

Critical political economy and materials transformation

Ray Hudson

University of Durham

Department of Geography

Durham

DH1 3LE

Email: ray.hudson@durham.ac.uk

“,, the ever growing literature . . . that deals explicitly with the subjects of *materiality* and *material culture* seems to have hardly anything to say about *materials*. I mean by materials the stuff that things are made of” (Ingold, 2007, 1).

“...an account of Fordism has yet to be written that takes seriously the properties of the new steels (hardness, ductility, physical and chemical stability, durability) in enabling the mass production of interchangeable parts and the cultural values associated with the mass consumption of standardized products” (Bakker and Bridge, 2006, 13).

Introduction

The long history of various strands of critical political economy (CPE) can be traced back to Marx’s seminal analyses of capitalist development. As capitalism developed, these analyses became more sophisticated but nonetheless there are issues that require further exploration. I therefore have three aims in this article. First, I argue that CPE – as do the social sciences more generally - needs to engage more

closely with the “the stuff that things are made of”, the properties of materials, their microstructures and transformations of these as such knowledge is crucial to understanding why materials acquire use values within the commodity production process. Put another way, CPE needs to open up the ‘black box’ of materials and their transformations in order to understand better why and how these can be manipulated in particular ways to create exchange value. Secondly, I offer an explanation in terms of competitive epistemologies, conceptions of theory and claims as to what constitutes valid knowledge as to why consideration of the microstructures and properties of materials and their transformations has persisted as a lacuna in CPE. Filling it is a necessary precondition to consideration of the limits to and possibilities for progressive change in the socio-technical relations that shape the economy. Knowledge of what it is materially possible to produce is a necessary precondition for consideration of alternative conceptions that challenge the hegemony of capitalist material interests and imagine alternative ecologically sustainable and socially just visions of the economy. Thirdly, I explore and exemplify the more general claims about the need to understand production as simultaneously a value-creation process and a materials transformation process, and that understanding the former requires grappling with the latter, via some illustrative examples drawn from the automobile and steel industries. While Bakker and Bridge correctly point to the neglect of materials transformations in analyses of Fordism, these issues have been addressed to some degree (for example see Best, 1990; Hounshell, 1984; Storper and Walker, 1989)¹. To develop these analyses further, I focus upon relations between producers of steel and producers of automobiles and their component parts and the ways in which specific sorts of steels have been

¹ I am grateful to one of the anonymous referees for reminding me of this.

developed to meet the requirements of particular end uses in automobile production. In this way I will seek to develop existing analyses and respond both to Ingold's plea to engage more deeply with "the stuff that things are made of" and how that "stuff" is itself produced and Bakker and Bridge's challenge to explore the development of particular types of a material often treated as homogeneous and undifferentiated by social scientists for the production of perhaps the iconic commodity of twentieth century capitalism.

Developments in and limits to CPE

In his analysis of the labour process in volume 1 of *Capital* Marx emphasised that production involved the application of human labour to materials taken from the natural world and their transformation into socially useful products. While Marx's focus was on capitalist production he was equally clear that, irrespective of the dominant social relations, any process of production was also one of materials transformation, with unavoidable material consequences and deleterious environmental effects.

However, having recognised that production always involves material transformation, Marx then focussed upon production – and the economy more generally – as a socio-technical system driven by specific material interests, on the social relations and technologies of production and the way in which these were shaped in specific configurations to enable the continuing (expanded) reproduction of capital.

Recognising the specificity of capitalist social relations had precise implications for the ways in which material transformations were shaped and delimited and for which materials from nature became part of these social processes of value creation and commodity production. His focus - and that of those who followed him - was upon

value creation and expansion, on the creation of surplus-value through the application of labour-power in production, the appropriation of surplus-value by capitalists and capitalist enterprises and its transformation into capital rather than on the properties of matter and material transformation per se.

The grounding of production in material transformations was thus acknowledged but then bracketed out. Its implications both for processes of value creation and the reproduction of the social and ecological conditions that enabled capitalist production to continue remained largely unremarked. This one-sided perspective remained dominant in subsequent developments in Marxian political economy: for example, in increasingly sophisticated analyses of the labour process (such as Braverman, 1974). The emphasis in analyses of capitalist economies upon circuits of capital and flows of value (for example, see Palloix, 1977; Harvey, 1982) further diluted the significance of the properties of matter for the possibilities of commodity production. Focussing on the commodity form emphasises the exchange of formally equivalent quantities of socially necessary abstract labour and neglects their material attributes and properties (Lütticken, 2008).

Furthermore, the development of modern capitalism and the practices of major capitalist enterprises increasingly emphasised the symbolic register of commodities and their socially ascribed meanings. Promoting the symbolic attributes of commodities through advertising, seeking to influence processes of consumer knowledge acquisition so that commodities are seen to be imbued with attributes that exceed their immediate functional and practical uses, and constructing the consumer via the deployment of psychological and social research were central to the rise of mass production/mass consumption in the 1920s and to subsequent capitalist

development (for example, see Williams, 1980²). Major companies, especially those producing for final consumer markets, became brand managers, creating extensive brand families incorporating diverse commodities under a particular brand label (Klein, 2000), thereby siphoning off monopoly rents. Systematic consideration of issues of meaning and semiosis is undoubtedly a major contribution to a more sophisticated CPE (or cultural political economy: Sum and Jessop, 2007). However, such approaches further divert attention from processes of materials transformation and the materiality of the processes and transactions of the economy.³

In general material matters, particularly concerns with “the stuff that things are made of” and processes of materials transformation, remained the domain of the physical and engineering sciences, which developed extensive theories and laws about material properties and transformations. While physical scientists and engineers developed important knowledge about chemical and physical processes, the possibilities that these allowed to shape matter in particular forms and the ways in which these could be deployed in economic activities, they did so in ways and via methodological and theoretical positions that bracketed out the social context and relations in which the economy was performed. Meanwhile, although there was often a concern with R&D, and more recently with ‘knowledge-based economies’, social scientists overwhelmingly bracketed out from their analyses of economies any consideration of issues such as the effects of the physical and chemical properties of materials on the capacity to create commodities embodying value.

² Originally published in *New Left Review* in 1960.

³ As Costis Hadjimichalis (personal communication) has pointed out, the postmodernism turn towards discourse analysis (in which everything was a linguistic construction) further diverted attention from any consideration of materiality.

More recently, however, building on earlier work by a few pioneers (for example, see Ayres and Kneese, 1969; Georgescu-Roegen, 1971; Kneese et al, 1970; Benton, 1989), there has been the beginning of a revival of social scientific interest in issues of materials transformation and related material aspects of the economy. As Harvey (1996) notes, all processes of industrialisation are fundamentally socio-ecological projects. However, such concerns have largely remained at an aggregate level rather than engaging with the micro-scale properties of materials and processes of materials transformations and their implications for and relationships to commodity production.

