RESEARCH ARTICLE OPEN ACCESS

Complexity of pilgering in nuclear applications

Krishna Aditya Y V
Department of mechanical engineering, SRM University, Chennai-603203

Abstract
Nuclear reactors use various types and sections of tubes manufactured with exotic materials meeting special requirements. These Tubes are manufactured using a Cold working process of Pilgering. Pilgering process is influenced by a lot of factors making it a highly complex process. In this paper the various influencing factors are compiled, segregated and briefly discussed.
Keywords – pilgering, cold working, nuclear applications, Vertical Mass Ring die mill, Cold Rolling Tube Mill

Introduction

Cold rolling on the pilger mills is considered as one of the most effective manufacturing process in the case of tube production for nuclear applications. In nuclear industry this technology is applied to the ferrous as well as non-ferrous materials even when they are hardly deformable. High Reductions in dimensions up to 70% can be achieved in a single operation what significantly reduces the number of required manufacturing operations and eventually lead to reduction in manufacturing costs. At the same time a high quality of the outer and inner surfaces of tubes and very high physical and mechanical material properties which suited for nuclear applications are obtained.

Pilgering is a cold operation consists of a set of dies that rock back and forth over the outside of the tube. A mandrel inside the tube maintains the desired size. So, pilgering process is highly complex process. The factors influencing the pilgering process are tabulated and briefly discussed in this paper.

