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Smart Motion

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***Abstract*—**Austenite and Martensite indicate the phases of solids undergoing phase transformation which we usually associate with materials and not with living organisms. This article provides an overview of bacterial proteins and structures that are undergoing phase transformation and suggests its probable effect on mechanical behavior. The context is mainly within the role of phase transformations occurring in the flagellum of bacteria. The current knowledge of molecular mechanism leading to phase variation in living organisms is reviewed. Since in bacteria, each flagellum is driven by a separate motor, similarity to a Differential drive in case of four-wheeled vehicles is suggested. It also suggests the application of the mechanism in which bacteria changes its direction of movement to facilitate single point turning of a multi-wheeled vehicle. Finally, examples are presented to illustrate that the motion due to phase transformation of flagella in bacteria can start a whole new research on motion mechanisms.

***Keywords*—**Flagella, Phase Transformation, Nanobots, Differential Drive, Single point turn, Biomimetics.

I. Introduction

PRODUCING movement with the current knowledge is very simple but the ability of a body in motion to access even the tiniest, generally inaccessible regions, is also an important criteria. Biomimetics [1] or mimicking biology is the study of the structure and function of biological systems as models for the design and engineering of materials and machines. Smart motion, as the title suggests is the use of smart materials to produce motion.

We are in the stage where we study different nature occurring phase transformations and their relevance to practical applications for making designs for machines and mechanisms.

II. Phase Transformation

Phase transformation is the conversion of the lattice structure from a more symmetric form to a less symmetric form and vice-versa depending on various factors such as temperature, level of pH, chemical reactions, load, etc. This is evident not only in metals but also in many living organisms for instance, the sheath of a virus called T4 Bacteriophage (IV) and the flagella (III) of a bacterium. A change in temperature, or load or any other change in the environment changes the structure of the material. This helps the bacteria propel its self and helps the T4 Bacteriophage inject DNA into the body of the bacteria. The two phases of a phase transforming body are Austenite and Martensite

A. Austenite Phase

Austenite is stable at high temperatures in case of steel and is highly symmetric. But the stability of austenite depends on various environmental factors in case of living organisms.

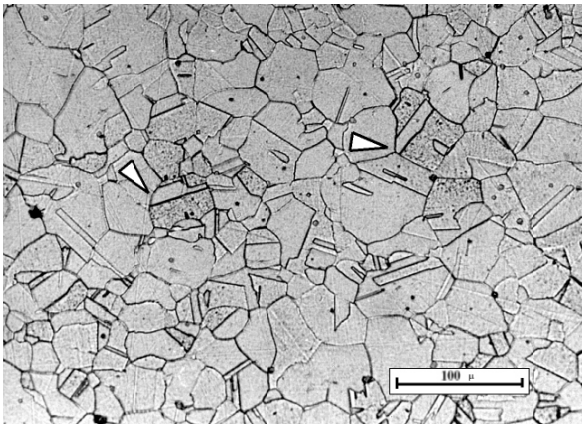

Fig. 1 Austenite phase in steel

B. Martensite Phase

Martensite is stable at low temperatures in the case of steel and is unsymmetrical. The stability of this phase in case of living organisms also depends on other environmental factors.

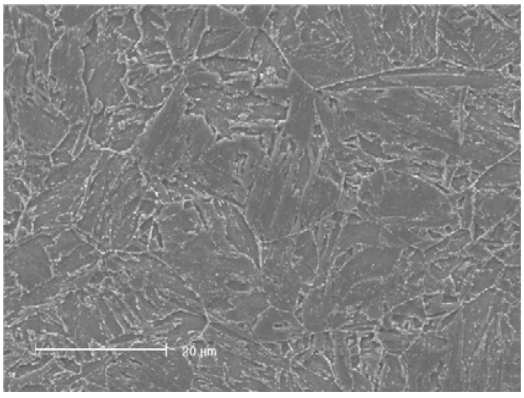

Fig. 2 Martensite phase in steel

III. What are Flagella?

The motion of flagella on live bacteria was first observed by Ehrenberg [2] in 1838. Motility based on flagella is a major mode of locomotion in bacteria. A bacterium has one or several flagella. The flagellum is mainly composed of three parts: a basal body consisting of a reversible-motor imbedded in the cell wall, a short proximal hook which works as a

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flexible universal coupling joint and a long helical filament which is the propeller made up of only one kind of protein called flagellin. The filament is a hollow tube with outer diameter of 20nm and a length of 15–20μm [3].