Why then is it important for CPE better to understand the micro-scale properties of the materials and the materials transformations that lie at the heart of production? Knowledge of these properties and the ability to manipulate them, or transform them via combination with other materials, to give desired use value characteristics is central to industrial capitalism and capital accumulation. Value is created via such manipulations and transformations as materials with use values are produced and in turn provide a basis for exchange value and further value creation as they are transformed into new commodities. Equally such knowledge is a crucial pre-condition for serious consideration of a transition to either a different form of capitalist economy or, more radically, to non-capitalist relations of production. Such changes would incorporate modification to both the volume and composition of production and the material composition of products themselves, reflecting a much greater emphasis on socio-spatial and ecological equity and sustainability rather than simply economic growth and accumulation per se,

Furthermore thinking about the economy in the way outlined in this paper, recognising the centrality of material flows and transformations, challenges and

problematizes established approaches that focus on firms and/or sectors.

Emphasising flows of materials as well as of values among firms and across sectoral boundaries suggests that a more productive way of thinking about the economy is in terms of production systems of varying organisational composition, complexity and spatiality. Such an approach could begin with the final commodity and work back through the various firms, in different sectors, involved in its production and the complex array of material and social processes and flows that this entails, back to the initial extraction and appropriation of materials from nature. Equally it could begin with that initial extraction and appropriation and follow the flows in the opposite direction. Either way, it would emphasise the connectivity, complexity and uneven development of the capitalist economy, especially as these flows typically now involve global trade patterns⁴.

In this paper, therefore, I want further to develop a concern with the properties of materials and materials transformations in critical political economic analyses, framed by a Marxian conception of the production process (understood in both its narrow and broad senses). I consider the properties of materials and materials transformation in greater depth because of their influence on use values and thus on their pivotal role in creating exchange value and the production of commodities and of the material worlds in which people live. Schematically three types of transformation can be recognised:⁵ molecular transformations that produce specific desired changes in the properties of the resultant materials and so directly affect their capacity to form use values and the uses that can subsequently be made of them

⁴ Several approaches to studying global flows have emerged in recent years – commodity chain analysis, value chains, Global Production Systems, for example (see Coe *et al*, 2004; Gereffi and Korzeniewicz, 2004; Gereffi *et al*, 2005) but all neglect the materiality of these flows (Hudson, 2008).

⁵ For a similar three-stage perspective (production; fabrication/manufacturing; use), see Michaelis and Jackson, 2000). The argument here is developed in relation to those commodities that involve such material transformations and that conventionally would be regarded as ‘manufactures’.

in production; forming and shaping of materials (into either final products or intermediate components); assembly into final products. These three types of transformation differ qualitatively in the character and scale of the changes that they encompass but are nonetheless related as changes of the first type can and typically do have implications for what is possible in terms of the other two forms of change and for relations between process and product innovation. .

Schematically, these links may be sketched out as follows. Once a material has been produced with required use value characteristics, the competitive imperatives of capitalism result in continuous pressures to reduce the exchange value of that commodity via process innovations as producers of it seek to maintain or increase market share and profitability, reducing the socially necessary labour time involved in its production⁶. This may also lead to a search for alternative materials via new forms of molecular transformation. At the same time the invention of new materials can create opportunities for product innovation and the creation of new higher value products through forming and shaping new and existing materials into new commodities. Such product innovation requires bringing together requisite technical knowledge with ‘softer’ knowledge and skills in activities such as design and marketing. Product innovation may well also require process innovation but in this case driven by a different logic to that of cost-cutting and price competition. For a while these new commodities may confer monopoly advantages on their producers until they diffuse more widely and competition lowers their value and market price. This in turn can set in motion a fresh wave of product innovation, seeking to create value in further new commodities.

⁶ Companies may adopt other strategies to combat falling market share and profitability – for example moving into other areas of manufacturing or services, as was the case with several steel companies in the 1980 s (Hudson and Sadler, 1989)

Much of the existing work in CPE (indeed more generally in social scientific work on the economy) focuses on the second and especially the third of these types of transformation. There is an extensive literature analysing the ways in which commodities are manufactured. Broadly speaking, this seeks to comprehend the various ways in which capitalist social relations are configured to ensure that the production of diverse components and their assembly into final products is successfully achieved such that the value embodied in the end product exceeds that of the inputs to the production process, creating the potential for capital to realise profits. Knowledge, know-how and know-who are crucial inputs to production processes. They include artisanal production, production through networks of small and medium-sized enterprises (SMEs) organised in industrial districts and a variety of methods of large scale production such as Taylorist/Fordist mass production, lean production and just-in-time methods of flexible high volume production (for example, see Hudson 2001, 96-216). In this sense, this literature does indeed engage with issues of material transformation as diverse components and materials are assembled into often very complex commodities. Consider, for example, the way in which manufacturing automobiles involves combining and assembling diverse components of steel, aluminium, plastics, rubber and electronics.

Nevertheless, I want to argue that this represents simply the final stage in a series of material transformations that are integral to all processes of manufacture. For before these varied components can be assembled to give the desired final product, there are other fundamental transformations of materials that must be successfully undertaken. Firstly, and critically, these involve molecular transformations so that materials from the natural world (typically referred to as having become natural resources) can be rendered into materials with use values in production. Knowledge

of the chemical and physical properties of materials and the processes through which desired properties can be achieved is a necessary pre-condition for exploring and exploiting their possibilities in commodity production while, at the same time, their production as commodities requires that they can be produced sufficiently profitably⁷. Secondly, the forming, moulding and shaping of these transformed materials into commodities with exchange value, either products for final markets or components and parts that will in due course become part of products for final markets. The crucial point is that it is the interplay of the social relations of production, the imperatives that they bring, and the properties of materials and knowledge about them that shapes the anatomy of commodity production.

Knowledge of the properties of materials and of how to manipulate transformative processes to produce materials with desired properties has long been the domain of natural, physical and material scientists. Since this knowledge also allows profitable commodity production (and indeed is often created specifically for that purpose in the R&D laboratories of major capitalist enterprises or in University laboratories that they support) social scientists who wish to deepen understanding of capitalist economies must conceptualise them as conjoined processes of value creation and materials transformation and be cognisant of the latter processes⁸.

⁷ Under certain circumstances, the state may step in (for example via nationalisation or public ownership) to ensure that materials that themselves cannot be produced profitably are actually produced and sold at prices that allow others to produce other commodities profitably. This was the case with steel in Italy and the UK, for example, for much of the latter half of the twentieth century (see Hudson and Sadler, 1989).

⁸ There are important differences between production processes based directly in nature and manufacturing processes. Biologically based processes that involve animals and plants as participants typically involve nurturing or enhancing natural processes of growth and development via manipulating the growth environment rather than materials transformation as an intentional strategy of production (for example, see Boyd et al, 2001; Prudham, 2005). In addition, activities such as mining involve winning natural materials and perhaps some in-situ processing but not their molecular transformation. In both cases, there are critical issues relating to the appropriation of nature (Hudson, 2005, 45-54), especially acute when this involves modifying of living organisms and associated deep ethical concerns. The transformation of natural materials into natural resources owned by specific capitalist interests, central to strategies of accumulation via dispossession

While social scientists have focused on the second and third types of transformation, the first has largely been left as the domain of physical/material scientists. My argument is that the critical political economists (and indeed social scientists in general) analysing the economy need to engage with the first type of material transformations and its implications for subsequent types of transformation as there are clear relations between the chemical and physical properties of matter and the ways in which this can then be shaped, formed and used in the economy. Where there needed to be dialogue, there has been silence. The result has been an impoverished political economy. The character and properties of materials do not determine their use value or exchange value, or their capacity to underpin profitable commodity production, since these are always socially defined. However, knowledge about these properties is a necessary condition for deciding what is possible, technologically and economically, in terms of the logic of capital. As such, critical political economists who wish better to understand capitalist production with a view to progressively changing it ignore them at their peril. First of all, though, I begin by considering an epistemological dilemma in seeking to understand why CPE has generally remained blind to the central role of the first set of processes of material transformations in economic activities.