1.2Process route for manufacture of pilgered tubes

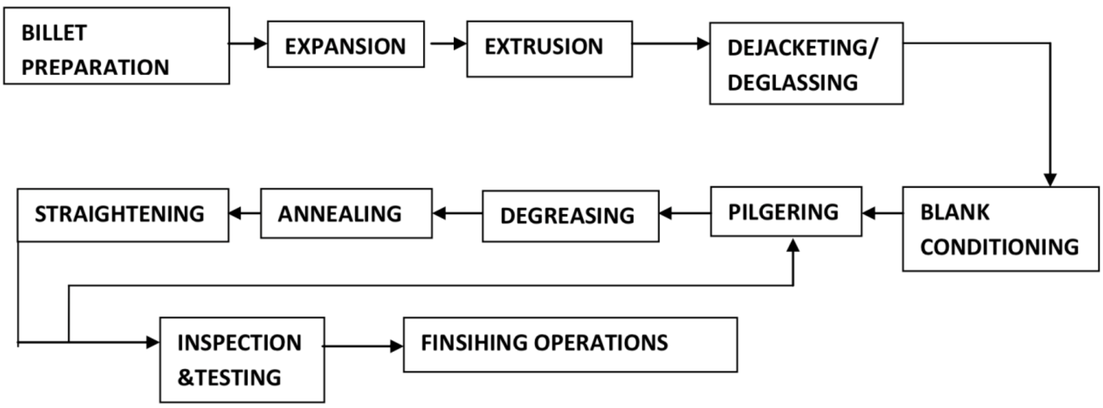

Fig.1. Process route for manufacture of pilgered tubes

1.3 chart representing factors influencing pilgering

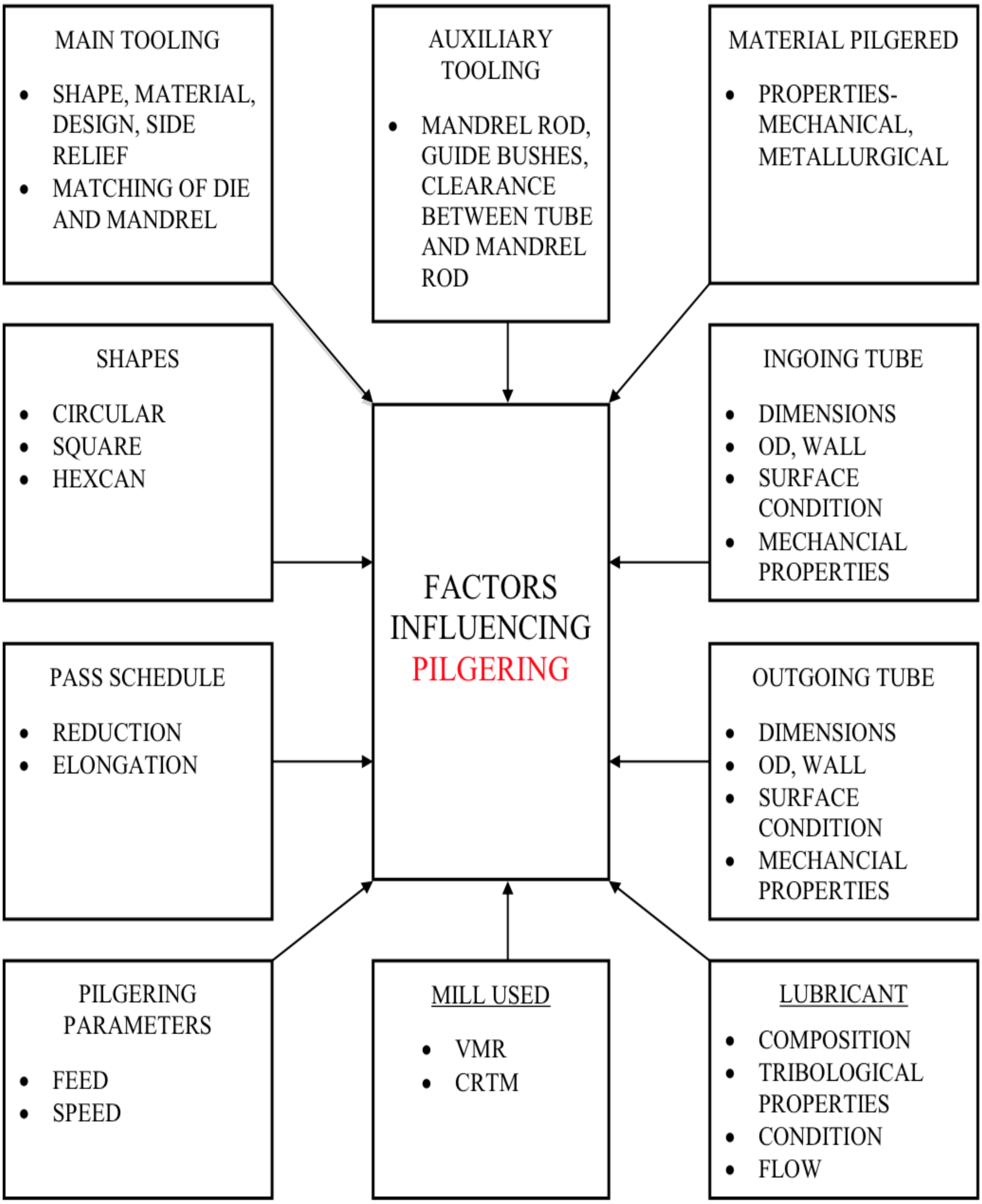

Fig. 2. Chart Representing factors that influence pilgering process.

II. Material pilgered

The use of natural Uranium dioxide (U02)as fuel in Pressurized Heavy Water Reactors (PHWRs) and slightly enriched fuel in boiling water reactors **(**BWRs) and Pressurized water reactors (PWRs) demands that the core structural materials such as cladding tubes (also called fuel tubes), pressure tubes (coolant tubes), calandria tubes, guide tubes and garter springs must have low neutron absorption cross-section and should satisfy the physical, mechanical, metallurgical and chemical requirements in radiation environment[1] .

Pu239 is used as fuel for the fast breeder reactors, which use liquid sodium as coolant. The intense fast neutron (energy > 1 MeV) flux coupled with liquid sodium environment and the temperature range of 675 to 975 K makes stringent demands on the in-core structural materials, i.e., clad and wrapper materials. These materials need to have resistance to irradiation-induced swelling and irradiation embrittlement, sodium corrosion and a good creep resistance for Prototype Fast Breeder Reactor (PFBR).