IV. Phase Change in T4 Bacteriophage

T4 Bacteriophage is a virus that attacks bacteria by injecting DNA into the bacterial body via phase transformations in its sheath. [4].

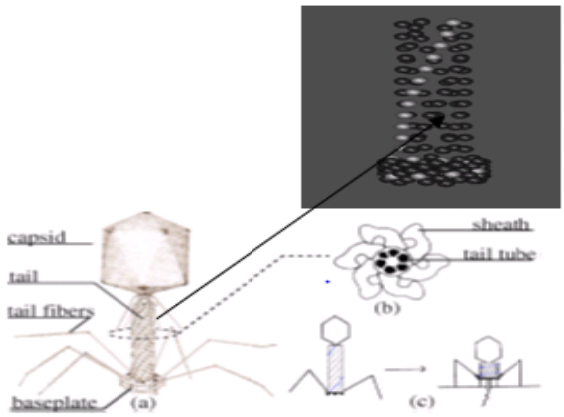

Fig. 3 (a) Structure of bacteriophage T4, based on electron microscope structure analysis to a resolution of about 2–3 nm (b)Cross section showing concentric tail tube and sheath annuli. (c) Schematic of contraction process [5]

Prior to invasion of the host, the sheath proteins are arranged as steeply pitched helices, and the tail adopts so called *extended* structure. During the virus' attack on a bacterium, the tail sheath changes shape dramatically; the protein helices compress, causing the sheath to shorten and fatten into a more compact *contracted* structure. This drives the relatively rigid inner tail tube through the cell wall, making a passage for the viral DNA to pass into the host [Fig. 3(c)]. During this process the sheath contracts irreversibly to about 1/3 of its original length accompanied by a 50% increase in outer diameter. The transformation has many features in common with martensitic phase transformations, as has been noted by Olson and Hartman [5].

V. Motion of Bacteria

When the bacterium swims, flagellum forms a rotating bundle. As the motor rotates in counter clockwise (CCW) direction and then suddenly changes to clockwise (CW) rotation, the bundle falls apart and the cell tumbles. At the same time when the motor rotation reverses a phase transition occurs in the flagellar filament.

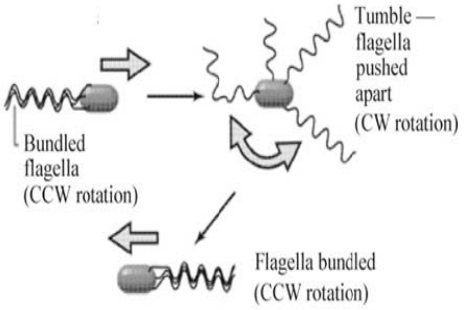

Fig. 4 Illustration of movements of *E. coli*, when its motor rotates CCW, flagella are in a bundle and the cell swims; when the motor reverses direction, flagella fall apart and the cell tumbles. The filament undergoes polymorphic transition when the cell tumbles

A flagellum has 12 different forms with different radii and pitch lengths, the phase transition can be induced by chemical change or by mechanical loading. The reason for the polymorphism of the bacterial flagellar filament is that its microstructure changes during the phase transition, a very slight difference of the protein subunit misfit, only 0.8Å, is responsible for helix formation of flagellar filaments. Before presenting the results of the analysis by **[3],** we shall first give a brief description of the conventions used in the analysis; summarized in Fig. 5.

In Fig. 5(a), helical sense is defined as left-handed (LH) or right-handed (RH) by the usual convention that the phase vector rotates CCW or CW, respectively, as the locus moves away from an observer looking along the helical axis.

In Fig. 5(b), sense of flagellar rotation is defined as CCW or CW from the viewpoint of an observer looking along the helical axis of the flagellum into its point of attachment to the cell.