An epistemological dilemma

Prima facie, it seems strange that critical political economists and social scientists interested in the economy have neglected the processes of transforming materials

(Harvey, 2003), can occur in diverse ways, ranging from military action and physical force linked to processes of (neo)colonialism to more subtle means, such as IPR legislation and the due processes of the rule of law (for example, see Prudham, 2007; Sneddon, 2007).

from one form to another, leaving this critical moment unexamined⁹. This is especially so of Marxian political economists, given the emphasis that Marx placed upon the labour process as also – and always – a process of material transformations. Why should this be so? One answer lies in the different conceptions of what constitutes valid knowledge and forms of theory in different disciplines and the purposes for which knowledge – or wisdom (Maxwell, 2007) – should be created.

There have been significant epistemological developments that have identified common ground in approaches shared by social and natural scientists since Horkheimer (1937) first drew a sharp distinction between “traditional” and critical” forms of theory. Moreover, as Vogel (1996, 7) points out, “little serious attention has been given to contemporary philosophy of science within the postwar tradition of critical theory, and this is a significant fault”¹⁰. Nonetheless, recognising this, I want to use Horkheimer’s distinction as a point of departure and reference in seeking to account for the neglect by social scientists of physical processes. Whatever its limitations, it remains relevant to my purpose here. In the physical and natural sciences the dominant conception of theory has been and for many physical scientists remains that of ‘traditional’ theory, ideally deductive in structure, empirically verified and validated via inter-subjectively available knowledge and, crucially, by its predictive capacity and power. Moreover, prediction and explanation are seen as synonymous in a world regarded as governed by universally applicable and invariant

⁹ Social scientists – for example, some anthropologists, geographers, and political economists - have of course shown interest in more general material aspects and forms of economy and society. As Ingold (2007), emphasises, however, they have had little to say about “the stuff that things are made of”. Similarly, and going on from Ingold’s observation, my point is that they have had little if anything to say about the processes of material transformation that precede as a necessary condition the creation of these forms (and indeed that follow the end of their lives as commodities) and shown little interest in knowledge and laws in the physical and natural sciences that explain and predict these transformations and allow them in principle to be managed and controlled,

¹⁰ Vogel (1996, 7) notes that Critical Theory has struggled to come to terms with such developments, which both elucidate and fundamentally complicate the epistemological and methodological accounts that it offers (for example see Sayer (1984) or Latour (2005) for very different but equally incisive critiques).

laws¹¹. Such a form of theory developed in the natural sciences was intended to be socially progressive by emancipating people from the constraints of nature, rendering the natural world amenable to control and so change in those directions that people preferred (Lewis and Melville, 1977)¹².

There are still those who see a ‘traditional’ form of theory as relevant in the social sciences¹³ but I take it as axiomatic that this is an inappropriate form of knowledge for understanding the social relations of the economy and the economy as a social process of value creation. In contrast, those working within the framework of CPE and critical social science favour ‘critical theory’, with different criteria for assessing the value and validity of knowledge. This is because, irrespective of the intentions of the theorist, translating the ‘traditional’ form of theory from the natural into the social sciences leads to possibilities of social control and engineering, premised – even if only tacitly – on a view of society as unchanging in its underlying and formative social relationships and structures. The ability to predict the consequences of intervening in a process, whether social or natural, is a prerequisite for successfully manipulating it (see Fay, 1975). Those who possess (social) scientific knowledge thus have the possibility of exercising social control. In this way the progressive role of traditional theory in helping emancipate people from the constraints of nature can become a repressive role in maintaining structures of social domination and repression. This is clearly problematic for political economists and social scientists who wish to develop a notion of ‘critical’ theory that relates theory to practice,

¹¹ Sayer’s (1984) work on critical realism emphasises the unobservable causal structures that underlie both natural and social events. Since the realisation of their causal powers depends upon contingent effects, which may or may not be realised in a given set of circumstances, the symmetry between explanation and prediction is shattered.

¹² The fact that it often had precisely the opposite effect because it led to unintended consequences is of great practical significance but is not the point at issue here.

¹³ It remains dominant in mainstream economics, for example.

informed by an emancipatory intent. This requires producing forms of knowledge – theories – that reveal the hidden character of mechanisms and social relations of domination and repression as a in particular ways necessary pre-condition for progressively intervening and changing them . Theory therefore becomes constitutive of, rather than simply descriptive of, the social world. Producing such change becomes the key criterion for validating theory¹⁴. A fortiori this is the case for those working from a Marxian or otherwise CPE perspective. The criteria for validating critical social theory are therefore radically different to those appropriate to ‘traditional’ theory developed in relation to the physical and natural worlds. As a result, there is a genuine epistemological dilemma for critical political economists and social scientists who recognise the need to engage seriously with the properties of matter and material transformations of elements of the natural world that are central to the production process and capital accumulation but can only do so via knowledge cast in the mould of ‘traditional’ theory¹⁵.

What then to do? To reject a concern with the properties of materials and their processes of transformations because they are tied to a particular conception of ‘traditional’ theory is unnecessarily restrictive and indeed counter-productive. Consequently, if we are serious about seeking a deeper understanding and integration of consideration of materials transformations and their relationship to commodity production within the realms of a CPE, there is no choice but to accept that different forms of knowledge are informed by different interests and purposes

¹⁴ However, the translation of theory into practice requires the undoubtedly problematic identification or constitution of subjects to effect such transformational change. This raises a different set of issues that are crucial but tangential to my main concerns here (for example see Castree, 2006).

¹⁵ Scholars working in the STS (science and technology studies) school and actor-network theorists (for example, see Latour, 2005) have emphasised the coupling of the social and the natural to produce hybrid actants and argued against drawing sharp distinctions between them. That said, there is equally a danger of reducing the material and the causal powers of materials to nothing more than a social construction

and to accept the dilemma that this poses¹⁶. Of course there is a need for eternal vigilance in pursuing such a path and to ensure that seeking to manage physical processes in socially progressive and ecologically sustainable ways via the approach of ‘traditional’ theory does not slide into the realms of social control. On the other hand, the danger of ignoring the implications of materials transformations as an unavoidable part of economic and social life is a greater risk, for two reasons. First, without an explicit recognition that social processes of value creation are always and necessarily processes of materials transformation, and that capital seeks to shape knowledge of these processes as well as the processes themselves to favour accumulation, then understanding of the accumulation process remains partial. The critical potential and transformational power of theory is thereby weakened. Secondly, therefore, ignoring the materiality of the economy, its transformational activities, their entanglement with processes of capital accumulation and their ecological impacts not only impoverishes theory but may well undermine the possibilities of moving to more equitable, humane and ecologically sustainable forms of economic relationships.

