomes more and the sensitivity of this dynamometer becomes more. They are more sensitive because of the structure itself.

Out of all this here, you can see that the extended octagon structure is more suitable for horizontal milling, horizontal surface grinding etcetera. here you can see one thing that I already mentioned earlier that these dynamometers that is drilling, turning and then milling or grinding these are dynamometers only for a specific purpose meaning that this milling dynamometer cannot be used as drilling dynamometers or cannot be used to measure forces in a turning or drilling processes and vice versa.

But these days there are universal dynamometers which are also made by the Chrysler where you can measure the forces in turning, drilling and milling together using one dynamometer. Those are more expensive devices. Rest of the topics in this discussion series I will discuss with you in the next session. Thank you for your attention.