Zircaloy-2, Zircaloy-4, Zr-2.5 Nb alloy and Incoloy 800 are used as cladding materials and pressure boundary material for PWR, BWR and PHWR. While 20% cold worked 14Cr-15Ni-Ti stabilized austenitic stainless steel called D9 is used as cladding and wrapper tube material for PFBR reactors[2][3].

III. Mills used

Based on the type of reduction pattern, production rate and shapes to be produced several types of pilger mills are available. They are VMR, and CRTM types.

VMR type and CRTM mills are used to reduce the tube size. Both processes use a reciprocating, or back-and-forth, motion. Tooling is a key difference between these mills. The grooves of VMR pilger mill tooling have a varying cross-section. With each cycle, the die does a partial rotation (270 degrees) as the tube advances; the die then rotates the other direction, to its starting position. CRTM has grooves with a single, constant cross section, allowing it to make complete rotations in both directions.

3.1 Vertical Mass Ring Die (VMR) type mills

In VMR type pilgermills, circular tubes only can be produced, as the tube rotation angle is an odd figure and fixed. Two specially grooved full ring dies with varying cross section along the periphery are used for reducing outside diameter, while the matching mandrel in the ID controls the reduction of inside diameter and wall thickness.

The rotation (NOT FULL) and guided reciprocation of the dies along the working length with reducing groove size results in progressive reduction of tube

On 150 VMR pilgermill, tubes having outer diameter of 60-146mm can be produced whereas 19-57mm can be produced on 75 VMR pilger mill.

3.2 Cold rolling Tube Mills(CRTM)

In this type of mill three / four rollers with single fixed cross section along the circumference is provided allowing it to make complete rotations in both directions. In this mill also, reciprocating, or back-and-forth, motion of rollers effect the reduction of ingoing sections. CRTM mill's rolling process is based on three components: working carriage, roller, and mandrel (just one of the three / four rolls is shown in the figure below for clarity). The simple tooling that positions the roller and cam determines the OD, while the cylindrical mandrel determines the ID. This allows for precise calculation of wall thickness, even for small tubes.

The mill cold-works the tube using a reciprocating motion, following a cycle of four basic steps in step 1, the housing moves forward. This causes the profiled cams / support plate to push the rollers onto the tube, compressing it. In step 2, the housing moves back to the start position, with the rollers following the cam until they are once again removed from the tube. In step 3, the tube and mandrel rotate. In step 4, the entire tube is advanced forward slightly. The mandrel is tethered to the rear of the machine and does not advance with the tube.

Unlike in VMR mills, provision for adjusting the tube rotation angle is provided in this mill. Odd angles are used for pilgering circular tubes, 90º angle for pilgering square sections from circular tubes and 60degree angle for pilgering of hexagonal tubes [4].

IV. Pilgering parameters

Incoming tubes are turned and fed into a pilger mill by use of a single gearbox using a rotating dual track drive system. The dual track system holds the incoming tube while tube reducing (metal tube forming) occurs by the pilger tooling. When the pilger tooling is free of the incoming tube product, the dual track drive moves the tube into the pilger tooling by feeding an incremental amount of tube product. The dual track drive also indexes the incoming tube at the correct time and at a pre-determined amount. Additionally, the gearbox sub-assembly bumps the tube at a pre-determined time while the tube is free from the tooling.Currently servo based feeding and turning mechanisms are also available [5].

Two primary characteristics determine the rate of production of the pilger machine, the stroke and feed rate. Do not confuse the rate of production with the productivity of the machine. Productivity takes into account the amount of good product produced. The machine may operate at very high rates of production, but have very low productivity if the output quality is sub-standard. The quality of the finished product usually limits the rate of production.