Material matters, material transformations and commodity production: the example of the automobile and steel industries

In this section, using the example of the automobile and steel industries and the links between them, I further explore the implications of examining the production process through the lens of materials transformations and the properties of matter. Contrary to popular misconception, steel is not a homogeneous commodity. Moreover, different components and parts of automobiles require steels with different properties

¹⁶ Habermas (1968) sought to resolve this dilemma through his theory of “knowledge-constitutive interests”; for a critique of his approach, see Vogel, 1996, especially Chapters 5 and 6.

appropriate to their specific uses in production. The central point is that the end uses of the steel, the forms into which it is transformed and the uses to which it will be put, are intimately connected to the properties of the metal. For example engine parts require very different types of steel to body parts. Thus the automobile-steel nexus provides a good exemplar through which to explore the ways in which different types of steel are developed and customised to meet the requirements of particular components and parts and/or particular customers. Conversely, automobile companies seek to shape the R&D and production strategies of steel companies as they refine the development of their products in search of competitive advantage or to satisfy changing regulatory requirements¹⁷.

Contrary to popular perceptions of steel that it is a technologically backward ‘smokestack industry, “steel making has now become a high tech industry ... [with] major gains in productivity and product quality” (Llewellyn, 1995, 11). The costs of R&D have led to collaboration and strategic alliances between major producers (see Table 1)¹⁸ and the demands of automobile producers have been an important motive for refining production processes and enhancing product quality. Production processes are highly automated, with sophisticated computerised process control systems (for example, see Arena et al, 2006)¹⁹. Furthermore because of continuous

¹⁷ There are several other reasons for choosing automobiles and steel as exemplars: both are major global industries, the chemical and physical processes of materials transformation are *relatively* simple (as compared to, say, carbon-based petrochemicals) and both have attracted considerable attention from social scientists (for example, see Beynon, 1973; Burn, 1961; Carr and Taplin, 1962; Hudson and Sadler, 1989; Hudson and Schamp, 1995; Warren, 2001; Womack et al, 1990).

¹⁸ Since the data in this table were compiled, there has been further major merger and acquisition activity in the global steel industry, notably the acquisition of Acelor by Mittal (2006) and of Corus by Tata (2007). Both were motivated by a desire to acquire more advanced technologies, know-how and higher value products. Automotive steels account for 25% of AcelorMittal’s annual R&D budget of \$US250m (AcelorMittal, n.d.). There have also been significant mergers in China involving Baoshan and Shagang (see World Steel Association, 2011).

¹⁹ Occasionally, such control systems fail catastrophically (for example, see Health and Safety Executive, 2008). Converting tacit to codified knowledge within expert systems can enhance the risks of catastrophic failure if deskilled operatives believe that monitoring systems are at fault rather than that the process is running out of

product and process innovation and the deployment of highly developed production technologies, it is possible to produce a great variety of cleaner, higher quality and higher value steels from the Basic Oxygen Steel (BoS) furnace²⁰. At the same time, production of steel from scrap via the Electric Arc Furnace (EAF) route has increased, often forming the starting point for producing more complex steels. However, in both cases technological and process innovations in secondary steelmaking have been crucial in enabling the production of a wide range of steels customised to the requirements of specialised uses and users. Steel producers have sought competitive advantage via developing specific qualities of steel unique to them and protecting this via patents.

Advances in computer modelling and the incorporation of tacit knowledge into sophisticated expert systems allow the properties and qualities of steels to be predicted accurately as compositions and processing technologies are varied, increasing capacity to manipulate material transformations so as to give steels with a desired mix of properties and qualities. Knowledge of the effects of compositional changes, interactions between added alloys, heating/cooling sequences and other material transformations linked to particular forming processes, enable steels and parts made from those steels to be produced as saleable commodities with defined desired qualities. Conversely, seeking to understand these processes of commodity production presupposes scientific knowledge of the underpinning material transformations and properties of the resultant materials.

control (Wiener, 1985). In this recognition of the limitations of human agency, there are similarities with approaches emphasising "vital materialisms" and the agency or "vitality" of matter (for example, see Bennett, 2010: Latour, 2005).

²⁰ Steel cleanliness (that is, the reduction of non-metallic inclusions in the steel) and quality have been improved via innovations in secondary steel making, including vacuum degassing (1950s), argon shrouding of the molten metal stream (1960s) and vacuum steel making (1970s) (Llewellyn, 1995, 128-9).

Drawing upon knowledge developed in the physical and materials sciences, therefore, steel can be produced with particular characteristics that are required for a given use. These characteristics depend upon the composition of the steel, the mix of alloys added to it and the type of production process and the way in which this is managed (for example, see Hawbolt et al, 1983). In particular, different combinations of heating and cooling the metal can be deployed so that the steel has a particular crystalline microstructure and mechanical properties, such as hardness, malleability or ductility, which are appropriate for shaping it in particular ways into particular forms for particular uses (for example, sheet for automobile bodies or engineering steels for engine components)²¹. The end uses of the steel, the forms into which it is transformed and the uses to which it will be put, are closely connected to the properties of the metal. Ensuring the appropriate properties often involves strategic collaboration between steel producers and users over R&D. Put another way, it is vitally important to have knowledge of materials, their properties and how these can be changed and manipulated, of how materials transformation processes can be managed so that steel can be produced with the characteristics – including an affordable price - required by customers and end users while yielding sufficient profit for the steel producer.

Automobiles constitute a major market for steel producers while steel is a major constituent of automobiles. For example, the automotive sector accounts for a majority of the production of Acelor, Nippon Steel and Bethlehem Steel and is a significant market for other major steel producers (Table 1) while steel accounts for between 50% and 70% of the total vehicle weight (Llewellyn and Hudd,2004, 115;

²¹ Relationships between temperature, time and microstructures can be displayed as Isothermal Transformations (IT) diagrams, also referred to as TTT (Time, Temperature, and Transformation) curves, or via Continuous-cooling transformation (CCT) diagrams (Llewellyn and Hudd, 2004, 205-7)..

Yakita et al, 2001). Steel is far from being a homogenous commodity, however, and steel producers have sought to move up the value chain to produce more specialised higher value steels, drawing on knowledge of materials properties and transformation to create new products, ideally unique to them²². Manufacturing automobiles requires many types of steels, varying in their chemical composition, microstructure and mechanical and physical properties. Understanding which types of steel are required for particular uses, and having the capacity to produce such steels, depends upon detailed knowledge of the transformations that steel will undergo, depending upon its composition and the processes (heating, cooling, hot and cold rolling, stamping and so on) to which it is subjected, Knowledge of these properties and their various interactions allows the qualities of steels to be accurately modelled and predicted, using powerful computer simulation models, and matched to the required end uses in automobile construction.