In Fig. 5(c), the torque applied by the motor to the flagellum combines with viscous resistance to rotation to give a twisting moment, or torsion, which is LH if the motor is rotating CCW and RH if the motor is rotating CW.

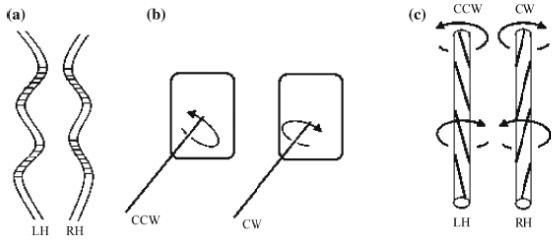

Fig. 5 Conventions

After performing experiments in viscous environments, from [3], we finally get the following generated hydrodynamic forces on the moving helical cross section for the right handed forms are:

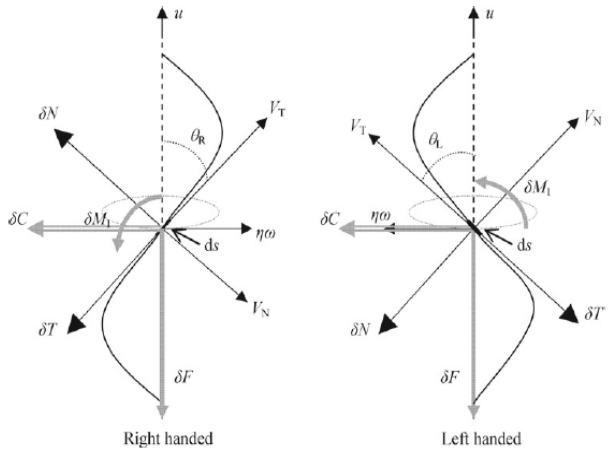

Fig. 6 Force Diagram

$$F = \frac{C_T m}{\sqrt{4\pi^2\eta^2+\lambda^2}}[-4f(\pi^2\eta^2\lambda) + (8\pi^2\eta^2 + \lambda^2)u] \quad (1)$$

$$C = \frac{2\pi\eta^2 C_T m}{\sqrt{4\pi^2\eta^2+\lambda^2}}[f(4(\pi^2\eta^2 + 2\lambda^2) + \lambda u] \quad (2)$$

$$M = 2\pi\eta C_T m^2\sqrt{4\pi^2\eta^2 + \lambda^2}(u - f\lambda) \quad (3)$$

The forces for the left handed form are

$$F = \frac{C_T m}{\sqrt{4\pi^2\eta^2+\lambda^2}}[4f\pi^2\eta^2\lambda + (8\pi^2\eta^2 + \lambda^2)u] \quad (4)$$

$$C = \frac{2\pi\eta^2 C_T m}{\sqrt{4\pi^2\eta^2+\lambda^2}}[f(4\pi^2\eta^2 + 2\lambda^2) + \lambda u] \quad (5)$$

$$M = 2\pi\eta C_T m^2\sqrt{4\pi^2\eta^2 + \lambda^2}(u + f\lambda) \quad (6)$$

Where, C_N and C_T are the frictional constants in the appropriate directions; θ is the pitch angle of the helix; F is force; C is torque, M is bending moment; u is velocity in axial direction, m is pitch number along the filament; λ is wavelength; η is radius of filament; δs is length of element of the filament. The medium offers a resistance to reactions

$$\delta N = V_N C_N \delta s \quad (7)$$

$$\delta T = V_T C_T \delta s \quad (8)$$

There is a little difference between the two forms in different charity in the force component expressions on the signs of velocity and frequency.

VI. Modeling Flagella

In the rigid-body model for the flagellin, we follow work by Namba and Vonderviszt [6] who set up a characteristic binding scheme.

Fig. 7(*a*) shows a short piece of the filament. Fig. 7(*b*) shows side (top) view and front (bottom) view of one of its flagellin molecules. Rigid black arms emanate from a central black spot to the binding sites. Whereas the black backbone symbolizes the rigidity of the molecule, the transparent blue form should only give an impression of its silhouette but has no physical meaning for the model. The gray binding sites with labels 1 and 2 are present in both states of flagellin, while the red binding sites (labels 5, 6) are only activated in the R-state and the green sites (labels 3, 4) in the L-state. This is the binding scheme suggested by Namba and Vonderviszt. Fig. 8 illustrates it for pure L-type (blue) and R-type (red) flagellin molecules. The elastic network following from this binding scheme is unstable and collapses to a non-tubular form, like a balloon which loses its form after deflation [8].