The following equation characterizes the productivity of the pilger machine (feet/hour):

P = (SPM (FR)(E)(N)(T)(60))/12

Where

- SPM is the stroke rate per minute
- FR is the feed rate in inches per stroke
- E is the elongation
- N is the number of tubes per roll
- T is the utilization.

If the process runs at too high of a feed rate or stroke rate, the problems such as self feeding, mandrel failure, lube breakdown, marred tools, loss of dimensions, bowing, twist can occur [6].

V. Pass schedule

The thermo-mechanical property of zirconium alloy tube is well known to be influenced by pilgering pass schedule and its tooling; thus the control of its microstructure and mechanical property in the final tube production stage for nuclear fuel applications is a major concern of tube manufacture.
The main factors to be considered when developing a Reduction Schedule are both Percent Area Reduction and Q factor at each pass. The Q factor is a ratio of the OD reduction to the wall thickness reduction and the ratio of the starting tube cross-sectional area to the final tube cross-sectional area is called the Elongation factor of the tube [7]. Q factor should be greater than 1. Presence of Micro cracks on inside diameter of the tube is one of the symptoms of Q<<1[6].
The advantages of 2 stage pilgering over 3 stage pilgering are superior quality, reduction in cycle time as well as manufacturing cost, increased overall recovery of the process, more uniform and superior microstructure, improved mechanical properties, better surface finish and superior texture in the final tubes [8].

VI. Shapes

Different types of sections required for nuclear reactors are:
1. Boling Water Reactor (BWR) : Circular, Square.
2. Pressurized Heavy water Reactor (PHWR): Circular.
3. Fast Breeder Reactor (FBR) : Circular and Hexagonal.

6.1 Circular channels

Circular shapes are pilgered from both VMR and CRTM type pilger mills. In VMR type mills outer diameter and wall thickness are simultaneously reduced over working length using specifically grooved ring dies with a matching tapered mandrel while in CRTM mills a two roller stand with dies having constant groove section and a mandrel having uniform cross section are used.

6.2 Square channels

Outside diameter, inside diameter and wall thickness are simultaneously plastically deformed to square shape over the working length under two pairs of dies with partial – square grooves cut on them. An uniform square mandrel, with a square contour dies, is placed centrally among the square profile rollers, which in turn determines the wall thickness and across flat dimension of the pilgered square channel along the working length[9]. In CTRM machines, a four-roller stand and a uniform square mandrel are used. The four rollers are assembled to form a square geometry around the square mandrel.
First pass pilgering to intermediate circular tube→ second pass pilgering to final square channel[9]

6.3 Hexagonal channels

The equipment for the Pilgering of hexagonal tubes Mainly consists of a roll stand with three rollers, each having a rolling groove with an included angle of 120°. The three rollers are assembled to form a hexagonal geometry around a hexagonal mandrel.
When the saddle is in the entry position, the rollers are separated and the tube is pushed into the rolling chamber by a predetermined amount called feed and is rotated by a pre-decided turn angle. When the saddle moves forward, the tube is held stationary and is de-formed to a shape hexagon by means of the rollers that converge on to a hexagonal mandrel. After the saddle returns to the entry position the above process is repeated[10].
First pass pilgering to intermediate circular tube→second pass pilgering to final Hexagon channel[10]

VII. Main tooling

7.1 In VRM Mills

The grooves on the dies are precisely cut according to design and the groove shape determines the reduction pattern on the out- side diameter from ingoing shell to the finished tube. A tapered mandrel, with a matching contour with the dies, is placed centrally between the grooves, which in turn determine the wall thickness of the reduced tube along the working length[8].
The extent of the requisite side relief depends on elongation and feed. It increases in proportion to the feed. For this reason, each pair of roll dies has to be 'side-relieved' to suit the maximum feed selected for particular reduction.The amount of side relief is also a function of the outside diameter reduction pattern also. In the case of die groove designs with tapered mandrel, the side relief increases progressively towards the end of the groove. With high degree of elongation and the large feeds, it does, in fact, becomes larger than the finished tube wall. The die groove design, therefore, must also take into account the elongation of the tube, if the requisite side relief is to be kept to a minimum[11].