Conversely, for over a century demand from the automobile industry has been a major driver of change in the steel industry. As Souther (1910, 437-8) noted: “At the beginning [of the automobile industry] there was available ... Bessemer steel, open-hearth steel and cast or crucible steel. Variations within these classes were regarded as unimportant and heat treatment was an unknown term”. However “during the last few years ... the steel business has advanced and changed rapidly and ... the incentive is found in the manufacture of automobiles”, an incentive that was to continue in future. In order to manufacture automobiles successfully and profitably as commodities, various steels must be available at appropriate prices, both high enough to enable steel producers to make sufficient profit while undercutting any

²² For example, in 2007 ThyssenKrupp announced that its tailored stripe line “is the first line in the world” capable of uninterrupted laser welds (Thyssen Krupp, 2007). Tailored Blanks are discussed below.

potential substitute materials and low enough to enable automobile manufactures to produce commodities that sell and realise the surplus-value embodied in them. Consequently different types of steel must be used for different parts and components, matching their characteristics with the required use²³. Even so, a century or so ago, choice of steels for automobile production was fairly straightforward: “With a given quality of automobile in view, the number of grades of steel necessary to construct it is few, namely, a good all-round forging steel, a steel of slightly better quality to be used for gears, a spring steel and a steel suited for the pressed-steel portions of it” (Souther, 1910, 459).

While initially automobile manufacturers had to learn about existing types of steel and their appropriateness to their activities, increasingly the emphasis switched to automobile manufacturers demanding new types of steel customised to their requirements. As Bensaude-Vincent and Stengers (1996, 190-1) put it: “... new industries – such as automobiles ... – called for specific materials with particular properties A new rationale for production was the result: given a function or performance to achieve, find the material that has the needed properties”.

Consequently, major steel companies devote considerable expenditure to R&D (see Table 1) and there have been, and continue to be, close and symbiotic relations between major steel producers and automobile manufacturers over issues of process and product innovation and design. As a result, knowledge of different types of steels available to car manufacturers and of their suitability for different uses has expanded dramatically. Indeed, such links have deepened as more technically

²³ As Souther (1910, 438-9) noted, while alloy steels began to be increasingly used in automobile manufacture “The alloy steel is no cure-all and must be used intelligently, if any compensation for increased cost is to be realised. Knowledge of steel is not sufficiently widespread. The history of the automobile is short and there has not been time enough to disseminate knowledge of so many special steels and special treatments”.

sophisticated types of steel have become necessary in response to regulatory requirements and market demands upon automobile manufacturers, expressed in a range of collaborative projects and strategic alliances and partnerships. As Schuberth et al (2008, 637, sic) note, “[t]he automotive industry of today is characterised by faster cycles in materials invention, development and application, coupled with the ability to tailor materials to specific end-users requirements ... It is therefore essential for materials development to be closely integrated with the final product and process concurrent engineering practice”, As a result, there is increasing cooperation between steel producers (especially those for which the automobile sector, and indeed particular companies within it, constitute a major market), original equipment manufacturers and parts producers from the concept design and tooling/prototyping stages in early vendor involvement (EVI) programmes²⁴. One consequence of this is that the boundaries between assemblers, component suppliers and steel producers have become more blurred as steel producers seek to move up the value chain by performing operations previously carried out by automobile companies²⁵. At least one major steel producer, POSCO, is extending the concept of EVI to include component manufacture and sub-assemblies, especially those requiring highly advanced technologies and processes (Kwon and Baik, n.d.). The fundamental point, however, is that “the key motivation

²⁴ For example, 34 steel producers, from 11 countries, collaborated in the ULSAS ((Ultra-Light Steel Automotive Suspension) project, coordinated by the International Iron and Steel Institute (Corus Engineering Steels, 2001). The Auto/Steel Partnership (A/SP), formed in 1987, includes major North American automobile and sheet steel producers (Auto/Steel Partnership, 2000). The Next Generation Vehicle (NGV) project, 2005-9, brought together major European automobile and stainless steel producers (Anon, 2008; Gehm, 2009). In Japan the High Strength Steel Working Group was established in 1998 by the Iron and Steel Institute of Japan and the Society of Automotive Engineers of Japan (Takahashi, 2003). There are also collaborative links between the major automobile producers. For example EUCAR (The European Council for Automobile R&D) brings together 13 major producers to engage in pre-competitive R&D in areas where their combined efforts benefit all participants and feed into future competitive product innovations (EUCAR, 2010).

²⁵ For example Corus has a dedicated Automotive Services Centre offering a wide range of first and second stage processing facilities for the volume production of car body panels and underbody components (Corus, n.d.(b)).

behind innovation in the steel industry has been the revolution in vehicle manufacturing, as automotive steel represents the largest source of revenue for integrated mills... [this has] increased the drive for innovation and process improvements in the value-added end of the automotive steel market” (Warrian and Mulhern, 2006, 162). In the remainder of this paper I will exemplify these points via reference to specific types of steel used in automobile production.

Strip (sheet) steel and automobile production

The introduction of the continuous hot strip mill in 1923 was critical in enabling the growth of mass production in the automobile industry. Prior to this, steel was rolled in individual sheets, a slower and more expensive process. The automobile industry remains the largest consumer of strip steel, the predominant material for auto bodies (body-in-white²⁶ and other body components) and structural components. It has provided the greatest stimulus and challenge for R&D and the development of new improved grades of steel strip. Increasing demands from major automobile producers for higher quality steels - for example in terms of gauge control, flatness, surface texture, resistance to corrosion and strength/weight ratios - have been and continue to be a major driver of product and process innovation. During the 1970s and 1980s the character and qualities of steel strip demanded by automobile manufacturers changed significantly as they sought to reduce fuel consumption, enhance resistance to corrosion and improve passenger safety as these became important dimensions of competition and regulatory requirements became more stringent (Llewellyn and Hudd, 2004, 115-28). Typically this involved simultaneous consideration of varied aspects of material transformations due to the

²⁶ The body-in-white refers to the welded sheet metal components which form the vehicle’s structure and to which the other components - engine, chassis, exterior and interior trim – will be added.

interrelationship between the microstructures of steel and the methods of working and forming it into components and parts. While steel can be hot rolled down to thicknesses of 2mm, automobile producers demanded thinner and so lighter cold rolled steel. However, while cold rolling increases the strength of steel, it reduces ductility. Annealing enhances ductility and malleability, restoring a high level of cold formability, making it easier to form complex shapes²⁷. In response to pressures to enhance resistance to corrosion and provide more comprehensive warranties against structural and cosmetic deterioration, cold rolled strip for automobile bodies was increasingly zinc coated and in some cases also organically-coated (Llewellyn, 1995, 58-60; Fujita and Mizuno, 2007). At the same time, automobile manufacturers increasingly used different types of strip for different parts of the vehicle body, depending upon their exposure to corrosive elements and upon the mode of pressing the steel into the required shape²⁸ (for example, see Dasarathy and Goodwin, 1990; Takahashi, 2003).

Higher strength steels (HSS) were also introduced, first in the USA, for structural members formed from steel strip, such as bumper reinforcements, side door beams and seat belt anchors, in response to regulatory pressures to improve in-vehicle safety. These components were manufactured principally from hot rolled, niobium-treated and precipitation-hardened micro-alloy steels. They had a favourable cost/weight ratio compared to conventional plain carbon steels and required only minor modification to manufacturing methods and facilities. HSS has a higher yield

²⁷ Reheating results in the grains within the structure recrystallising into many finer grains, enabling dislocations to move more easily. As a result the steel becomes softer.