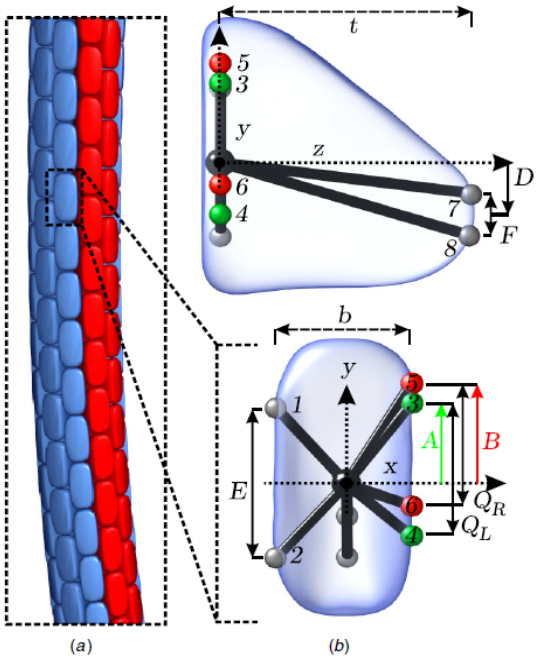

Fig. 7 (*a*) A microscopic view of a short piece of filament. It shows the arrangement of the model flagellin in the protein network. (*b*) One model flagellin viewed from the side (top) and from the front (bottom). Rigid black arms emanate from a central black spot to neutral binding sites 1, 2, 7, and 8, which exist in both states of the flagellin. The green sites 3, 4 and the red sites 5, 6 are only activated in the L- and R-state, respectively. The blue transparent surface only symbolizes the borders of the rigid body. The central black spot is also the origin of a Cartesian coordinate system attached to the rigid body. The origin lies in the plane of binding sites 1–6 and its horizontal position is in the middle between sites 1, 2 and 3–6. The *y* coordinates *A* and *B* define the respective axial positions of the binding sites 3, 5 and thereby the internal twist of the pure L- or R-form of the filament. The distance between the two binding sites 3, 4 and 5, 6 are given by Q_L and Q_R, respectively. The distance between sites 1, 2 is *E* and their *y* coordinates are *E*/2 and −*E*/2. The inner binding sites 7, 8 are characterized by the axial displacement or *y* coordinate *D* of their center and their distance *F*. For further use, the difference $C = Q_L - Q_R$ is defined, which is the difference in length of the flagellin in the L- and R-state. Finally, *b* and *t* are the width and depth of the model molecule [8].

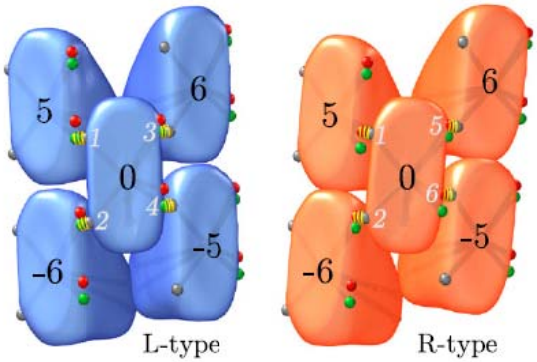

Fig. 8 Assembly of L-type (blue) and R-type (red) rigid bodies in the filament. In the L-state the green binding sites are active, in the R-state the red sites are switched on. They always form bonds tothe neutral gray binding sites along the 5-start and 6-start directions. Due to the different axial positions of the green and the red pairs of binding sites, a different internal twist occurs in the straight filaments of pure L-type and R-type protofilaments. The different distances between the binding sites in each pair cause different lengths of the flagellin molecules and therefore of the L-type and R-type protofilaments. If the domain of L-type rigid bodies on the left meets the domain of R-type rigid bodies on the right, the active binding sites 3, 4 do not match with the neutral binding sites 1, 2. Therefore, elastic deformations occur in the domain wall, the energy of which is described by the Hamiltonian *H*RB of equation [8].