7.2 In CRTM Mills

As tooling is the key difference between these two types of mills. The CRTM has grooves with a single, constant cross section, allowing it to make complete rotations in both directions. The simple tooling that positions the roller and cam determines the OD, while the cylindrical mandrel determines the ID. This allows for precise calculation of wall thickness, even for small tubes.

VIII. Auxiliary tooling

Auxiliary tooling mainly consists of mandrel rod and guide bushes. The mandrel clearance denotes a gap between the insert material and the pilger mandrel at the point at which the tube comes into contact with the pilger mandrel. The mandrel clearance varies along its length so that the tube can smoothly come into contact with the pilger mandrel after it comes into contact with the pilger dies. In addition, towards the sizing section, the mandrel clearance increases[12].

Guiding systems are designed to ensure close tolerances between guide buses and tube OD. Nylon and Teflon materials are generally used as guide bushes because they provide advantages such as self-lubrication, durability and toughness.

IX. Ingoing and Outgoing tube conditions

Pilgering is a longitudinal cold rolling process that simultaneously reduces the outer diameter and wall thickness of the metal tube to maximum reduction possible. The majority of the forces acting are compressive forces, for reducing outer diameter and wall thickness.

A metal particle undergoes a very complex stress & strain history in a pilger mill. It undergoes a series of about 100 strokes during its motion from entry to exit . Each stroke imposes a small amount of strain . The particle experiences all those states of stress as it rotates after each stroke.

Pilgering provides highly accurate dimensional control, required [2] surface finish, high reductions assure fine grain control and improved mechanical strength[13].

While cold working Yield Strength, Ultimate Tensile Strength and hardness increases due to work hardening while percentage elongation decreases due to work hardening, which implies that ductility of material is reduced. The formability of material substantially reduces with the increase in cold work, there-by sizing / shaping of the material will not be possible. Thus intermediate annealing is carried out to regain its ductility & for further cold working[14].

9.1Possible conditions of tubes that need to be corrected in pilger mills

9.1.1 Bowing & Twist

It is condition of the tube that after being pilgered, annealed to relieve stresses causing a bend in the linear shape of the tube. The pilgered tubes after stress relieving / annealing exhibit ovality& bow in case of circular tubes whereas skew & bow in case of hexagonal sections. Circular tubes common in industry, a 3 x 3 roller-straightening machine can be used for correcting the deviation.

Since hexagonal sections being a specialized product, process improvements during pilgering itself are made to reduce the corrections required later. Increasing the length of hexagonal mandrel reduces the twist of pilgered channel appreciably. A tailor made special purpose bow correction unit is being used to correct these sections.

9.1.2 Bulging

Due to force of the pusher, the feed tube experiences shear forces across it causing bulged condition at the mouth of the tube.

9.1.3 Wall thickness variation

This condition of the tube arises majorly from the mother blank itself at extrusion

X. Lubricant

In order to withstand the severe operating conditions during cold pilgering of tubes, lubricant formulations containing extreme pressure (EP) additives are used to prevent seizure, reduce friction and wear and minimize severe surface damage to the tube surface[15].

Where large reductions in tubing diameter are being achieved, excellent lubrication is particularly essential as any failure, especially of the internal lubricant, could cause serious harm. For example, it is feasible that the pressure generated could cause the tubing to stick the mandrel, which would, of course, be a very expensive and time-consuming failure[16].

So, factors such as compatibility of the specific lubricant with the pilgering material, its condition and flow characteristics should be analyzed before proceeding.

Castrol TDN 81 is generally used lubricant for pilgering purposes.