²⁸ There are four methods of press-forming steel: that is, pressing the sheet steel between a punch and die, blanked to the appropriate size: deep drawing; stretching; stretch flanging; bending. The required properties of steel, for example ductility and formability, depend upon the press forming method(s) required for a given component (Takahashi, 2003). More recently hydroforming has become more common – see below.

strength and failure strength compared to mild steel and so improves the impact energy absorbing capacity and resistance to plastic deformation (Li et al, 2003).

The oil crises of the 1970s greatly reinforced the impetus to increased use of higher strength but thinner and lighter steels, especially cold-reduced strip for inner and outer body panels, in order to reduce vehicle weight and fuel consumption²⁹. This, however, posed problems in forming existing types of such steels into more complex or shape-sensitive components such as body panels. While strength increased, the formability of steel decreased and springback increased (as compared to plain carbon steels)³⁰. This stimulated further R&D and innovations in strip production as steel producers developed new grades of high performance advanced high strength steels (AHSS) (Kwon and Baik, n.d.; Llewellyn and Hudd, 2004, 56-85; Takita and Ohashi, 2001)³¹. These steels have very high strength but are easily formed to produce complex automobile parts³². They have specific chemical compositions and microstructures, the latter produced via precisely manipulating sequences of heating and cooling, first slowly cooling, then rapidly cooling (quenching) the steel. This results in morphologies which provide the desired mechanical properties, qualities

²⁹ Plastics or aluminium would have reduced weight further but at considerably increased cost (for example, see Kelkar et al, 2001).

³⁰ Springback refers to the tendency of a metal partially to return to its previous shape. It is positively correlated with the degree of work hardening or strengthening.

³¹ These included dual phase (DT), complex phase (CP), Ferrite-bainite (FB), Transformation Induced Plasticity (TRIP), Twin Induced Plasticity (TWIP) and Martensitic steels. A “phase” is a form of a material having an identifiable composition, characteristic microstructure and properties, and boundaries separating it from other phases (Gourgues et al, 2000; Smith and Hashemi, 2001, 394-6; Toribio, 2004). Phase diagrams show the conditions in terms of temperature and composition that need to be satisfied to produce steels with particular crystal lattice microstructures and so particular properties suited for different uses, the use value of the steel being directly related to its composition and microstructure..

³² Dual-phase and TRIP steels have tensile strengths up to 600 and 800 N/mm² respectively. N/mm² is a measure of pressure, one Newton per square millimetre equating to 145.0377 pounds per square inch. Ultra-high strength steels have tensile strengths up to 1,200 N/mm².

and strength characteristics for a given end use (Takahashi, 2003; Geck, 2010)³³.

The critical element in the manufacturing process, therefore, is precise control of the processing conditions to optimise the microstructure of the steel and produce steels with very specific qualities for particular end uses³⁴. On average replacing conventional steel designs with optimised AHSS designs in a typical five passenger compact vehicle results in a 25% reduction in body structure weight, a 8% reduction in vehicle weight, and a reduction of more than 5% in fuel consumption and lifecycle emissions of greenhouse gases (Opbroek, 2008; see also Obenchain et al, 2002). This allows compliance with tightening environmental regulation while enhancing the ‘green’ credentials of the vehicle and lowering running costs³⁵.

At the same time as new AHSSs have been developed, there have been significant related process innovations that optimise their use, contributing to further weight and cost reduction, linked to advances in computer simulation that enable optimisation of choice of steels and tools (Takita and Ohashi, 2001). For decades each body panel was formed from a single sheet of steel, cut to an appropriate blank size and shape prior to forming, with each part of a pressing made from the same grade of steel. As a result, certain parts of a pressing may have been stronger than strictly necessary or additional strengthening members may have been required to reinforce parts of a pressing that might otherwise have been too weak. In contrast, tailored blanking combines steels with different qualities and thicknesses into a single sheet by laser

³³ Broadly speaking, end uses can be classified as: panels; structural members; reinforcements; and chassis. Steels are produced with the combination of attributes most appropriate to a given use (for details, Takahashi, 2003).

³⁴ Often the introduction of new AHSSs has been synchronised with that of new automobile models (Takita and Ohashi, 2001).

³⁵ The search for more cost-effective grades of steel via collaboration between automobile and steel producers in pursuit of competitive advantage via product innovation is continuous and on-going. For example, following collaboration with several automobile OEMs, Corus announced the creation of a new DP steel, 800 HyPerform, with a hot-dipped galvanised zinc coating, specifically targeted at the automobile sector. It is claimed to be the first to allow automobile manufacturers to use a single steel to produce highly crash resistant lightweight structural and reinforcement components while lowering their price (UK Government, 2010)..

welding prior to pressing. Different parts of the component are designed to optimise shape, thickness and welding arrangements and produced with appropriate properties so as to maximise strength where needed and eliminate excess mass (Trem, 2004). The use of advanced forming technologies such as hot press forming and hydroforming has also increased (Kwon and Baik, n.d.; Obenchain et al, 2002; Singh, 2003). Hot press forming, involving heating steel sheets to which boron has been added to above 900°C and then pressing with cold dyes, is used to produce bumpers, pillars and cross-members. Hydroforming involves forming parts via hydraulic pressure, increasing yield strength and the dimensional stability of steel components while enabling complex parts (such as pillar reinforcements and suspension members) to be formed via a single process. This obviates the need to combine the products of multiple stamping processes and enables AHSSs to be used for a greater range of components and parts. However, the costs associated with fixed capital sunk into presswork technology and the resistance of engineers experienced in that technology have inhibited the speed with which automobile companies have adopted hydroforming in producing the body-in-white (Godwin, 1998).

As pressures to reduce the weight of vehicles continue, especially with the introduction of electrically-powered automobiles with electric motors powered by heavy batteries, European automobile manufacturers and stainless steel producers collaborated in the Next Generation Vehicle (NGV) project. This involved exploring the use of stainless steels for various structural components of vehicle frames, such as door pillars³⁶. In particular, nickel-containing grades of metastable, austenitic

³⁶ There are alternative materials such as aluminium alloys, against which stainless steels compete on both price and qualities.

stainless steels were identified as particularly appropriate³⁷. These austenitic steels have a high work hardening rate, becoming stronger as they are deformed and hydroformed or cold-rolled into components. Moreover, in a collision they absorb more energy than carbon structural steels. They can therefore replace carbon steels while meeting regulatory crash-safety standards and providing greater protection to the vehicle occupants in a crash (Anon, 2008). Computer Aided Engineering (CAE) programmes allow engineers to simulate crashes using dynamic material properties and ensure that vehicle designs maximise safety (Oberchain et al, 2002).

Using austenitic stainless steels for structural components could reduce the weight of an average-sized European automobile by 90-110 kgs (Robert Gustafsson, manager of the NGV project: cited in Gehr, 2009, 37). In addition, these steels can be welded to carbon steels, enabling different types of steel to be used as appropriate in the vehicle body (Schuberth et al, 2008, 6). This is important, as austenitic stainless steels can be up to three times more expensive than carbon steels (Gehr, 2008). In the logic of commodity production it is important that they are only used in applications that optimise the benefits of their particular qualities and allow a cost effective trade-off of weight reduction against greater unit price.