The most important result of this [8] work is that the axial distance between the inner and outer binding sites reveals the mechanism via which the associated stress is produced and released. It only depends on the overall shape of the flagellin protein and does not rely on molecular details [9]. There is a remarkable agreement between the elongated shape of flagellin and the model protein. The normal helical form is the most efficient one for bacterial propulsion.

The paper [8] presents a mechanism related directly to the shape of the flagellin molecule via which the flagellar filament selects its helical ground state. This confirms the common view [6, 9, 10, 11, 12] that the L- and R-states of the outer (D1) domain of flagellin enable the formation of the different polymorphic forms of the flagellum, whereas the inner (D0) domain plays a crucial part in selecting the energetically preferred helical configuration.

VII. Probable Applications inspired from the Bacteria

A. Turning Mechanism

The conventional differential drive can be replaced by a mechanism inspired by the bundling phenomenon in bacteria. This can help facilitate a single point turn of vehicles.

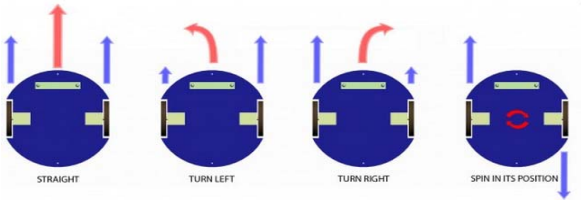

Fig. 9 Single point turning mechanism

In Fig. 9, we see that a single point turn is possible in case of a two-wheel set up. But this design is unstable; so we opt for a 4-wheeled set-up. A 4-wheeled vehicle without complicated mechanisms cannot facilitate a single point turn

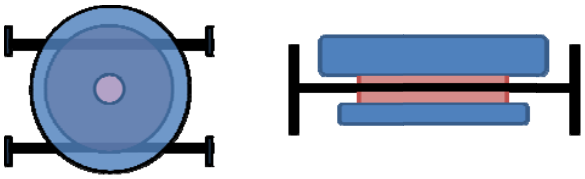

Fig. 10 Left Top view and right: side view of a probable design to facilitate single point turn

The orange portion in the fig. 10 represents a rotatable disc in which the shafts are mounted. When the vehicle needs to turn about a single point, it comes to a halt, rests on the base, the disc rotates, the base rises and the vehicle moves in the desired direction.

B. Other Applications

1) *Space vehicles and Submarines:*
The idea mentioned in 7.1 can be used in space vehicles. Also, understanding the phase change in bacterial flagella can help us design propulsion mechanisms for submarines and space vehicles.

Fig. 11 A nanobot

2) *Nanobots:*
The bacterial motion mechanism can also be applied to small scale robots (fig. 11) which are in the making mainly to serve medical purposes like providing drugs to cancer cells and to reach the internal liquid parts of the body that are impossible to access with the current technology. This can be done better by understanding the role of effect of chemical reactions on the bacterial flagella.

3) *Aircraft:*
Phase transition of bacterial flagellar filament can be used in the dynamic system of twin tail aircraft to suppress the vibration

VIII. Conclusion

1) Previous studies [7] have revealed that a string of phase transforming material cannot propel itself in the environment. But, in bacteria, there is more than one flagellum. The interlude of phase transformations in these flagella results in an effective force on the bacteria in one direction.
2) The motion of bacteria is propelled by the propulsive force which is generated by the bacterial flagella filament rotation and the viscosity of the fluid. The flagella filament parameters such as wavelength, radius and rotation frequency of the filament can influence the motion velocity.
3) Phase transition of the bacterial flagellar filament in both vivo and vito environments can be induced by mechanical forces [3]. It is motivated by the bacterial flagellar motor in the former case and it is motivated by the flow of viscous fluid in the latter case.
4) Studying the Phase transformation in living organisms and the factors which affect this transformation can help us devise a mechanism that can be applied at macro level.

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