XI. Conclusions and future scope of study

1. Pilgering is complex process covering mechanical, metallurgical, Tribological and surface engineering.
2. This paper briefly discusses about major influencing factors of pilgering process.
3. Since pilgering is a complex process, there is a lot of scope for study and carrying out analysis. Some of those are:
   - Characteristics of different materials.
   - Study on work hardening.
   - Kinematic study of pilgermills.
   - Force calculations.
   - Tribological studies.
   - Spring back aspects.
   - Metallurgical and micro structural studies.

REFERENCES

[1] Dietz W 1994 Structural materials, *Materials Science and Technology. A comprehensive treatment*, Cahn R W, Haasen P and Kramer E J (eds), 10B Nuclear Materials, Chapter 8, 53.

[2] A K Suri,Material development for India's nuclear power programme, *Indian Academy of Sciences, Sadhana Vol. 38, Part 5, October 2013, pp. 859–895.*

[3] S.L. Mannan, S.C. Chetal, Baldev Raj, S.B. Bhoje, Selection of materials for prototype fast breederreactor ,*Transactions of the Indian Institute of Metals*, 56 (2) (2003), pp. 155–178.

[4] Chiranjib K. Mukherjee (CJ), John P. Reinhart, The metallurgical benefits of cold rolling high performance alloys instead of cold drawing to manufacture thin wall tubing.

[5] Glen Stapleton, Carlsbad, Apparatus for feeding and turning tube products into a pilger mill machine CA (US).

[6] Steven Hofstetter,*Process improvement through designed experiments, master thesis*,Massachusetts Institute of Technology, June 1993.

[7] Ki Bum Park, In Kyu Kim, Min Young Park, JongYeolKahng, and Hung Soon Chang(KEPCO NF), Development of Cold Pilgering Technology for PLUS7 Guide Thimble Tube, *Poster (Nuclear Fuel and Materials) 2013- Autumn.*

[8] Saibaba.N.,Fabrication of seamless calandria tubes by cold pilgering route using 3-pass and 2-pass schedules, *Journal of Nuclear Materials 2008.*

[9] Singha, Utpal; Deshmukh, Vinayak; Tonpe, Sunil; Saibaba, N.; Jayaraj, R.N,Process development for manufacturing of square channels through seamless pilgering route,*Nuclear Fuel Complex, Hyderabad ,India.*

[10] Singha, Utpal; Deshmukh, Vinayak; Tonpe, Sunil; Saibaba, N.; Jayaraj, R.N, Hexagonal channel by seamless pilger route for prototype fast breeder reactor,*Nuclear Fuel Complex, Hyderabad ,India.*

[11] Gerretz .J, stinnertz .H, Mannesmann-Meer Aktiengesellschaft, *The new mannesmann-meer Tooling design, cold pilger symphosium 24th-25th march 1969.*

[12] Sun Doo Kim, Chan Huyn Park, In Kyu Kim, Ki Bum Park, Seung Hwan Lee,Pilger die and pilger mandrel for manufacturing dashpot tube for nuclear fuel assembly, method of manufacturing the pilger die and the pilger mandrel, and dashpot tube for nuclear fuel assembly,*US20120079864 A1,KEPCO NUCLEAR FUEL CO., LTD., KOREA, REPUBLIC OF.*

[13] Chiranjib K. Mukherjee (CJ), John P. Reinhart, The metallurgical benefits of cold rolling high performance alloys instead of cold drawing to manufacture thin wall tubing, *Pipe & Tube Nashville 2012*.

[14] Krishna Aditya Y V, Study of change in mechanical properties of Zr2, Zr4, INCOLOY 800 and D9 materials on pilgering *Int. Journal of Engineering Research and Applications ISSN: 2248-9622, Vol. 4, Issue 4(Version 2), April 2014, pp.60-68.*

[15] Hardell, Jens, *Tribology in Cold Pilgering, master thesis, Luleå University of Technology, march 2005.*

[16] PatrickJ.Ruane, Lubricant, *US5580845 A, Castrol limited.*