Potentially more significant, however, is the further development as part of the NGV of software programmes that simulate all stages of production, taking metal through each step of forming and welding in the process of materials transformation. These programmes enable engineers to model the transformation process and see how substituting grades and fabrication processes can enhance the qualities of the

³⁷ Stainless steel, the most corrosion resistant type of steel (Ashby and Jones, 1992, 119), became increasingly used for vehicle exhausts from the 1970s, in addition to radiator grills and external and internal trims. Austenitic stainless steels contain a maximum of 0.15% carbon, a minimum of 16% chromium and sufficient manganese and/or nickel (at least 8%) to retain an austenitic structure at all temperatures (Llewellyn and Hudd, 2004, 515-6, 330-332).

finished part. According to Gustafsson, “Without the software it wasn’t really possible to simulate this [the transformation process] in a proper way, taking into consideration the deformation hardening and the way that happens. It’s a big step forward, enabling car makers and other manufacturers to determine the best materials and applications without having to build and test parts that won’t make the grade” (cited in Anon, 2008, 7)³⁸. Consequently, these developments are important in minimising R&D costs as well as of subsequent production costs via optimising the use of materials.

Engineering steels and automobile production

Very different types of high tensile strength ($> 750 \text{ N/mm}^2$) steel are required for engine and transmission components that will be subjected to high levels of service stress. These engineering steels encompass a wide range of compositions, all of which until recently have generally been heat treated to produce the required tensile strength levels via generating lower temperature transformation microstructures, principally bainite and martensite. The critical property of engineering steels is their hardenability³⁹, their capability to produce a particular level of strength in a specific section size (the ruling section) and harden in depth (rather than simply on a surface layer). Achieving hardenability depends upon the addition of appropriate alloying elements and the cooling rate on a specific composition or section size.

There have been important innovations in engineering steels, especially following the development of isothermal transformation (ITT) diagrams in the 1930s (Bain and

³⁸ Individual steel companies make such software freely available to potential users (for example, see Corus, n.d. (b)). For a further example of developments in simulation via finite element modelling (FEM) of the fabrication and use of TRIP stainless steels see Schedin et al, 2008. FEM involves computer simulation of a wide variety of different forming operations for 3-D shapes by computer-aided engineering (Llewellyn and Hudd, 2004, 35-6).

³⁹ Although rather clumsy, this term is used in the technical literature on steel and so is used it here

Davenport, 1930, reprinted 1970). Until the late 1940s engineering steels for automobile engines and transmission parts were largely based on compositions containing substantial amounts of nickel and molybdenum (Ni-Mo) to give the required high levels of strength (from nickel) and toughness and wear (from molybdenum). During the 1950s, however, research revealed that many such steels were over-alloyed in relation to the hardenability requirements of the components and that the required levels of strength could be achieved with steels of leaner compositions – and so produced at lower cost, giving them a competitive advantage. In the 1960s, the emerging technology of fracture mechanics provided greater knowledge of the level of toughness required in engineering components and revealed that satisfactory performance could be provided by alternative steel compositions. Coupled with major advances in heat treatment technologies⁴⁰, this led to the gradual replacement of Ni-Mo grades by cheaper steels involving additions of manganese, chromium and boron to enhance hardness and tensile strength, By the 1970s the potential for alloy reduction had largely been exhausted but competitive pressures among automobile manufacturers translated into competitive pressures among steel producers as they fought for market share. As a result, there was increasing exploration of the scope for reducing manufacturing costs, especially those of heat treatment processes. The established method of producing components such as crankshafts or connecting rods involved specific sequences of heating and cooling⁴¹. In the mid-1970s German steel companies created a micro-

⁴⁰ Heat treatment allows manipulation of the properties of steel by controlling the rate of diffusion of carbon and the rate of cooling within the microstructure. Phase transformations in steel are heavily influenced by kinetics and result in varied crystalline microstructures and varying grain sizes, both of which are strongly influenced by the rate of cooling, and steels with varying mechanical properties appropriate to different end uses.

⁴¹ Cool to room temperature, reheat to about 850°C, then quench in oil. Tempering at 550-650°C then yields a tensile strength in the range 800-1,100 N/mm².

alloy, medium-carbon steel⁴² after air cooling following forging, eliminating the need for expensive heat treatments. Subsequently, other steel producers, especially in the rest of Western Europe and Japan, developed similar micro-alloy⁴³ forging steels, which gradually replaced quenched and tempered steels in the production of components such as crankshafts, connecting rods, steering knuckles, axle beams and tension rods (Korchynsky and Paules, 1989). Adoption of such micro-alloy steels generates substantial cost savings, for three reasons: they incorporate less expensive alloys than the alloy grades they replaced; they eliminate heat treatment costs; and they give improved machining characteristics. The ability to reduce costs became increasingly important to engineering steel producers in North American and Western Europe as the international division of labour in steel changed and NICs, especially India and those in the Far East, developed the capacity to produce engineering steels. For example, by the latter part of the twentieth century, gearbox forgings from these places were 40% cheaper (Corus Engineering Steels, 2001, 10).

Machinability is a particularly important attribute of engineering steels, since machining can account for up to 60% of the cost of production of automobile components. It can be enhanced via adding small amounts of sulphur, calcium and tellurium (Llewellyn, 1995, 164-7). Machining involves a variety of operations (for example, turning, milling, grinding, and drilling), several of which may be carried out in sequence on an automated lathe in the production of a single component, while each involves differing metal cutting actions and conditions of temperature, strain rate and chip formation. Indeed, for components that are mass produced at high machining rates, such as hose couplings and spark plug bodies, the mechanical

⁴² A carbon content of between 0.30% and 0.59% balances ductility and strength.

⁴³ The most commonly added alloy is vanadium, which effectively combines grain refinement and precipitation hardening, maximising the strengthening process: Korchynsky, 2001)

property requirements of the steel are minimal and the pre-eminent requirement is a high and consistent level of machinability in low-carbon free-cutting steel.

For other components, however, machinability matters for different reasons.

Automotive transmissions components, such as gears and axles, must be produced to very demanding tolerances, minimising distortion in order to prevent misalignment, overloading and premature failure. Distortion represents a potentially significant problem in producing precision engineered gears and axles. Slight inaccuracies in shape lead to irregular tooth contact patterns and to problems ranging from a high level of noise in the gearbox or axle to premature fatigue failure because of overload. Given that dimensional change under fast-cooling conditions is inevitable, coping with it depends upon control and consistency of response and this requires predictable and appropriate properties in the steel used to form the component.

As a result, automobile manufacturers generally specify carburised steels with narrowly defined hardenability bands to minimise the variation in distortion such that changes can be accommodated in the pre-treatment geometry, while reducing temperature gradients during quenching to reduce the degree of irregular dimensional change. Carburised steels have a duplex microstructure combining a hard fatigue-resistant martensitic case with a lower strength but tough and ductile core⁴⁴. Tempering at about 200°C then releases the internal stresses in the steel without causing any significant softening in either core or case, minimising distortion and allowing very accurate forming and machining of components (Llewellyn and Hudd, 2004, 210-227).

⁴⁴ They have a surface layer with a carbon content of about 0.8% and a lower carbon content core - around 0.2% - a result of gaseous diffusion of carbon in the austenite state into the surface layers of low carbon steel.

In summary, a considerable variety of types of steel can be made to meet the demands of automobile producers. In part this is a result of steel producers responding to competition on performance and costs from other materials (chiefly aluminium and plastics). In part it has been driven by competition among steel companies. The net result is that steel producers have found it imperative to improve production processes and devise new steel compositions and ways to produce and process them. There have been significant process and product innovations in steel production, which is now deeply grounded in scientific knowledge about materials, their properties and processes of materials transformation and in sophisticated computer-controlled production processes managed via expert systems that combine scientific knowledge created in research laboratories with knowledge that once was tacit but has now been captured in codified form. As a result, it is now possible to manufacture an immense variety of types of steel, depending on the interplay of chemical composition, production processes, production costs and market forces, on the interrelations between processes of material transformation and those of value creation. Different combinations of alloying elements result in steels with different properties such as hardness, tensile strength and ductility. The properties of steels can be further manipulated via physical processing (such as rolling, pressing and forging) and sequences of heating and cooling. Consequently, the type of steel required for a particular end use – in this case automobile manufacture - can be precisely specified and the production process designed to result in steel with the required and desired properties. This ability to manipulate the properties of the metal is critical in establishing its use value, the use to which the steel will be put and the possibilities of using it as a component of constant capital in

commodity production, although there is also an important relationship between the complexity of the transformation process, the cost of the product and demand for it.

Conclusions

The starting point for this paper was that a CPE needs to take on board the challenge that originates in Marx's seminal contributions of conceptualising the economy as conjoined processes of value creation and material transformations, whatever the epistemological dilemmas this might pose. This is because, *inter alia*, the successful production of commodities requires knowledge of their constituent materials and their potential transformations and the ways in which these can be managed through the production process to allow the creation of surplus-value and profits.

Over a period of many years, chemists, metallurgists and physical scientists have built up, and continue to expand, a body of knowledge about the compositions and processes through which different kinds of steel can be produced. This enables them to predict the attributes and qualities of the resultant steels. Consequently, they can respond to the demands of – say – automobile producers for steels with particular characteristics. This is crucial since the ability to manufacture particular components of a vehicle to the required standard and accuracy depends upon the characteristics of the steel used for that component. The use value of the steel – and hence its potential exchange value – is a consequence of its microstructure and chemical and physical attributes. For example, to produce a smooth, efficient transmission system requires the use of appropriate types of engineering steel for each of its component parts. To produce light, corrosion-resistant and safe car bodies requires very different types of sheet steel. Understanding the basis of the use value and

exchange value potentially contained in these steels – and so their potential for the creation of surplus-value - therefore presupposes knowledge of the material transformations involved in steel production. Clearly, the realms of value creation and materials transformation are inextricably conjoined as different steels are produced as commodities which in turn enter (in the form of constant capital or elements of fixed capital) as inputs into the creation of other commodities

The example of the steel industry illustrates how a wide range of materials can be produced with a variety of desirable properties via combining alloying metals with iron and through careful (now typically computer) control of the production process, especially in terms of the composition of the metal and heating and cooling in particular ways. Manipulation and sophisticated management of the production process depends upon knowledge of the attributes and properties of materials and of the ways in which they can be combined and transformed to give types of steel with particular desired combinations of properties. Capitalist interests have increasingly shaped the processes of R&D through which knowledge about materials, their properties and their transformations have been developed and deployed to produce profits via producing steel and – inter alia - automobiles .

The paper can thus be seen as a response to the challenge laid down by Bakker and Bridge (2006, 13) to understand better how “the properties of the new steels (hardness, ductility, physical and chemical stability) [enabled] the rise of production of interchangeable parts and the cultural values associated with the mass consumption of standardised products” that was central to the rise of Fordism and its high volume flexible production successors. Knowledge of material properties and transformations is certainly required for successful commodity production, but it is a necessary not sufficient condition. While there have been references to the

economics of production, market competition and regulatory requirements and the influences that shape these, a more comprehensive critical political-economic analysis would need to bring together consideration of the properties of matter and material transformations with fuller consideration of the ‘traditional’ concerns of political economists and economic geographers, such as analysis of the labour process, production costs, IPR and patents, markets and profits and so on, and the ways in which these influences intersect with the characteristics of places to shape the spatiality of production. In this way a thorough recognition that production is always both a value creating process and a process of materials transformation could be restored to the centre of a CPE. As a necessary corollary, however, critical political economists need to engage with the forms of knowledge of ‘traditional theory’ used by physical scientists in their studies of materials and materials transformations in order to appreciate the material limits to and possibilities of transforming production.

Furthermore, while steels are very important materials in the economy, there are many others, with more complicated processes of transformation, such as carbon-based chemicals, that require analysis if the links between materials transformations and value creation are to be more fully explored within CPE, perhaps via detailed case studies of the production of particular commodities. Explicitly exploring the properties of materials and processes of material transformations alongside considerations of value creation, meanings and symbolic representation opens the possibility of filling a void in CPE and analyses of economies and their socio-spatial organisation.

I want to end, however, on a normative point that relates to the sort of economy that might be imagined as an alternative to contemporary forms of capitalism, What, to

borrow and adapt a phrase from Vogel (1996, 168), could and should the communicatively and practically constituted economy be like? To begin to answer this question, not only do we need better understanding of the relationships between the properties of materials and the mix of commodities currently produced but also better understanding of the limits to and possibilities of what it is materially as well as socially possible to produce. Such knowledge is crucial to any consideration of different ways of organising the economy and of producing a different material world in which people could live (for example see Allwood et al, 2010). Put another way serious consideration of what we ought to produce requires knowledge of the material possibilities for and limits to production.

Acknowledgments

This paper draws on work carried out as part of the ESRC-funded project, “The Waste of the World” (RES-060-23-0007). Thanks to Richard Thackray for helping me better understand processes of steel production. Thanks also to Noel Castree, Mike Crang, Peter Dicken, Nicky Gregson, Costis Hadjimichalis, Ron Johnston and Roger Lee for illuminating and valuable comments an earlier draft. I’d also like to thank three anonymous referees for their detailed and constructive, comments on this version, to which I have attempted to respond. However, all are absolved from remaining errors and the usual disclaimers apply.

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Table 1 Production, R&D and partnerships of selected major steel companies, early 2000s

Company	Capacity (mt)	Automotive steel as % total production	R&D – average annual expenditure \$USm and/or R&D staff	Global R&D partnerships
Acelor	46.0	68	175m, 1500 staff	NS, TK
POSCO	27.0	14	151 m	NS
Nippon Steel	25.2	67	74m	AG,PS
JFE Group	23.9	37	307m	TK
Riva Group	21.6	N/A	N/A	N/A
Thyssen-Krupp	17.0	16	176m, 3500 staff	JFE, AC
US Steel	14.4	55	N/A	N/A
Bethlehem Steel	11.3	20	200 staff	N/A
Baoshan Iron and Steel	11.0	N/A	430 staff	NS

Corus	8.8	16	199m	N/A
Dofasco	4.4	35	N/A	AG

Notes: PS – Pohang Steel

Source: adopted from Warrian and Mulhern, 2006; with additional material from Acelor, 2005; ThyssenKrupp, 2010; Corus, n.d.